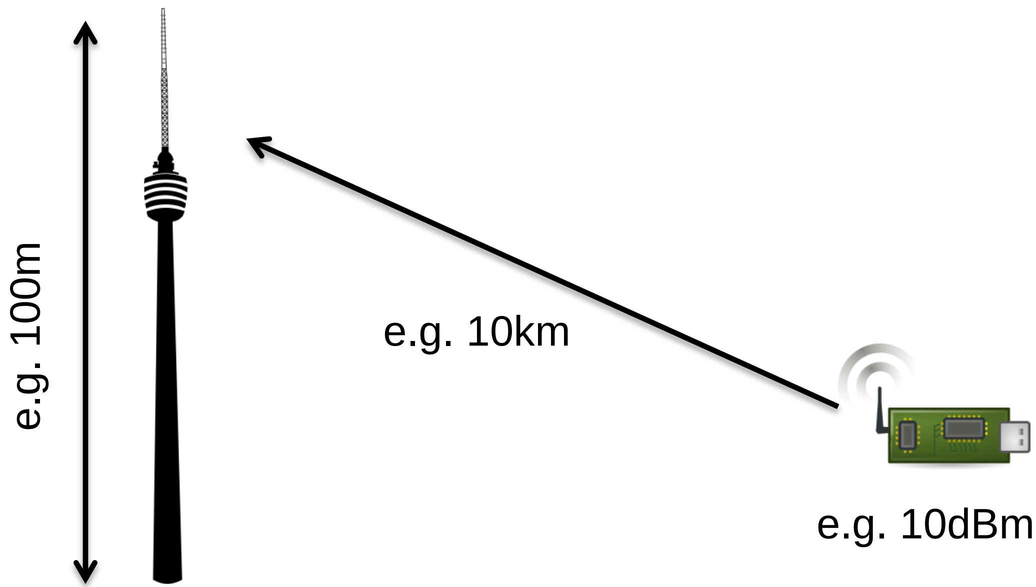
LoRa Technology for low power area networks

Ilenia Tinnirello, Università di Palermo
ilenia.tinnirello@unipa.it

Concept of Low Power Wide Area Networks (LPWAN)



- ⇨ Small and cost-efficient sensors nodes communicate using ultra-low power over ultra-long distances
- ⇨ A base-station at highly exposed sites serves up to one million sensor nodes
- ⇨ Typical application scenarios: Water/gas metering, environmental monitoring

Challenges of LPWAN

- ➔ **Ultra-low power in addition to long distances leads to very weak reception levels**
  - ⇨ typical assumption < -140dB
  - ⇨ very low bit rates (1 < kbit/s)
- ➔ **Interference from other services as license-exempt bands are commonly used**
  - ⇨ e.g. 434MHz, 868/915MHz, 2.4GHz
- ➔ **Further increased interference at base-station due to highly exposed antennas**
- ➔ **Concepts as CSMA do not work because of the hidden node problem**
  - ⇨ Use of spread spectrum (e.g. DSSS) or frequency hopping

Potential Standards for LPWANs

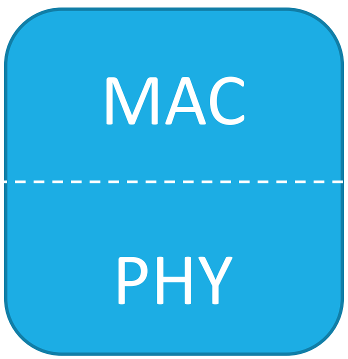
- ➔ **Focusing on license-exempt bands:**
  - ⇨ IEEE 802.15.4k
  - ⇨ SIGFOX
  - ⇨ LoRaWAN
  - ⇨ ETSI LTN, Weightless, IEEE 802.11ah
  - ⇨ ...
- ➔ **Focusing on licensed bands:**
  - ⇨ 3GPP standards, e.g. NB-IoT (Narrow Band IoT)

LoRa Technology and Stack

Typical Stack

Standardized MAC/PHY

One stack, many suppliers



LoRa Stack

Patented PHY + open LoRaWAN MAC

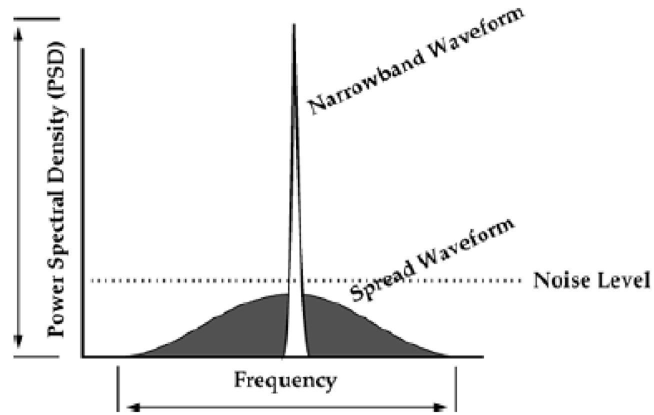
One supplier, personalized stacks

LoRa PHY

How to reach very far distances?

➔ **Increasing energy per bit**

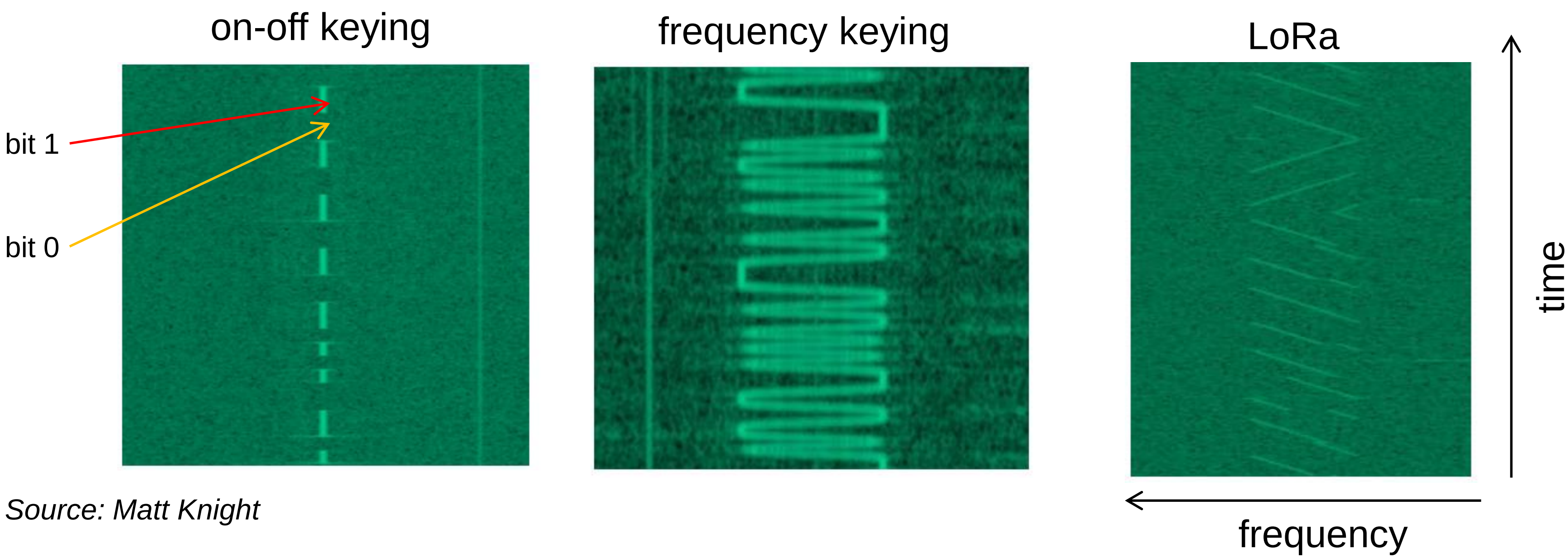
- ⇨ By acting on transmit power
- ⇨ By using spread spectrum for coding a bit with a large bandwidth



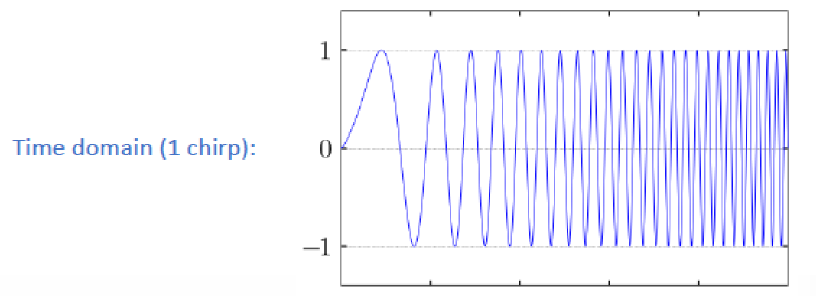
➔ **LoRa acts on spread spectrum**

- ⇨ A variation of chirp-spread spectrum
- ⇨ Robust to interference, multipath, and fading
- ⇨ Developed by Cycleo, acquired by Semtech in 2012

