LoRa Technology for IoT Networks

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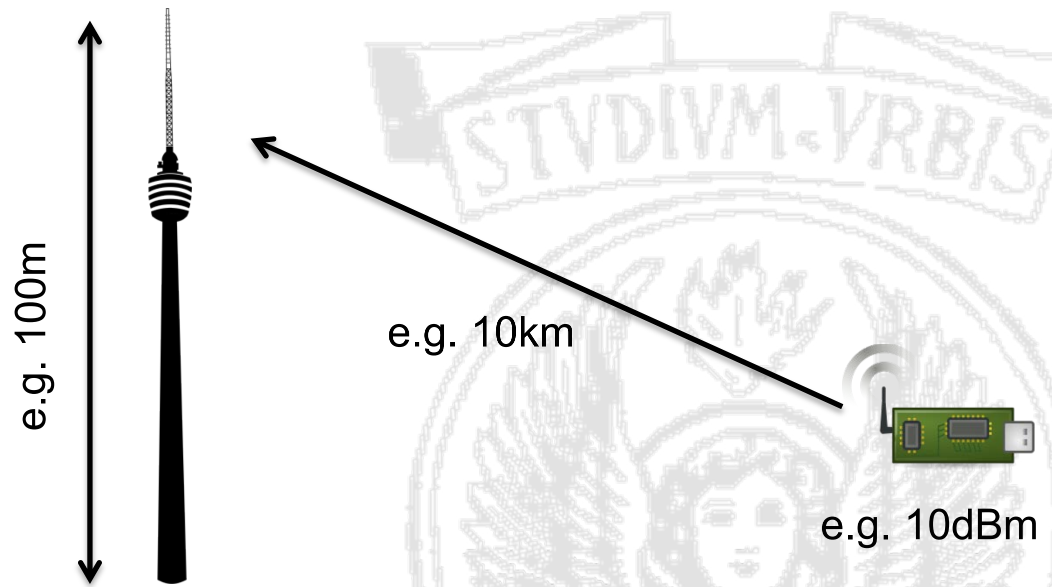
Slides partly by prof. Ilenia Tinnirello *et al.*

IoT radio technologies

- Different options available…

Local Area Network Short Range Communication	Low Power Wide Area (LPWAN) Internet of Things	Cellular Network Traditional M2M
40%	**45%**	**15%**
Well established standards In building	Low power consumption Low cost Positioning	Existing coverage High data rate
Battery Live Provisioning Network cost & dependencies	High data rate Emerging standards	Autonomy Total cost of ownership
Bluetooth 4.0, ZigBee, WiFi	LoRa	GSM, 3G+ / H+, 4G

Low Power Wide Area Networks (LPWAN)