Comparison with other modulations

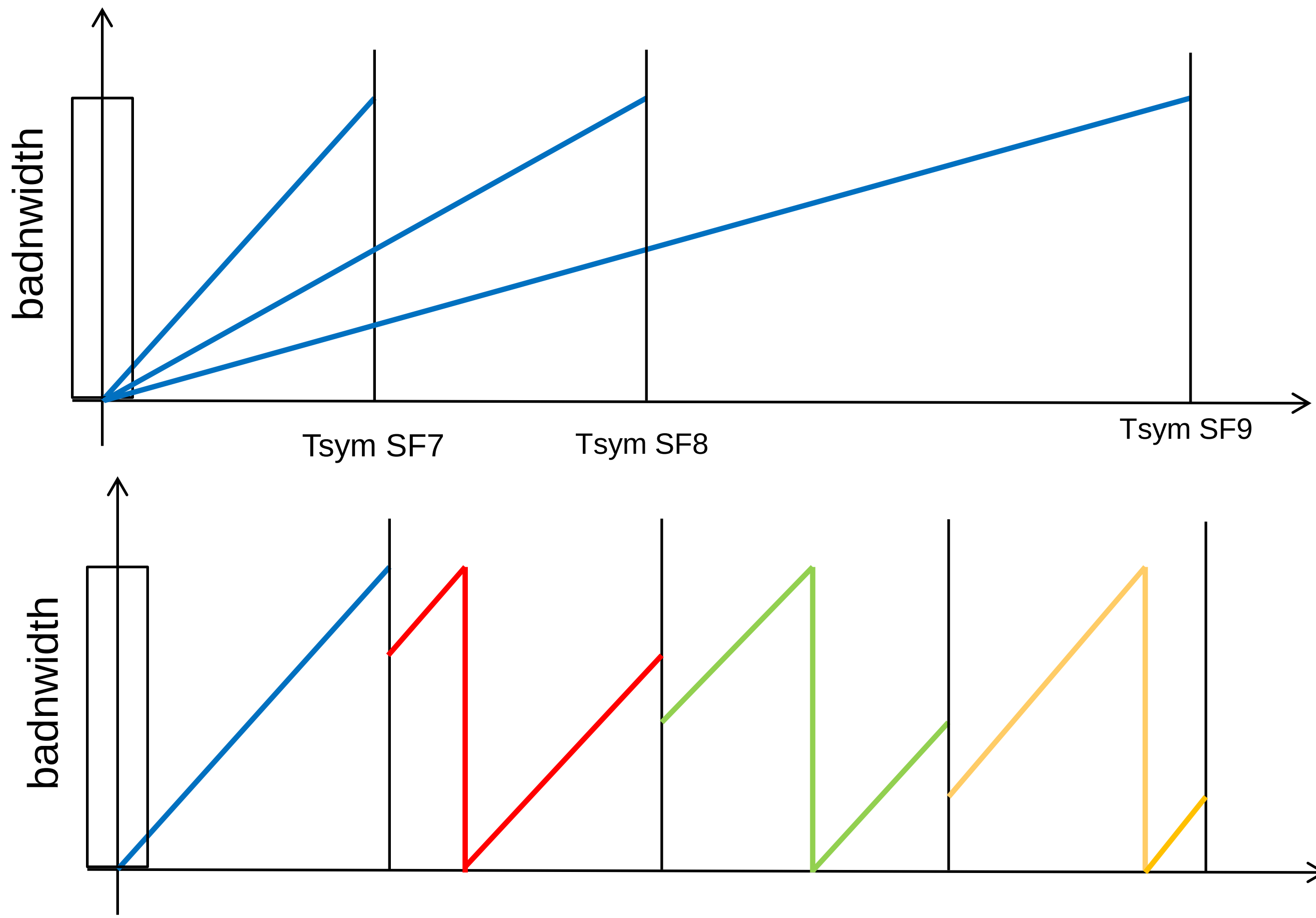


Source: Matt Knight



constant envelope modulation,
easy to implement

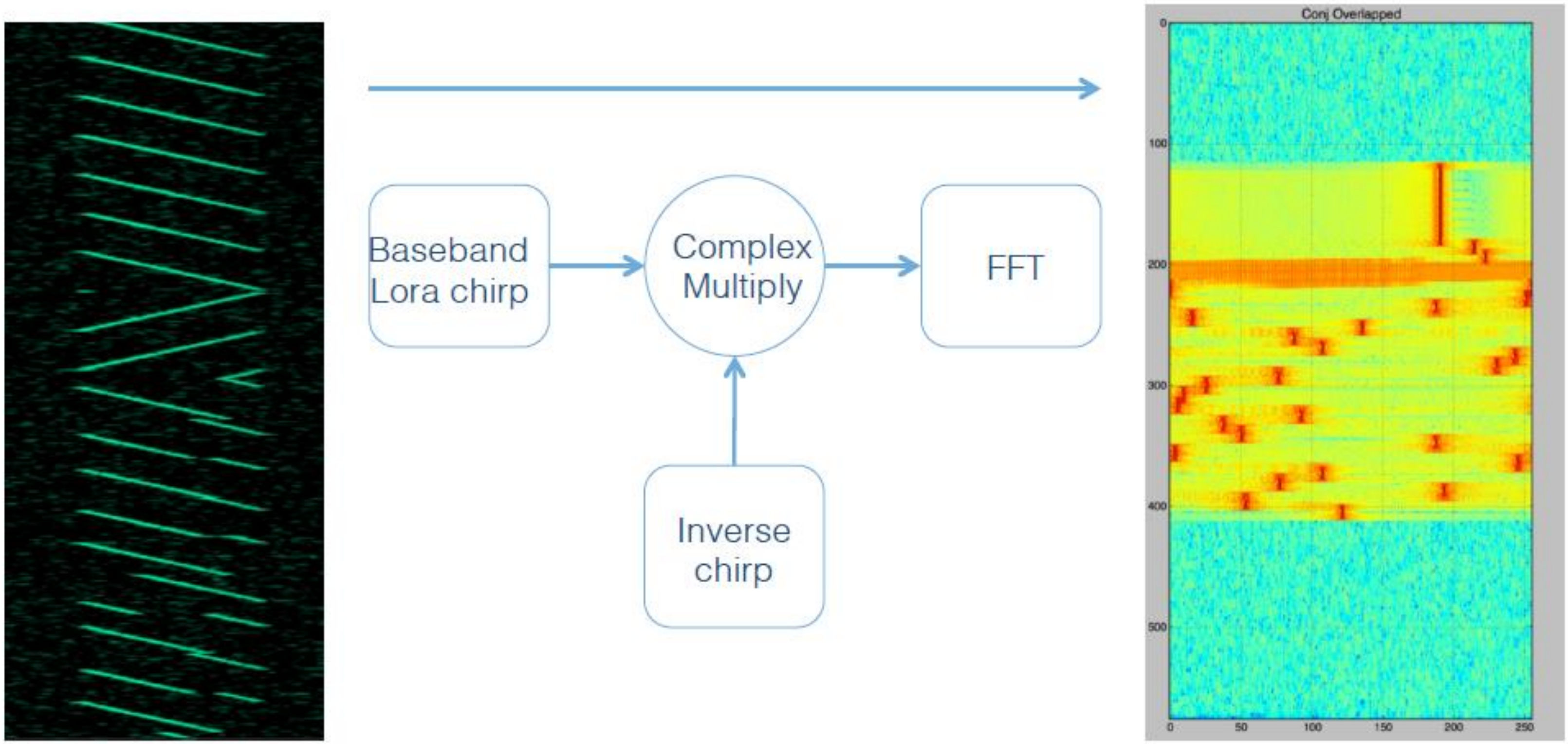
Symbols and Spreading Factor



Different SFs are namely orthogonal!

2^{SF} different symbols coding SF bits in Tsym

LoRa Demodulation



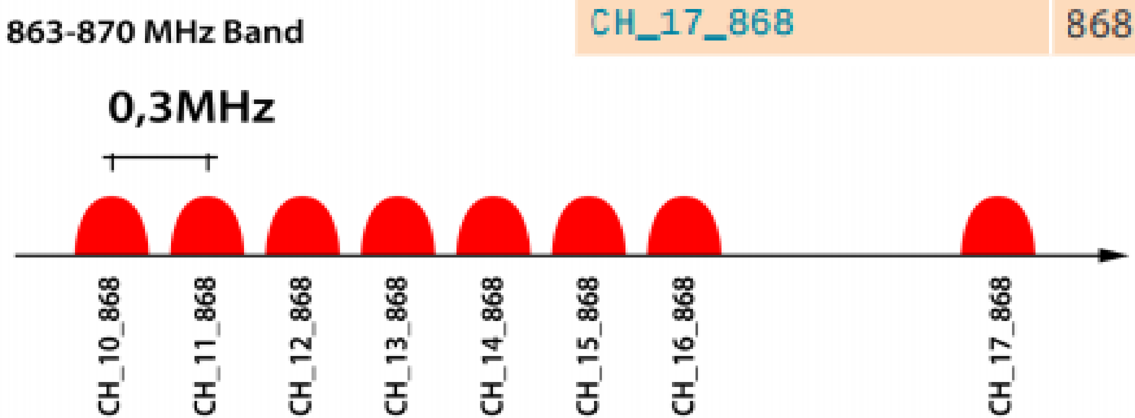
Source: Matt Knight

It can work 20dB under the noise floor!

LoRa ISM frequency bands

- ➔ **Maximum transmission power 14dBm (25mW)**
- ➔ **Three possible bandwidths**
  - ⇨ 125, 250, 500KHz
- ➔ **6 SFs available**

Channel Number	Central Frequency
CH_10_868	865.20 MHz
CH_11_868	865.50 MHz
CH_12_868	865.80 MHz
CH_13_868	866.10 MHz
CH_14_868	866.40 MHz
CH_15_868	866.70 MHz
CH_16_868	867 MHz
CH_17_868	868 MHz



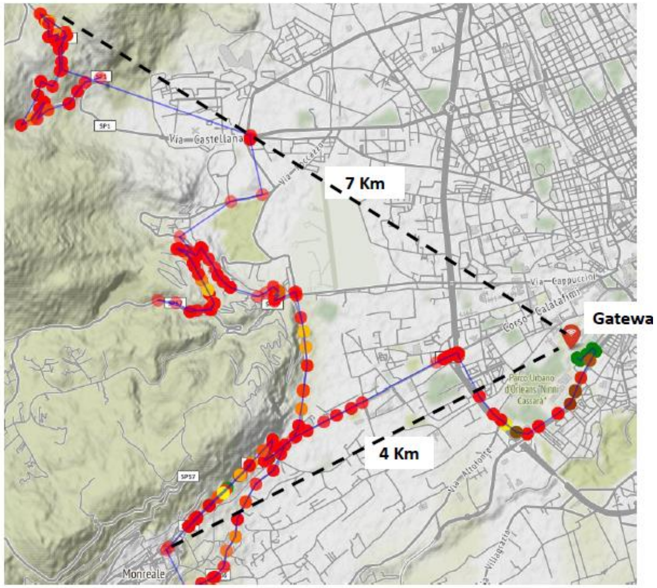
Summary on Data Rates 125 KHz

Spreading Factor	Chips/symbol	SNR limit	Time-on-air (10 byte packet)	Bitrate
7	128	-7.5	56 ms	5469 bps
8	256	-10	103 ms	3125 bps
9	512	-12.5	205 ms	1758 bps
10	1024	-15	371 ms	977 bps
11	2048	-17.5	741 ms	537 bps
12	4096	-20	1483 ms	293 bps

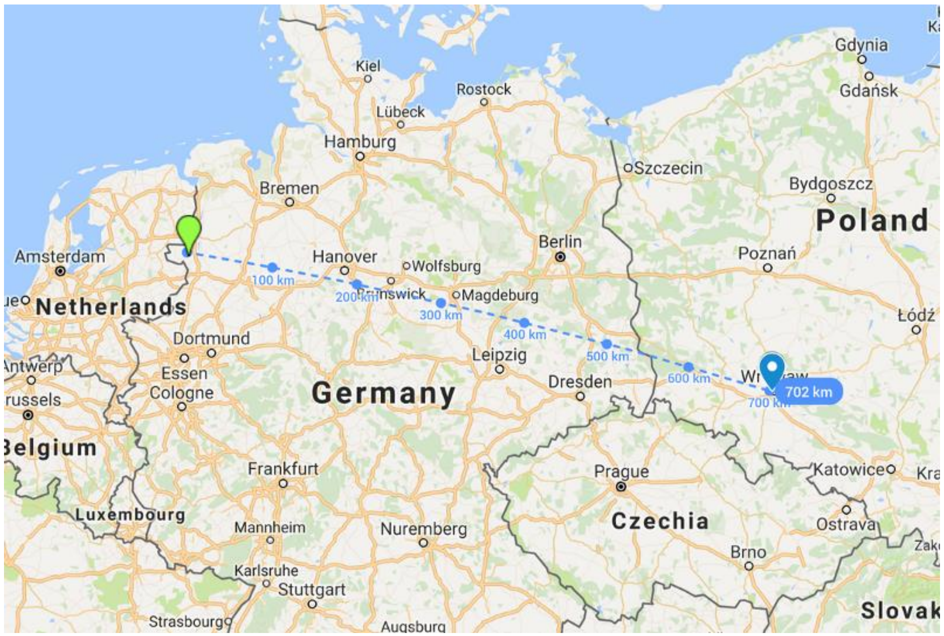
with two additional high-speed channels at 11kbps and 50kbps (FSK modulation)

Coverage

- ➔ **Different sensitivities map to different distances**
  - ⇨ e.g. from -126.50 dBm for SF7 to -133.25dBm for SF12
  - ⇨ 7 dB of difference with a propagation coefficient equal to η=4 correspond to a factor of about 2.5 between range(SF12) and range(SF7)
- ➔ **Typical links of a few Km**
  - ⇨ Experimental tests with an indoor GW at our Department for SF12



..up to hundreds of km!



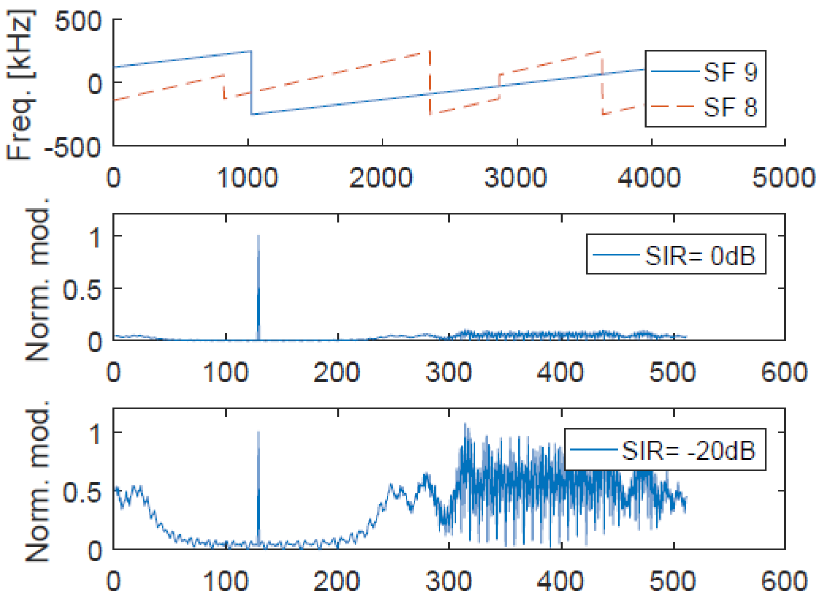
LoRa from a balloon at 38km from the ground

LoRa from space?

- ⇨ the Norwegian Space Centre, NORSAT-2 which normally transmits AIS information in the VHF bands was modified to transmit LoRa messages from 600km!
  - → Sent on the Ku band, but on LoRa modulation

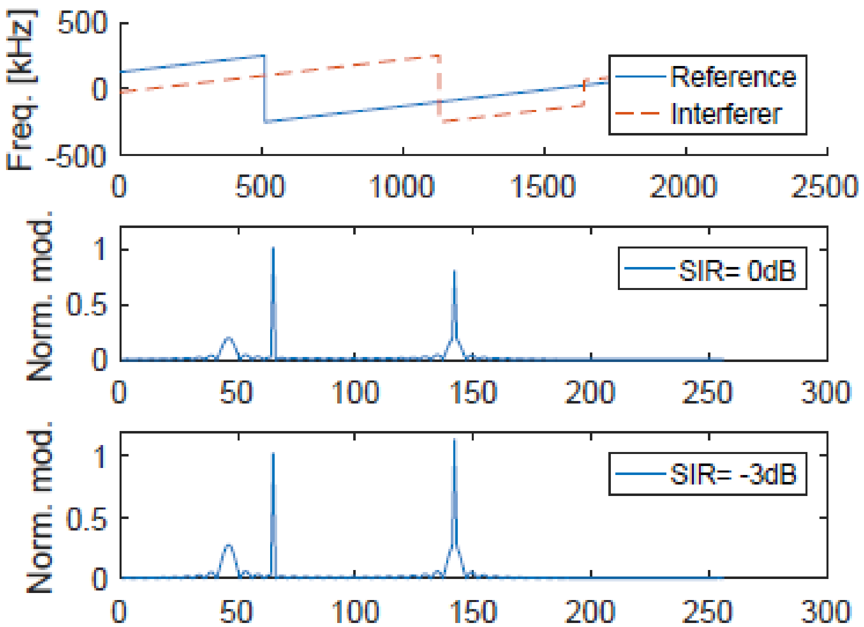
LoRa Inter-SF Interference

- ➔ **Symbols using different SFs are orthogonal only if perfectly synchronized!**
  - ⇨ In practical, never!
  - ⇨ Capacity is affected by non-null cross-correlation
    - → Rejection thresholds as low as -10dB



LoRa Intra-SF Interference

- ➔ **If the symbol is correctly synhcronized, very high capture probability**
  - ⇨ Collisions with signals transmitted at the same SF very often result in the correct reception of the strongest one!
    - → Capture threshold of about 1dB

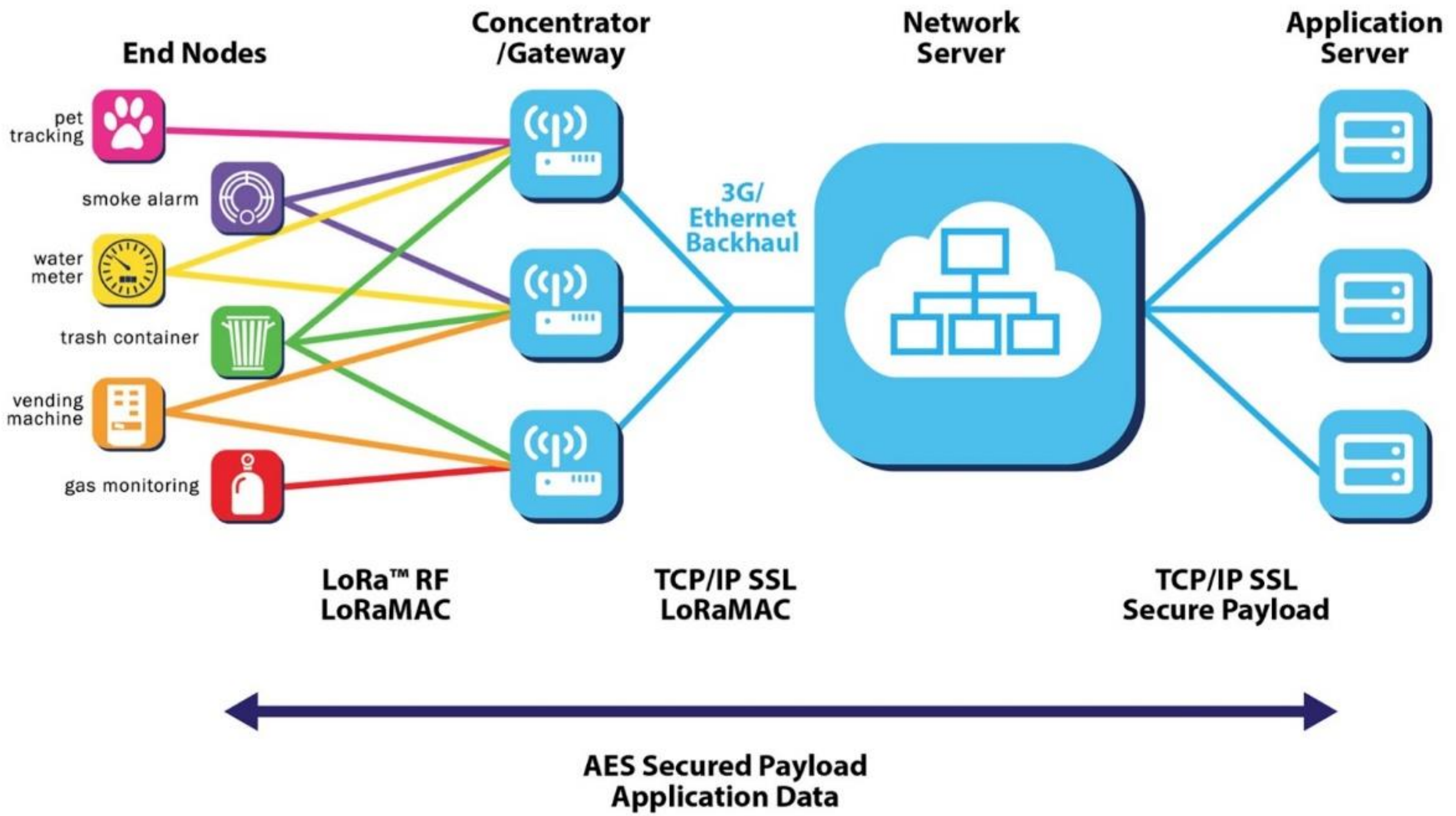


LoRaWAN

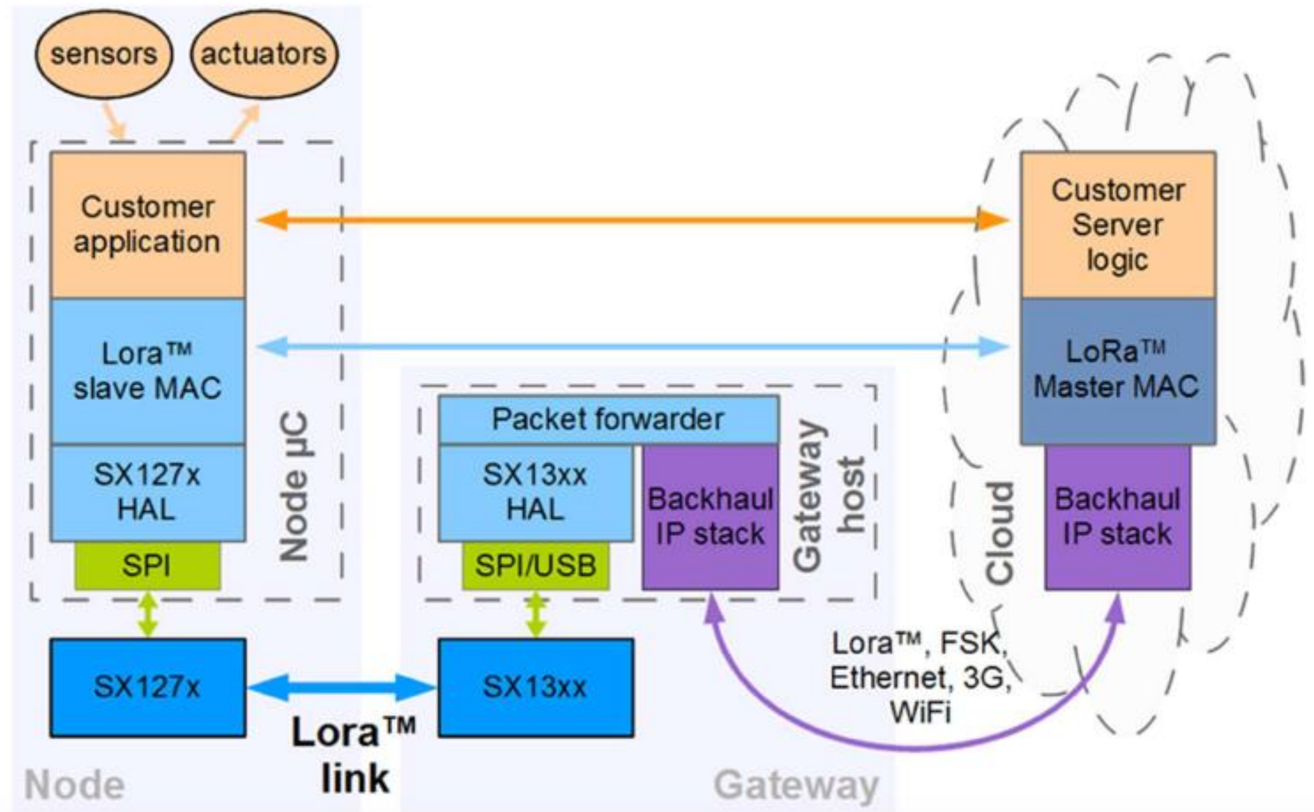
What is LoRaWAN?

- **Communications protocol and architecture that utilizes the LoRa physical layer**
  - Standardized by the LoRa Alliace
  - www.lora-alliance.org
- **Supports:**
  - secure bi-directional communication,
  - mobility
  - localization