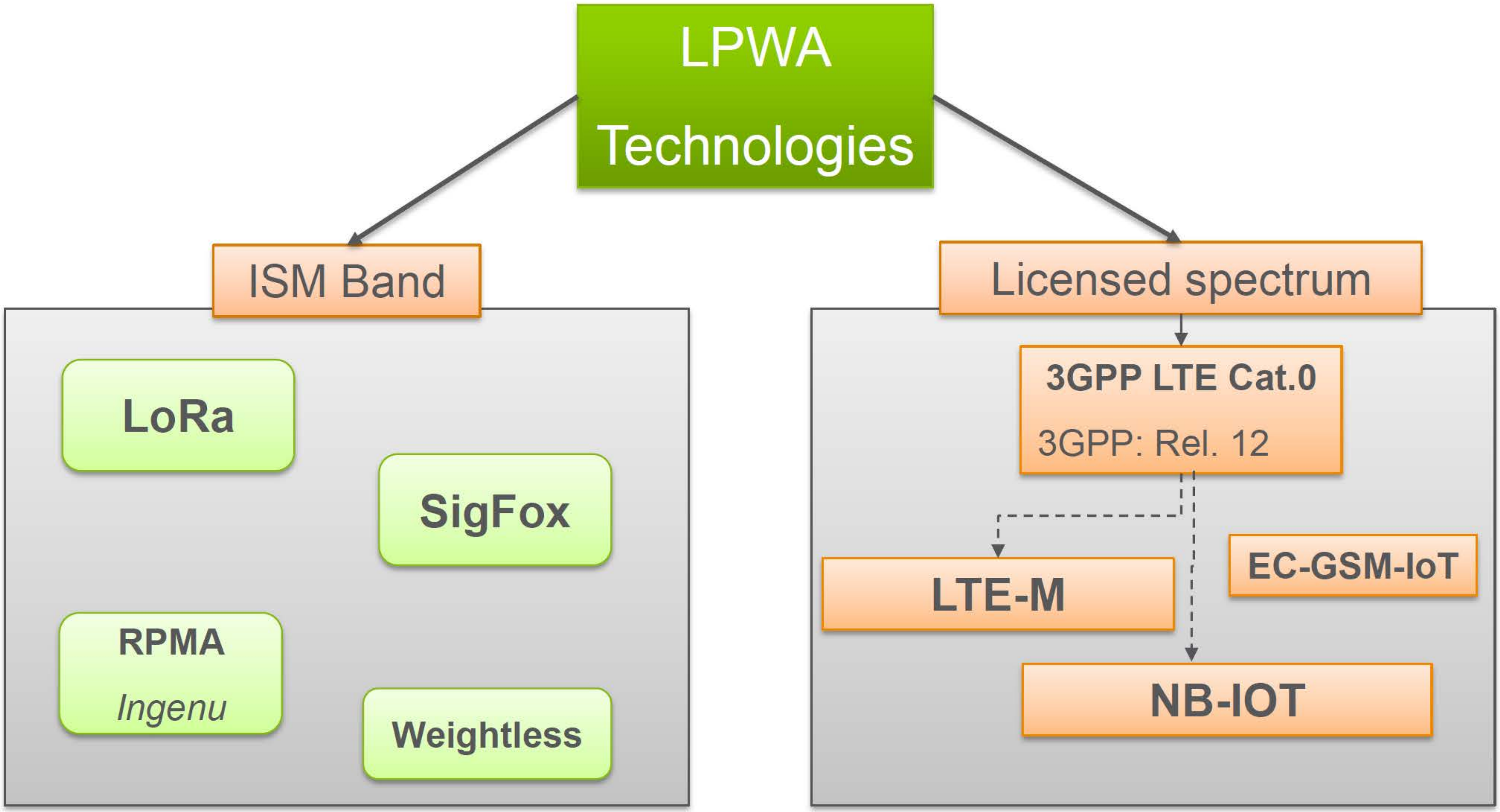


- Typical network architecture:
  - A base-station at highly exposed sites serves up to one million sensor nodes
  - Small and cost-efficient sensors nodes communicate using ultra-low power over ultra-long distances

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 when license-exempt bands are used (ISM)
  - 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

Licensed or ISM?



What are LoRa and LoRaWAN?

- LoRa: an innovative physical layer, very robust, for providing connectivity to low power smart objects

- LoRaWAN: a complete stack for building wide area networks on top of LoRa links

LoRa Technology and Stack

Patended PHY layer, standardized MAC (LoRaWAN):

Typical Stack	LoRa Stack
Standardized MAC/PHY	Patented PHY + open LoRaWAN MAC
One stack, many suppliers	One supplier, personalized stacks