Network Nodes



LoRaWAN Architecture



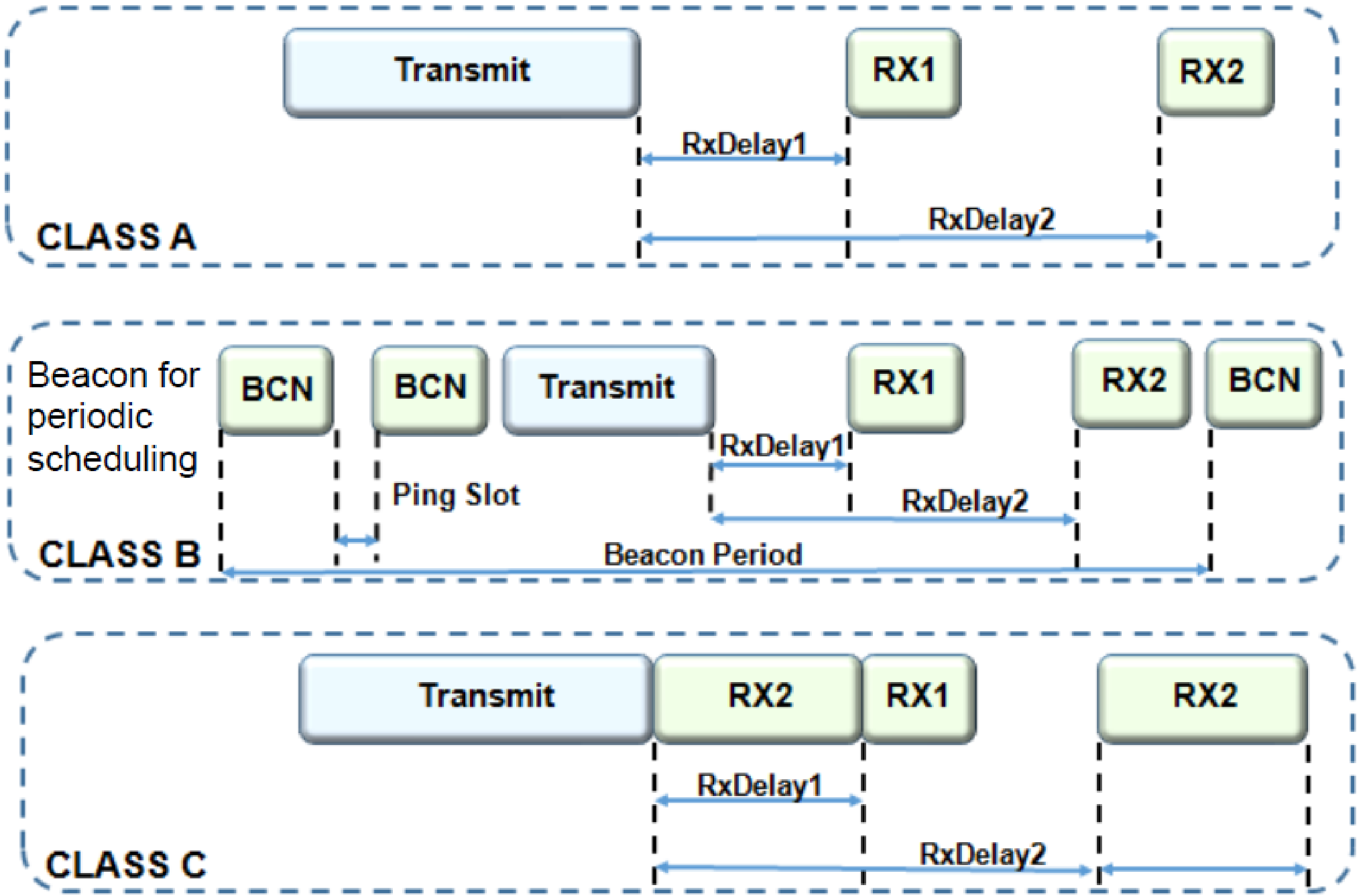
Source: Thomas Telkamp

End Devices

➔ **Three classes of devices for different application requirements**

- ⇨ **Class A**: each uplink transmission is followed by two short downlink receive windows
- ⇨ **Class B:** like A, but extra receive windows at scheduled times
- ⇨ **Class C:** continous receive window, except when transmitting

Receiver Windows



Gateway

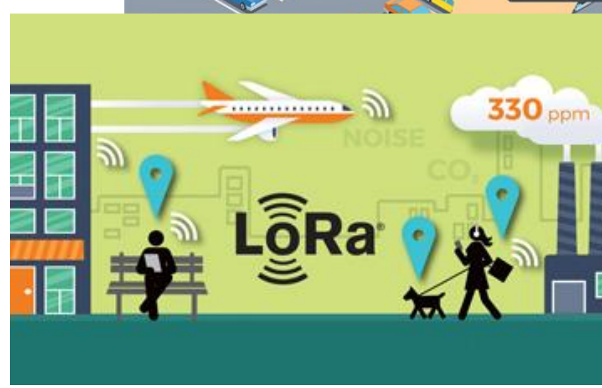
- ➔**Collection points deployed on field**
  - ⇨All GWs receive ALL channels ALL the time
    - →No network controller or reuse planning required
  - ⇨Sensors can communicate with any gateway
  - ⇨All correctly demodulated packets are forwarded to the network server

Network Server

- ➔ **Network intelligence centralized**
  - ⇨ Responsible of identifying duplicates between packets
  - ⇨ Data validation and demultiplexing / multiplexing to application servers
    - → Multiple application providers can co-exist on the same network
  - ⇨ Localization possible, thanks to a central time referene for all gateways
- ➔ **Low cost gateways, since decisions on network configurations (if any) are taken by the server**

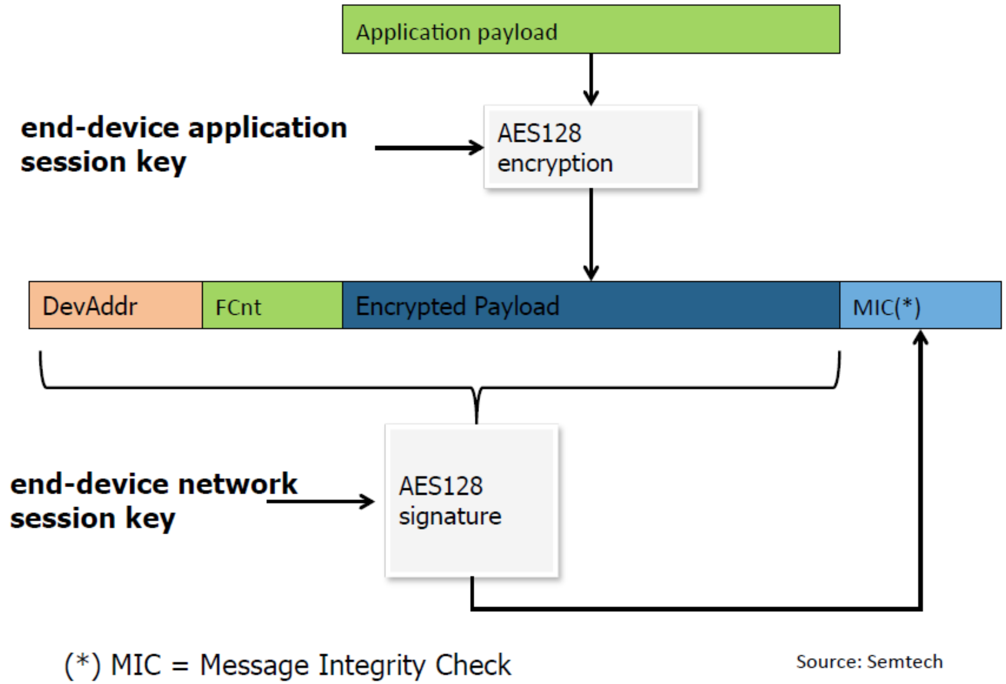
Application Examples

- **Agriculture**
  - Animal health monitoring
  - Water conservation
- **Asset management**
  - Utilization of resources
  - Asset tracking
- **Smart City**
  - Energy conservation
  - Operational efficiencty
- **Smart Buildings**
  - Deep indoor pentratation
  - Safety and security

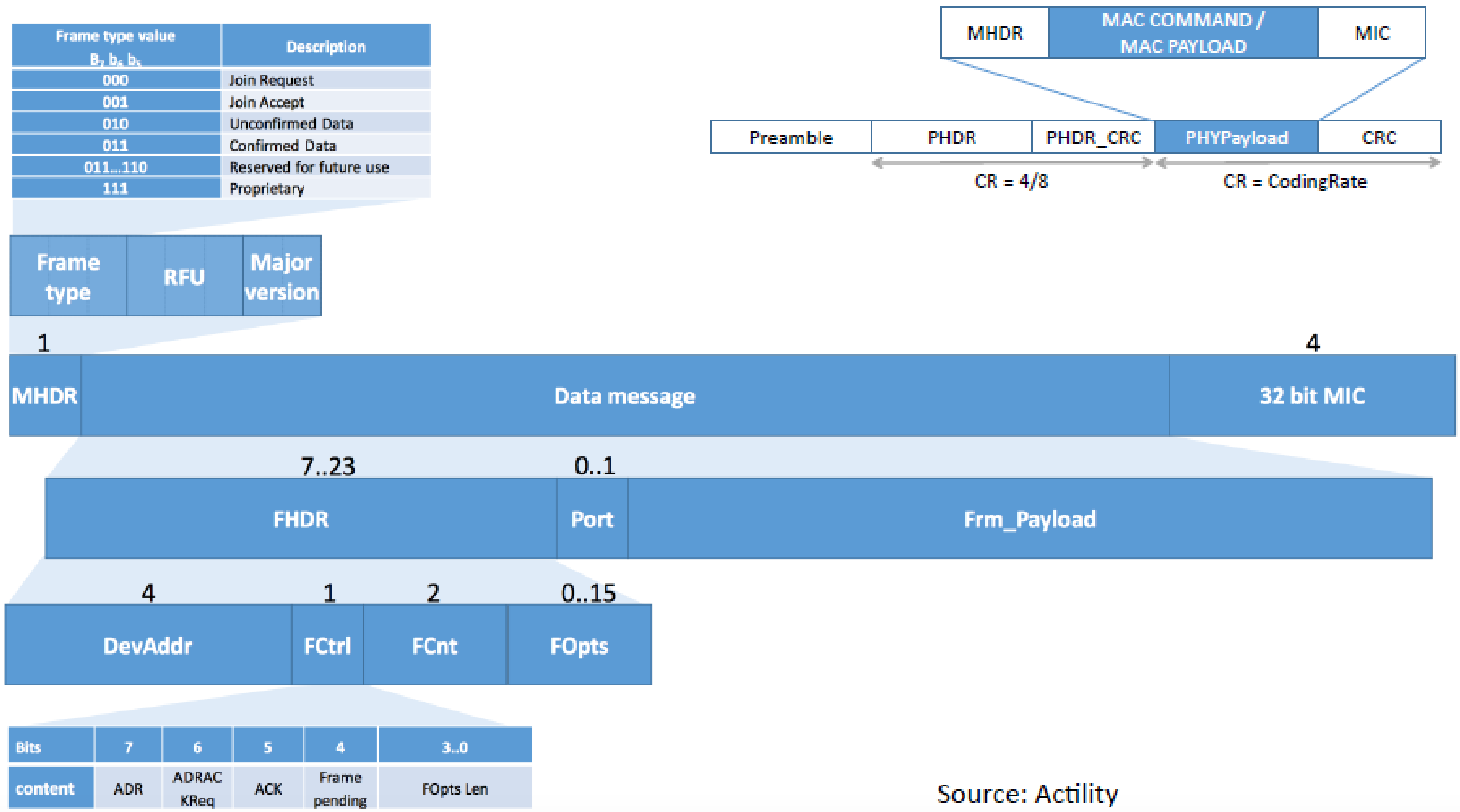


Security

- ➔ **Two layers of security**
  - ⇨ Network (newSkey)
  - ⇨ Application (128 bit key length)
- ➔ **Network security for authenticating users and add message integrity check**
- ➔ **Application security for separating application data from network operators**
- ➔ **Activation by Personalization or over the air**



LoRaWAN Frame



Source: Actility

MAC Commands

Command	Description
LinkCheck[1]	has the purpose of validating the connectivity of the device to the network
LinkADR	used to request to the end-device to change data-rate, transmit power, repetition rate or channel
DutyCycle	allows to set the maximum duty-cycle of a device for transmission
RXParamSetup	used to change the reception parameters of the device
DevStatus	used by the network server to reset the status of the device
NewChannel	allows to modify the definition of the radio channel parameters
RXTiming	used to setup the time slots for reception by the device
TXParam	used to change the transmission parameters
DlChannel	allows to create an asymmetric channel by shifting the downlink frequency band with respect to the uplink one (otherwise they have the same band)

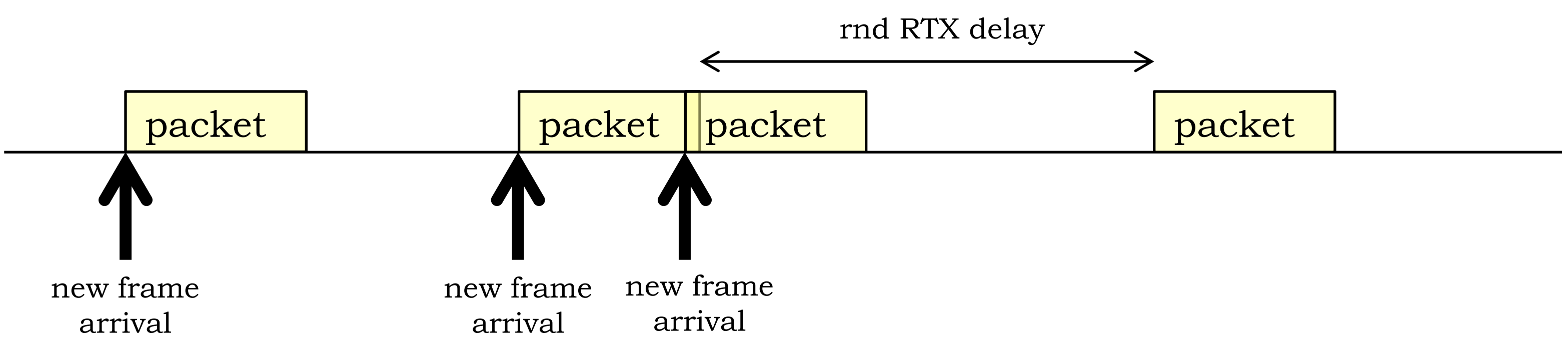
Cell Capacity

Single cell LoRa Capacity

- ➔ **Basically, a pure aloha system**
  - ⇨ Very limited system efficiencty of about 18%!
- ➔ **For a given traffic model, what is the maximum number of nodes which guarantees to work in stable conditions?**
- ➔ **Can capture effects improve such a result?**

Back to ALOHA

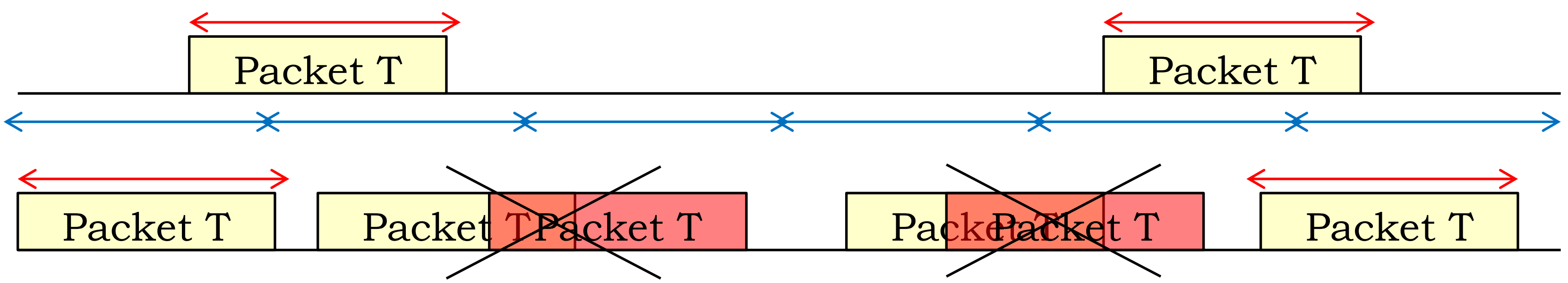
- ➔ **No synchronization at all between transmissions**
- ➔ **If a pkt needs transmission:**
  - ⇨ send immediately, provided that duty cycle is satisfied
- ➔ **In case of collisions, reschedule or cancel**
  - ⇨ In LoRa ACKs from the gateways are used rarely, therefore cancel
- ➔ **Simplifying assumptions:**
  - ⇨ Extremely high number of devices,
  - ⇨ Fixed length frames
  - ⇨ Frame arrival rate follows Poisson distribution



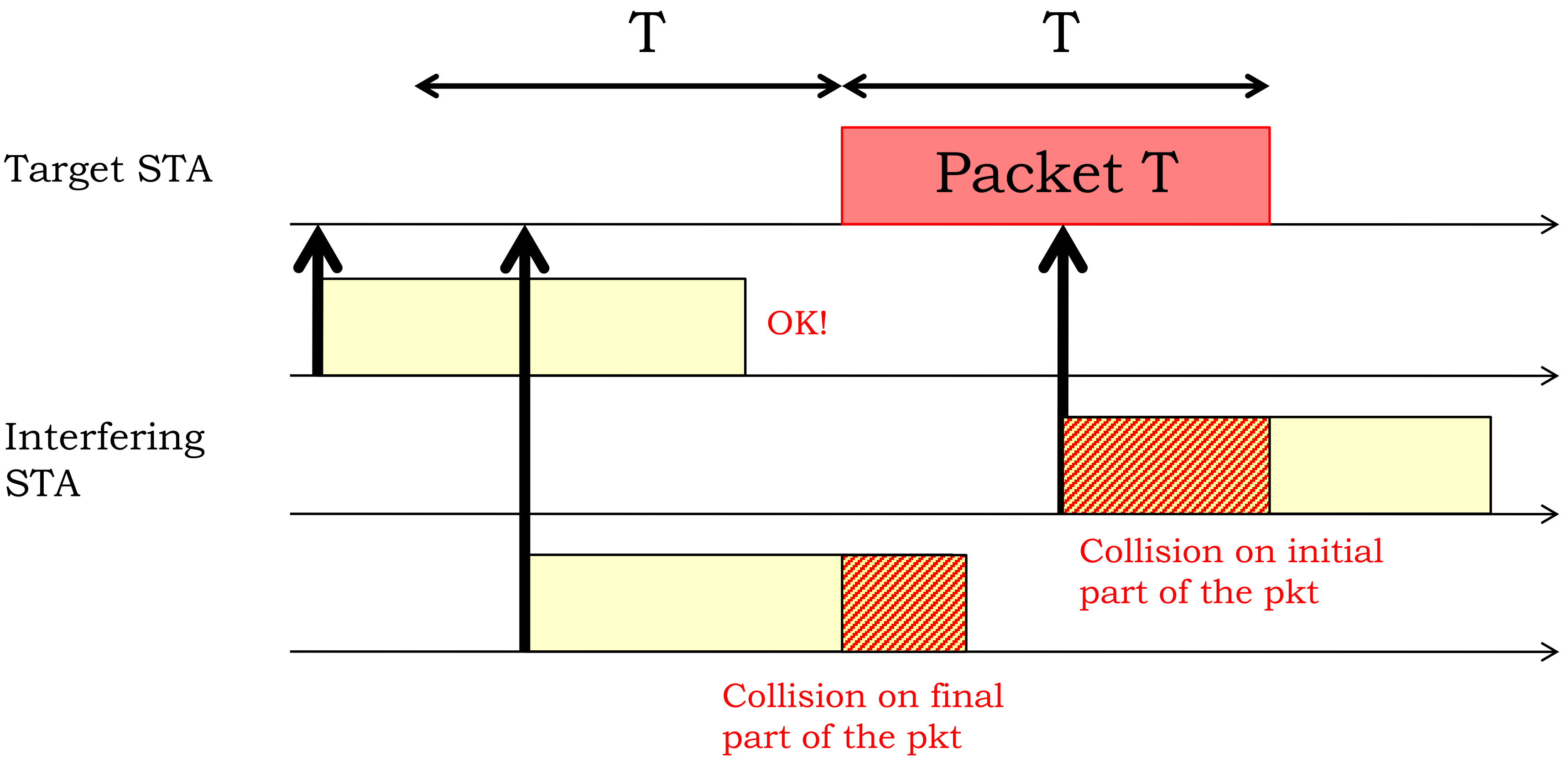
Analysis of Pure ALOHA

➔ Notation:

- ⇨ T = pkt_time
- ⇨ *S*: Average number of successful transmissions per pkt_time ; that is, the *throughput* or *efficiency*.
  - → e.g. 2frames/6pkt_time
- ⇨ *G*: Average number of total frames transmitted per pkt_time
  - → e.g. 2frames/6pkt_time in the first case, 6frames/6pkt_time in the second case



Vulnerability period: 2T



Analysis of Pure ALOHA

Using Pr to have k tx in t:

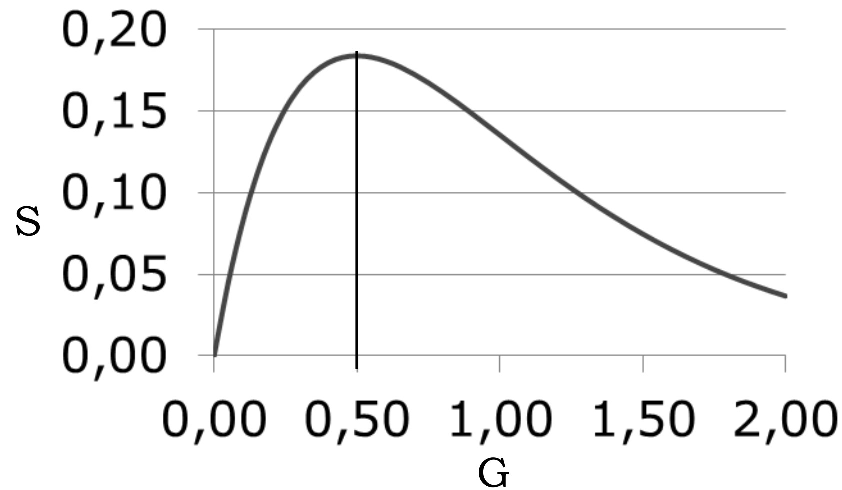
$$P_k(t) = \frac{(\Lambda t)^k e^{-\Lambda t}}{k!}$$

and considering:

$$\Lambda \cdot 2T = 2G$$

we have:

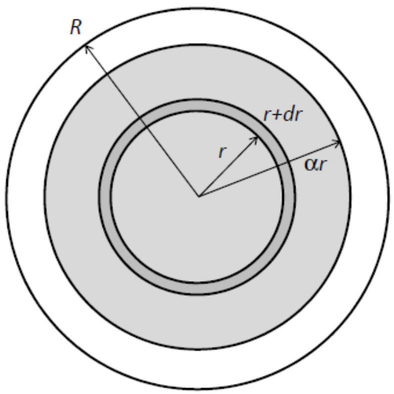
$$S = G \cdot \left[\frac{(2G)^k}{k!} e^{-2G} \right]_{k=0} = Ge^{-2G}$$



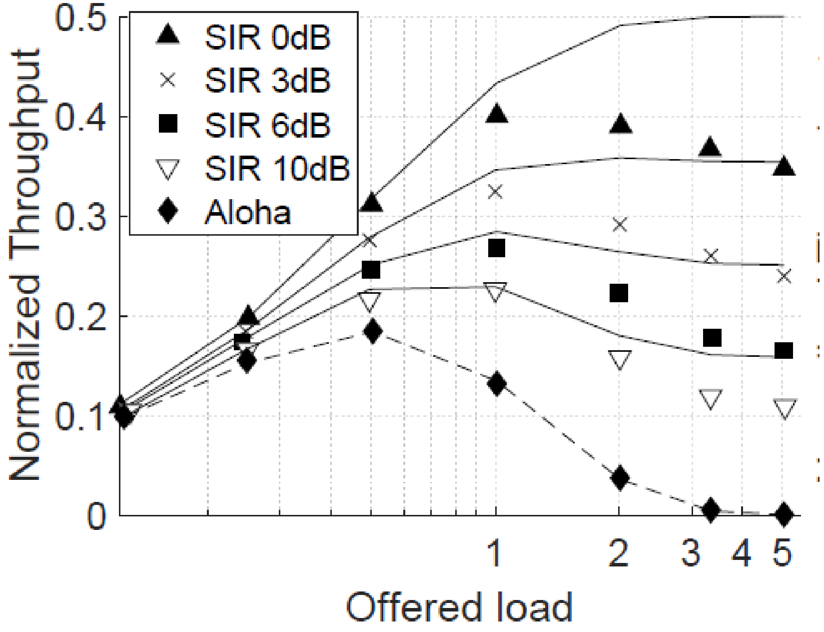
Intra-SF Interference

➔ **For each node, packets received at lower power, do not prevent correct reception**