MAC

PHY

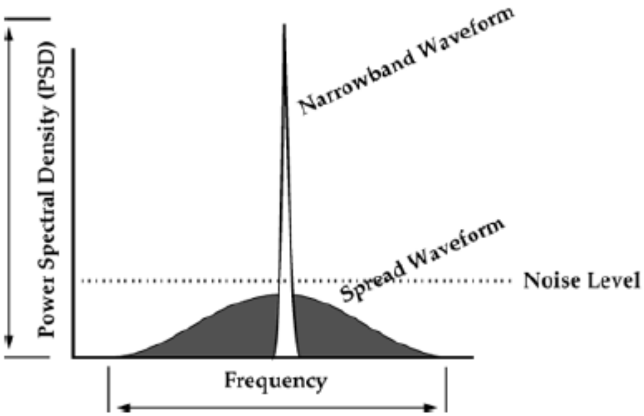
MAC — LoRaWAN

PHY — SEMTECH

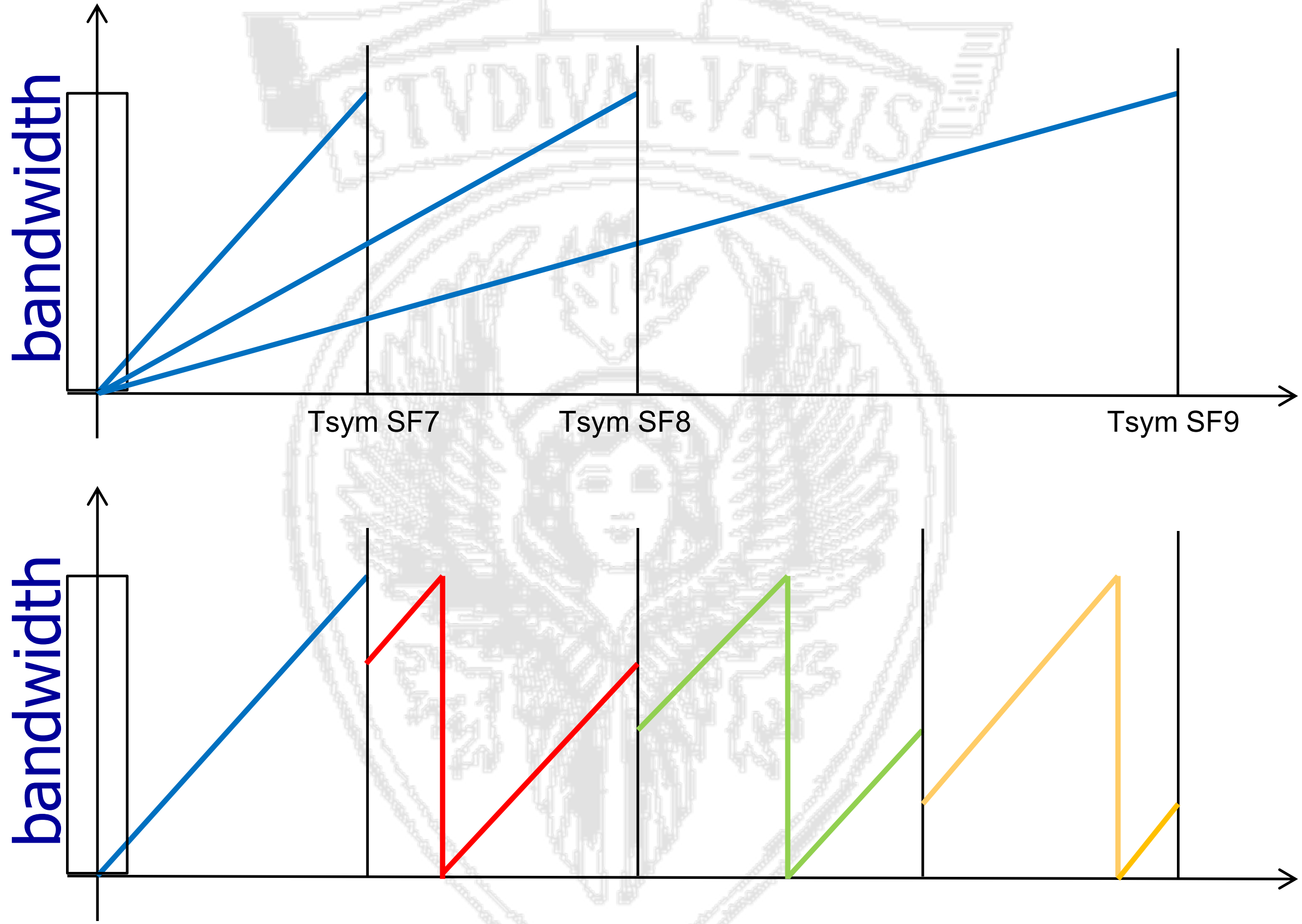
LoRa PHY

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