- ⇨ Competing load for each device at distance r is lower than the whole G

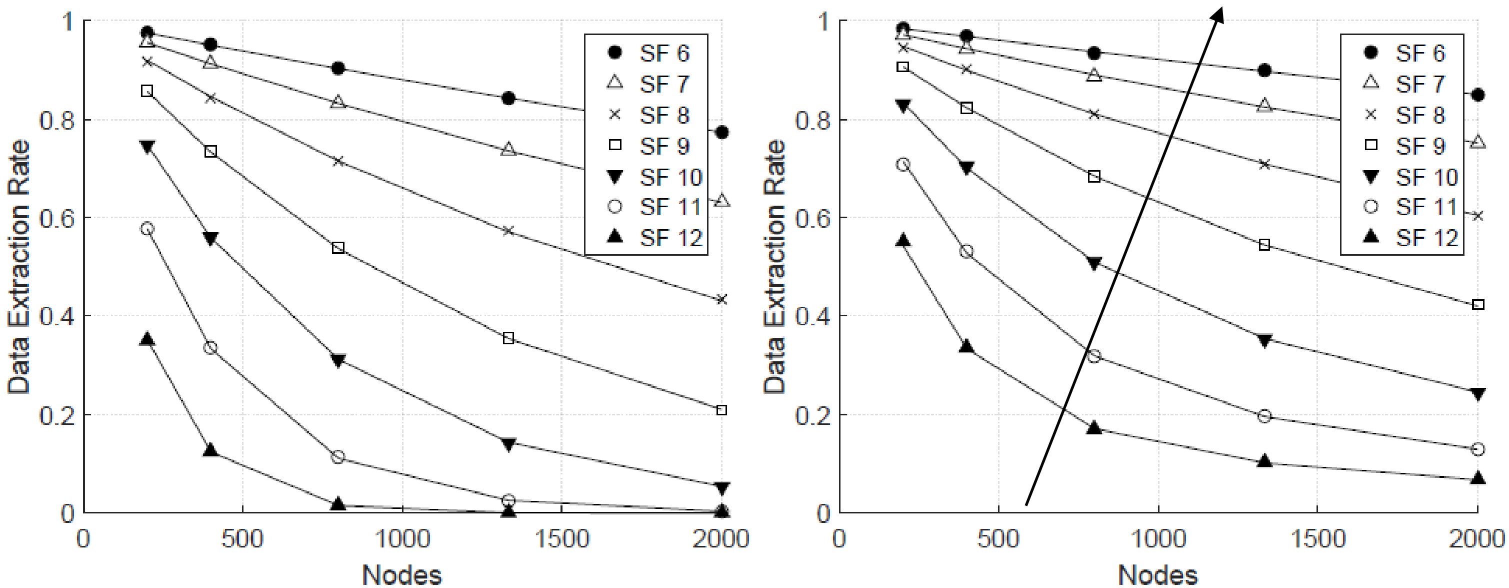


LoRaSIM Open Source Simulator



Maximum Throughput can be much higher than 18%!!

Data Extraction Rates with captures



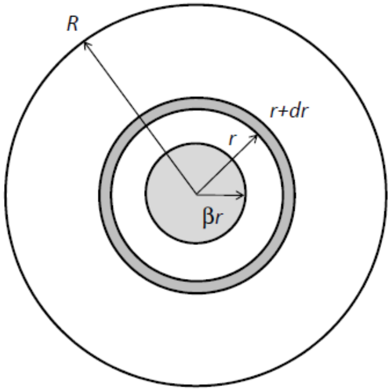
(a) Aloha (no capture)

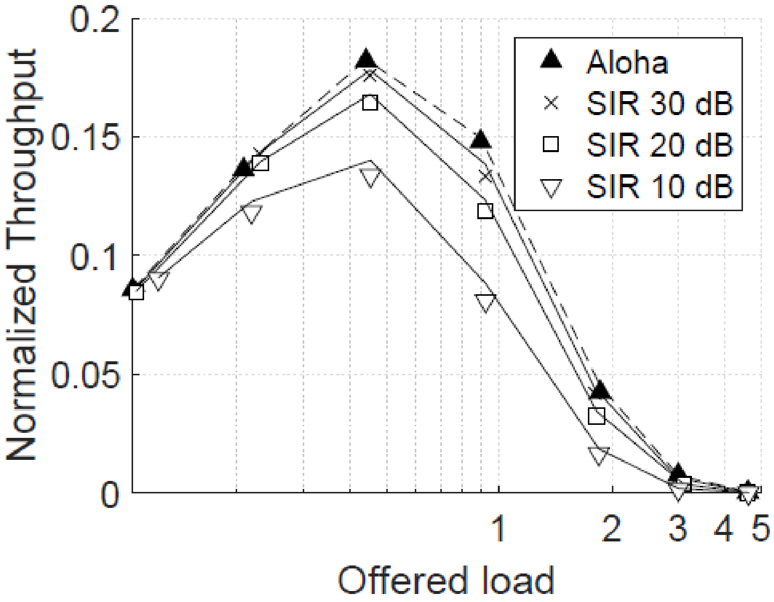
(b) Capture

1 msg every 90 seconds, 20 bytes of payload

Inter-SF Interference

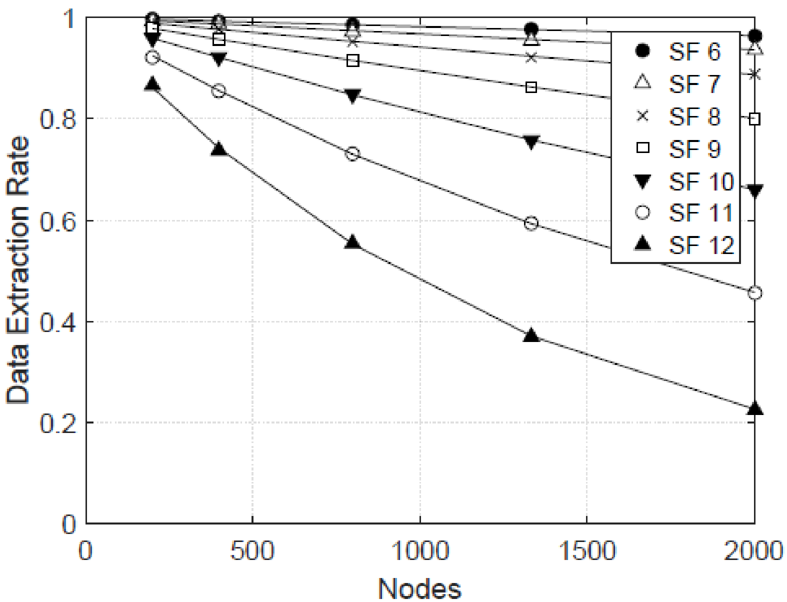
- ➔ **Each SF, cannot be really considered as independent channel**
  - ⇨ Close nodes can create collisions with different SFs
  - ⇨ Each device at distance r has an extra competing load from other SFs



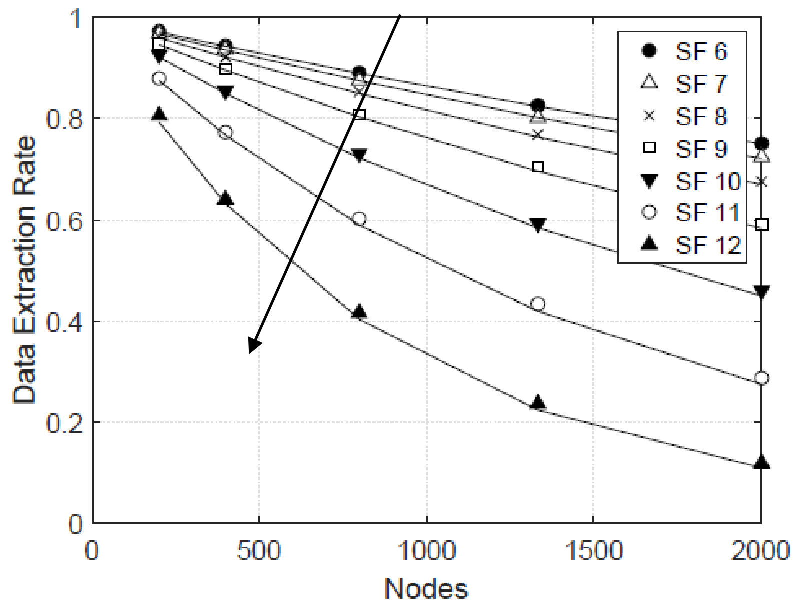


In presence of multiple SFs, maximum throughput of each channel could be much lower than 18%!!

Data Extraction Rates with inter-SF interferece



(a) Orthogonal SFs



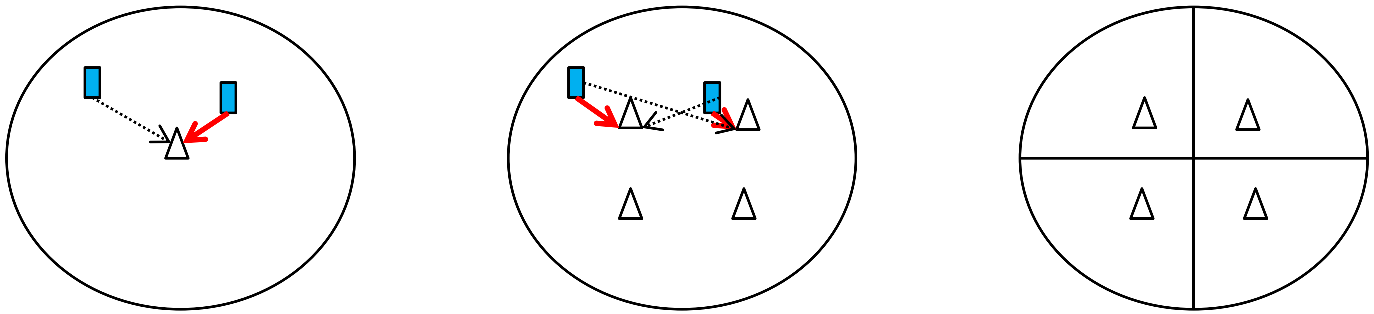
(b) Interfering SFs

1 msg every 90 seconds, 20 bytes of payload

Considerations on Scalability

- ➔ **LoRa cells cannot sustain high loads**
  - ⇨ Maintain reception duty-cycle under 10% per channel
  - ⇨ Gateways working on multiple channels at the same time (up to 8)
  - ⇨ Manage opportunisticaly SFs and transmision power
- ➔ **How to deal with increasing density of end devices?**
  - ⇨ Deploying multiple gateways!

Multi-Gateway Scenario

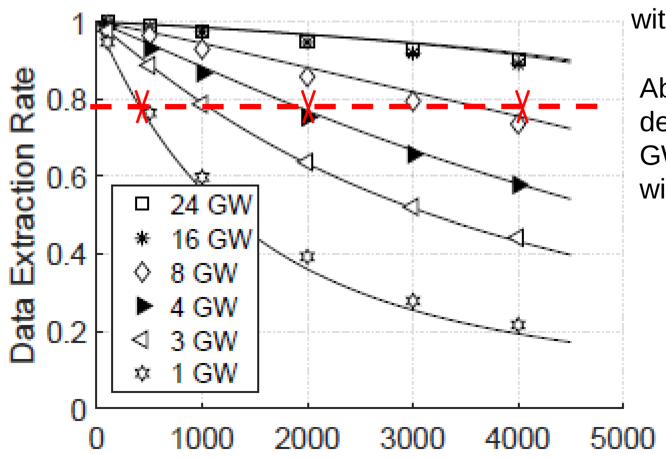


Collision event: only the closest device is received

Two correct receptions at two different gateways

The system with M gateways tends to be equivalent to M systems with G/M load

- ➔ **Cell capacity can be improved by deploying multiple gateways**
  - ⇨ If S(G) is the cell throughput, with M gateways the thorugput tends to be M*S(G/M)



500 devices with 1 GW

About 2000 devices with 4 GW or 4000 with 8 GW

SF Allocations

Adaptive Data Rates

- ➔ **Basic mechanism: select smallest possible SF for a given SNR/RRSI**
  - ⇨ Highest possible data rate