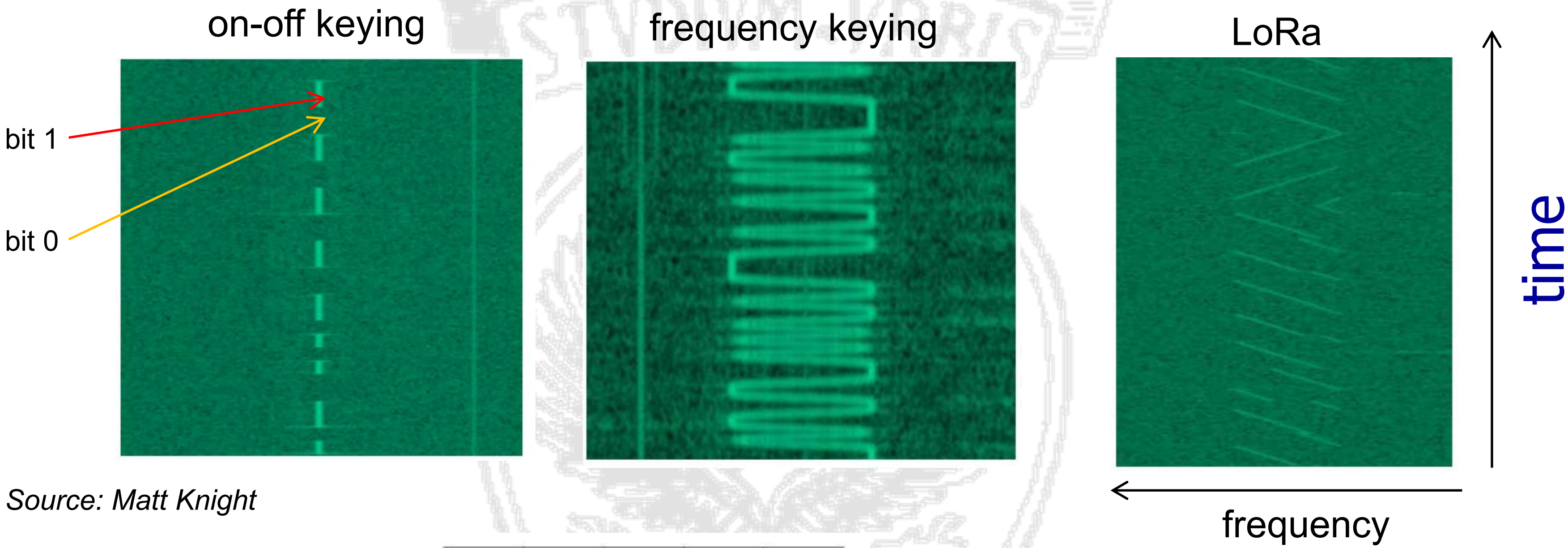
Symbols and Spreading Factor (SF)



Different SFs are namely orthogonal!

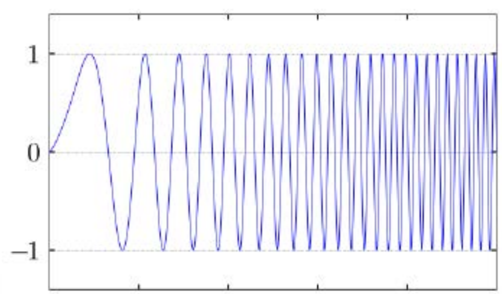
2^{SF} different symbols coding SF bits in Tsym

Comparison with other modulations



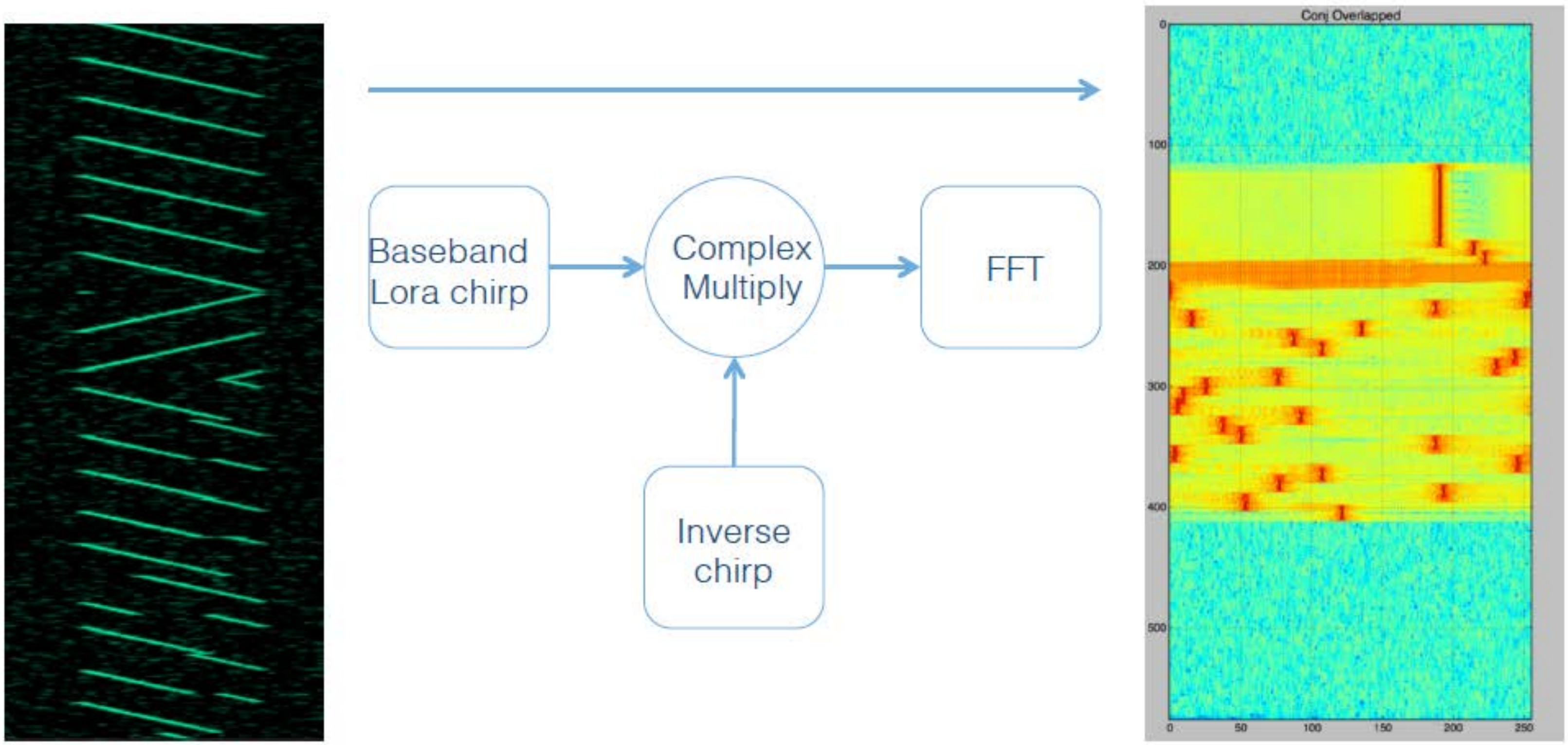
Source: Matt Knight

Time domain (1 chirp):