Received packets

SF = 12
MaxSNR = -10 dB

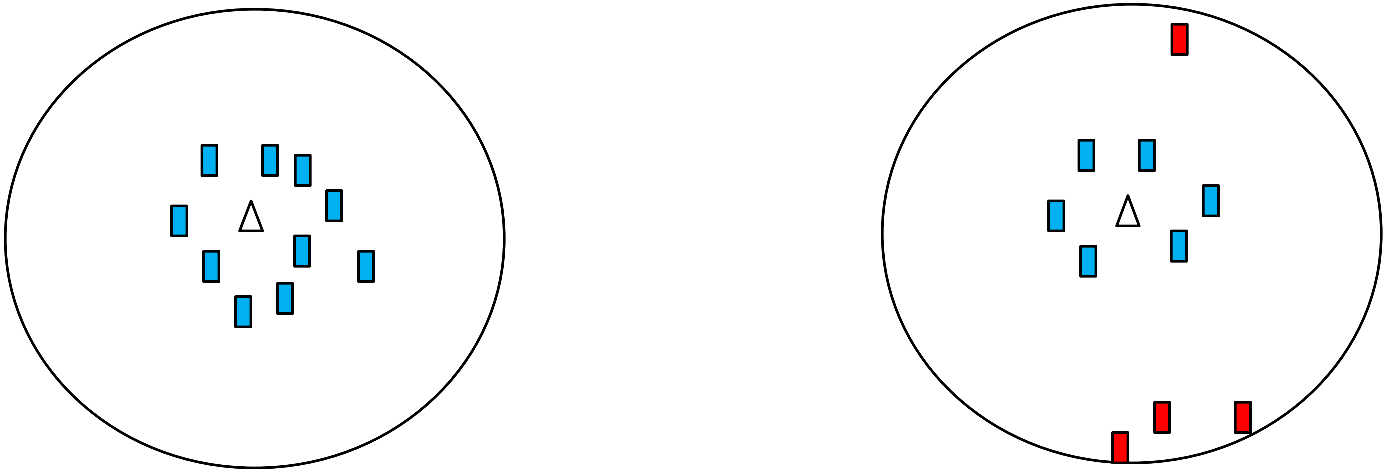
Spreading Factor	SNR limit
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

Can increase rate to SF10:
-10 dB (SNR) - 5 dB (margin)
= -15 dB

Link ADR request: SF10

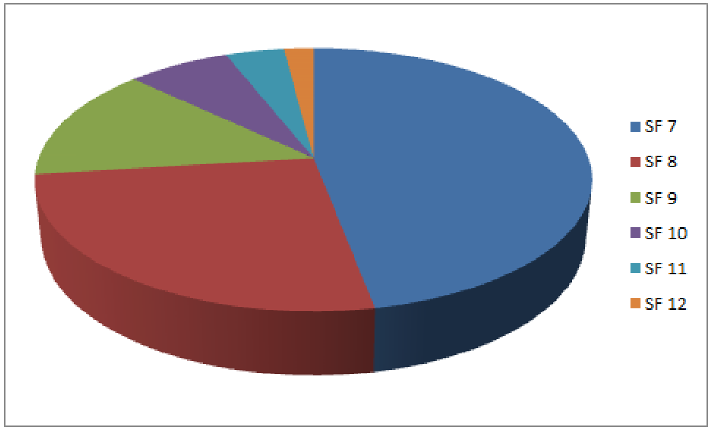
Can ADR only work on link-level measurements?

- ➔ **Sub-optimal in many scenarios, although standardized by the LoRa Alliance**
  - ⇨ If all devices are close to the gateway, they will work on the minimum SF7
  - ⇨ Cell capacity depends not only on the number of devices, but also on their position
    - →Load offered on different SFs critically affected by ADR



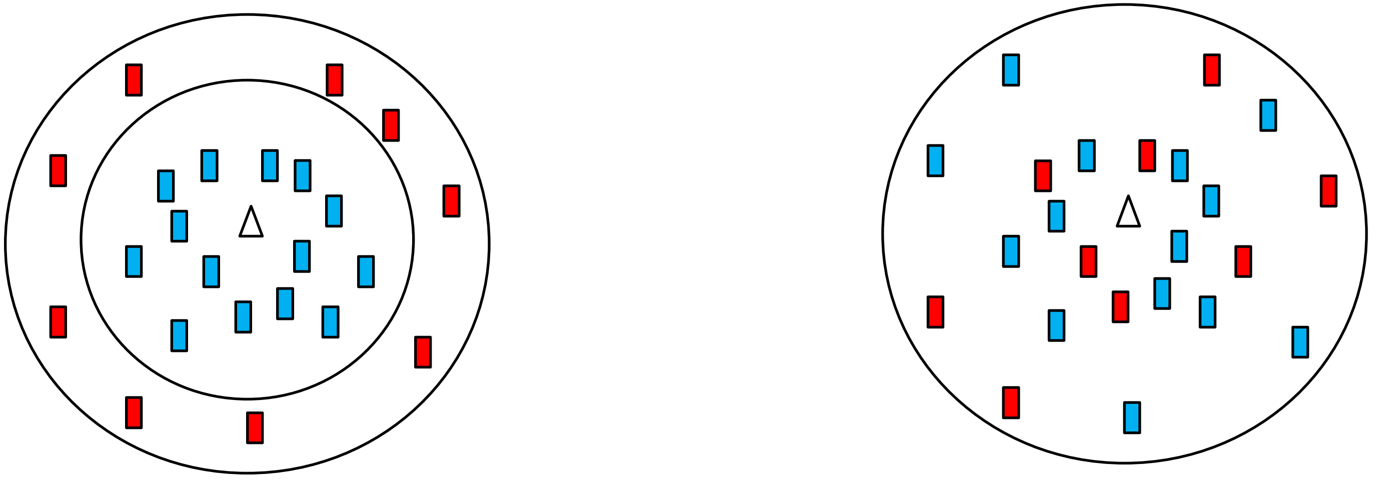
How to balance between SFs?

- ➔ **Airtimes at each SF are not equal**
  - ⇨ Roughly, transmissions times are in the ratio T(SF12)=2 T(SF11)=4 T(SF10)=..32 SF(7)
- ➔ **With uniform application rates, load balancing requires different nodes on each SF**
  - ⇨ More nodes with lower transmission times
    - →47%, 26%, 14%, 7%, 4%, 2%
    - →Only a few nodes on SF12



And which distribution within the cell?

- ➔ **Consider two SFs only**
- ➔ **Assume all the nodes can be served at the smallest SF**
- ➔ **Which allocation is better?**
  - ⇨ Different circular rings or uniform spreading?

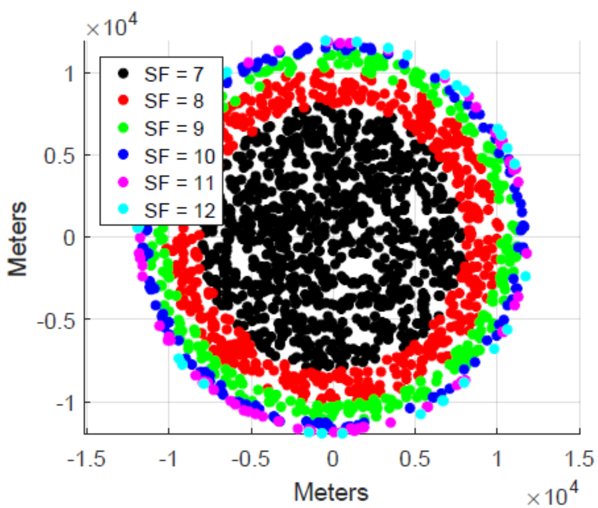


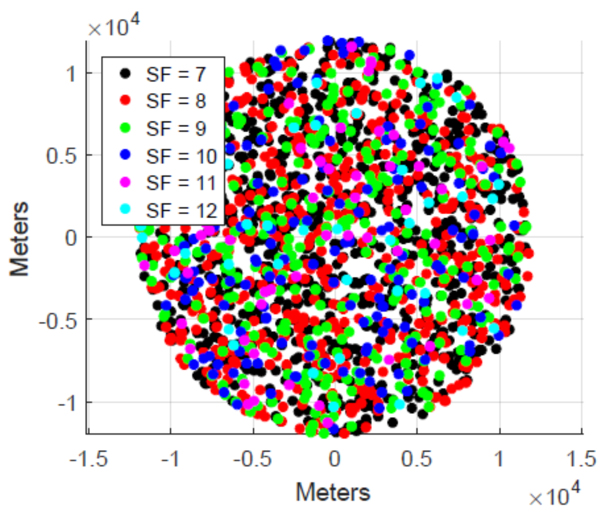
Some Performance Results

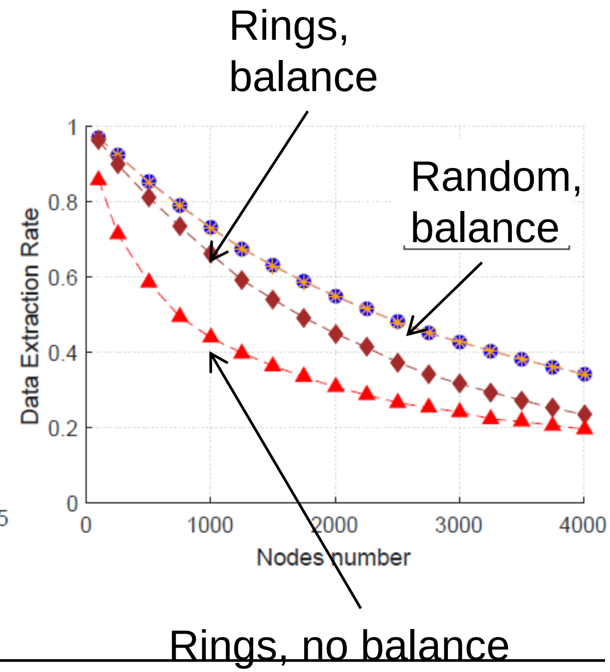
➔ **Why spreading?**

⇨ Increases capture opportunities and avoids that far users suffer of higher inter-SF interference

⇨ Inter-SF interference unbalanced, because only far users suffer of it!





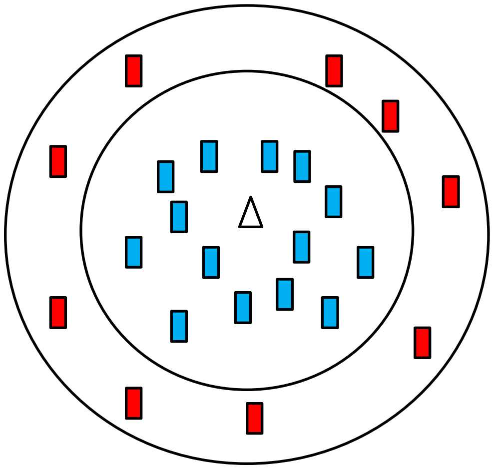


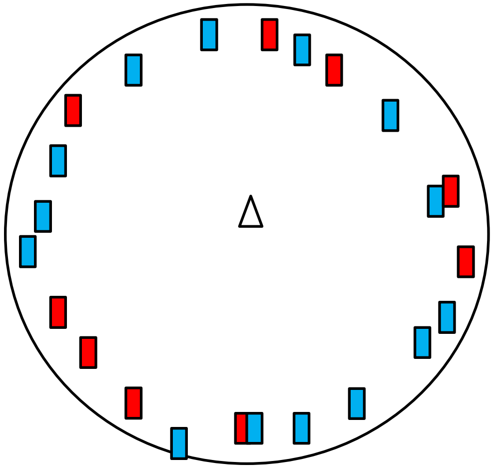
Can Power Control mitigate inter-SF interference?

➔ **Inter-SF interference can be avoided but..**

➔ **No real benefit, because destroies capture opportunities!**

⇨ Equivalent to move nodes to the same distance from the gateway





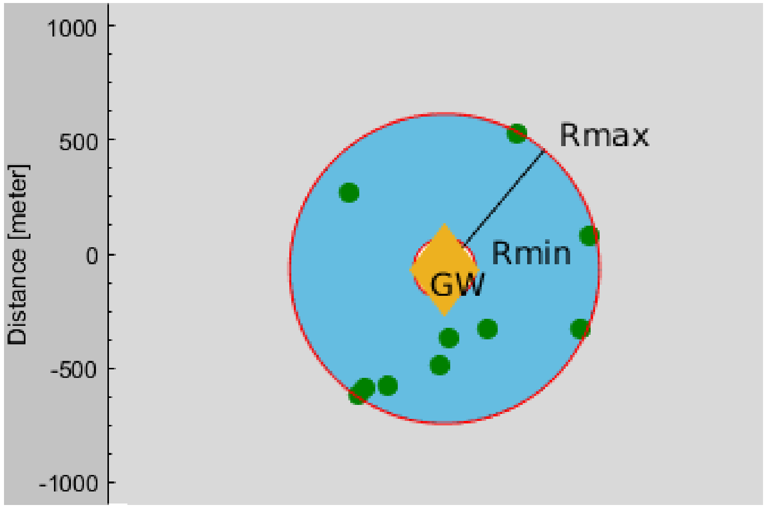
Technology Strong Points

- ➔Outdoor and deep indoor connectivity
- ➔Low cost of ownership with private or public networks
- ➔Scalable architectures robust to interference
- ➔Strong ecosystem of partners and applications

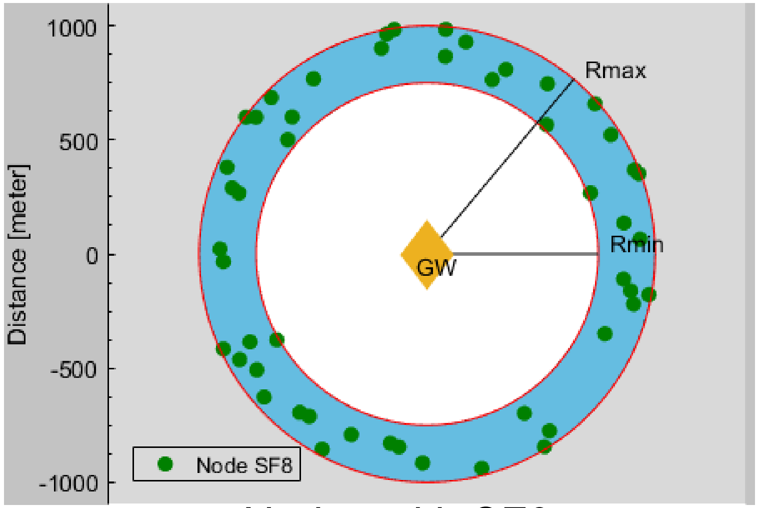
Open Issues

1) Experimental Studies with thousands of devices

- ➔ **Possible idea: work on traffic emulator, given:**
  - ⇨ # of nodes and source rates
  - ⇨ Location of the nodes (Rmin and Rmax)
  - ⇨ SFs of the nodes
- ➔ **Schedule transmissions (including collisions) and generate aggregated signal to transmit via USRP**

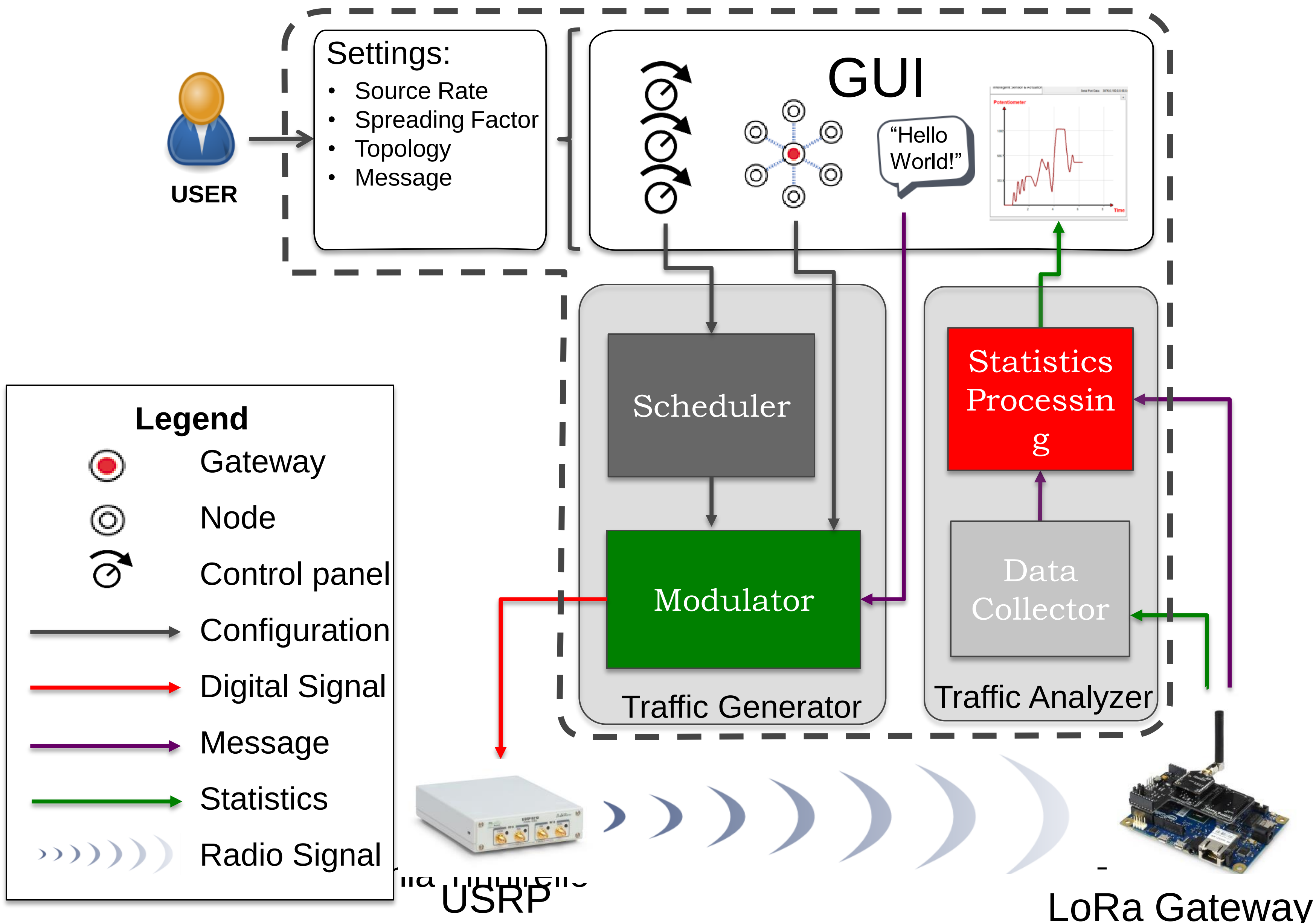


Nodes with SF7

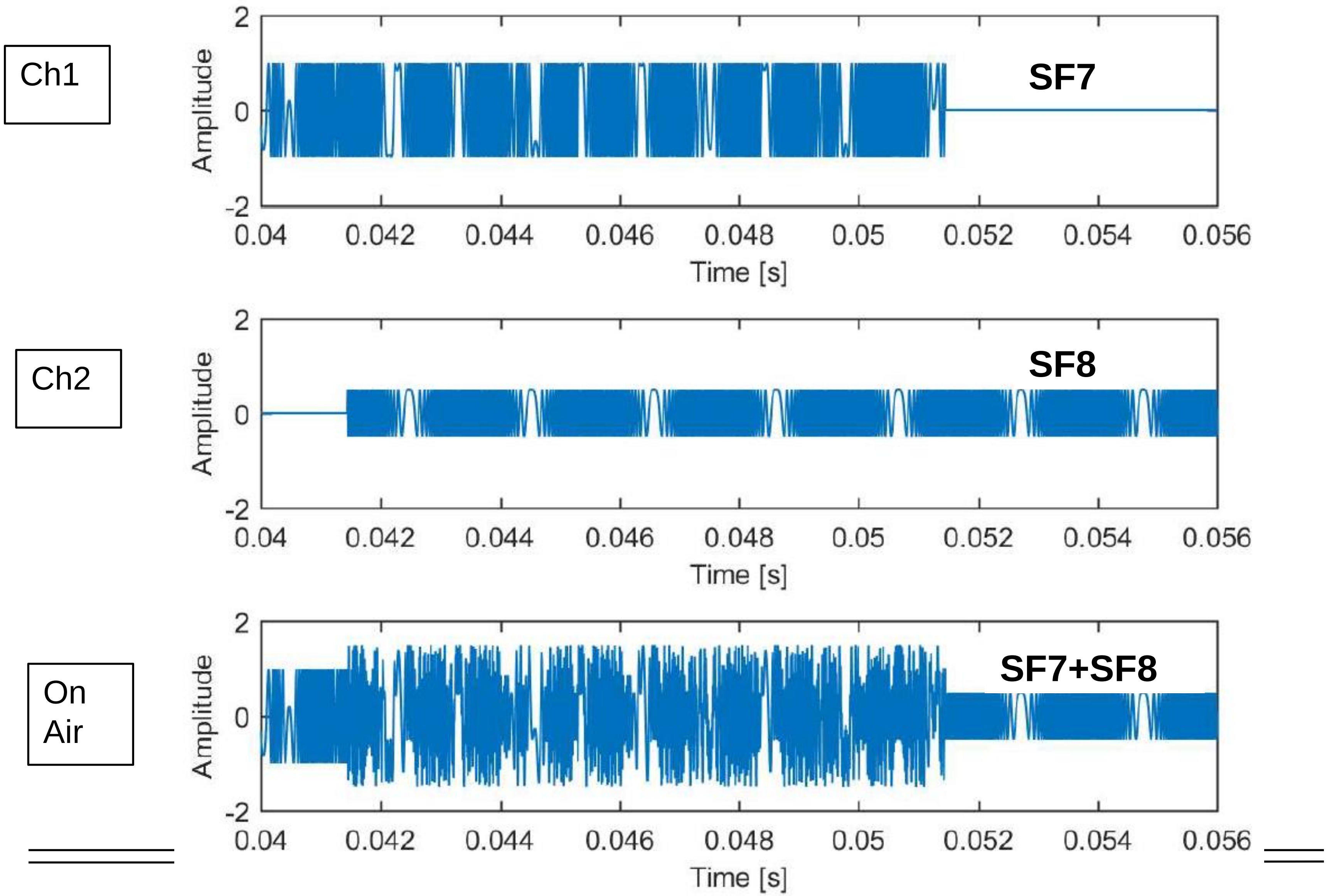


Nodes with SF8

Emulator architecture



An example of aggregated trace



2) Network optimizations

- ➔ **Definition of network capacity predictors for general gateway deployments, traffic scenarios and network configurations**
- ➔ **But how to enforce optimal configurations?**
  - ⇨ Simple rules, for avoiding per-device commands sent by the network server
    - →Unfeasible to dynamically change per-device parameters over time (too much downlink bandwidth)
  - ⇨ Which alternative solutions?
    - →Choose SF7 with a given probability, within a given RSSI range, etc.
    - →support broadband configuration commands

3) Interference Cancellation

- **Since collisions result in the correct demodulation of the strongest signal, is it possible to cancel the signal and recover the weakest one?**
  - In principle yes.. but complex estimation of frequency and time off-sets between colliding transmitters
    - Current receivers are very simple, although at the gateway we can envision something more complicated
  - Ongoing work..

References

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- **Impact of LoRa Imperfect Orthogonality: Analysis of Link-Level Performance**
  - D. Croce, M. Gucciardo, S. Mangione, G. Santaromita and I. Tinnirello, in IEEE Communications Letters, vol. 22, no. 4, pp. 796-799, April 2018
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  - F. Cuomo, M. Campo, A. Caponi, G. Bianchi, G. Rossini and P. Pisani, WiMob 2017
- **LoRaSIM simulator**
  - https://github.com/adwaitnd/lorasim

Backup

Example of RX Data


```
{"rxpk":
[{
   "tmst":87485028,
   "time":"2016-12-06T11:15:50.763950Z",
   "chan":6,
   "rfch":0,
   "freq":867.700000,
   "stat":1,
   "modu":"LORA",
   "datr":"SF9BW125",
   "codr":"4/5",
   "lsnr":-11.8,
   "rssi":-118,
   "size":29,
   "data":"QDABAUCA3CMBnpi48xb25eMnX2iH5sA/8RqLqNg="
   }]
}
```

Inter-SF Rejection Thresholds

SF_{ref} \ SF_{int}	7	8	9	10	11	12
7	1	-8	-9	-9	-9	-9
8	-11	1	-11	-12	-13	-13
9	-15	-13	1	-13	-14	-15
10	-19	-18	-17	1	-17	-18
11	-22	-22	-21	-20	1	-20
12	-25	-25	-25	-24	-23	1