constant envelope modulation,
easy to implement

LoRa Demodulation

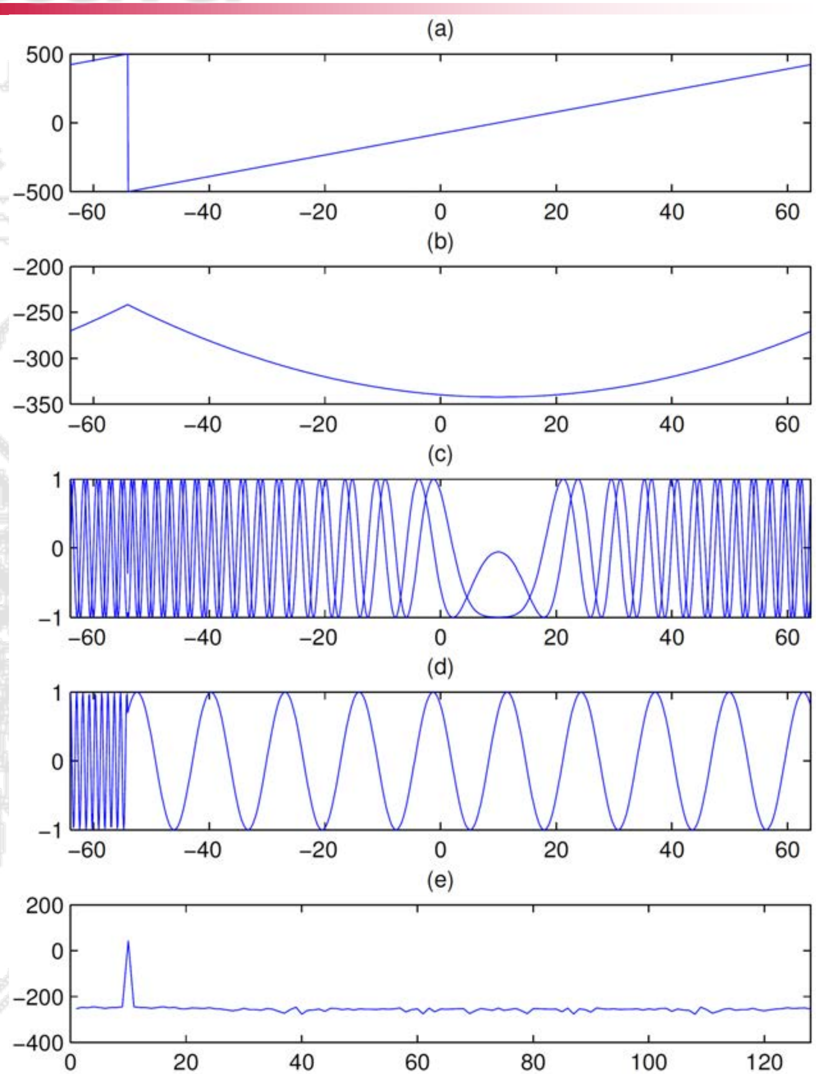


Source: Matt Knight

It can work 20dB under the noise floor!

LoRa receiver

- Multiply the received signal with the raw down-chirp
- The resulting signal is made of two periods, each having a constant frequency (d)
- (Down)sample the signal at the chip rate, i.e., at *BW* Hz
- The estimated symbol index $\hat{n}$ is the position of the peak at the output of an iFFT (e)

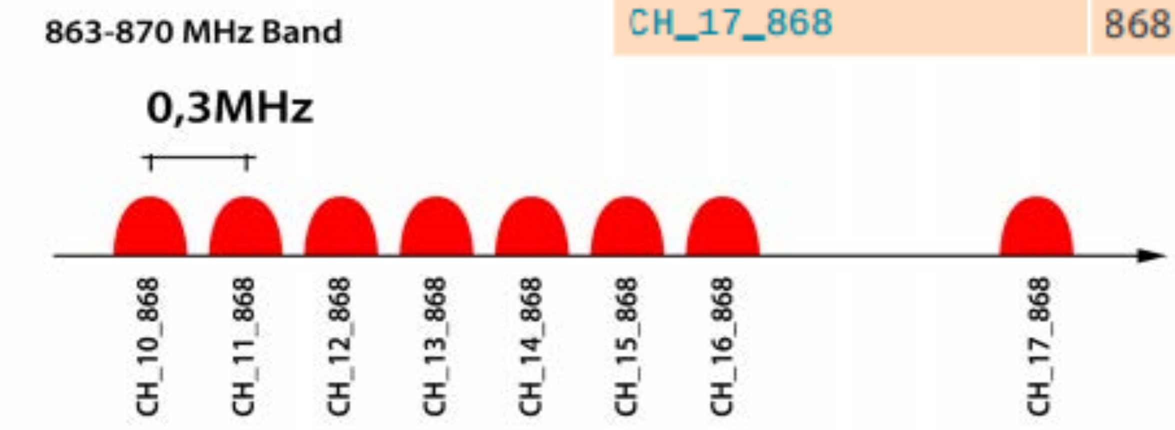


[Source] C. Goursaud, J.M. Gorce, "Dedicated networks for IoT: PHY / MAC state of the art and challenges", in EAI endorsed trans. on IoT, 2015.

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



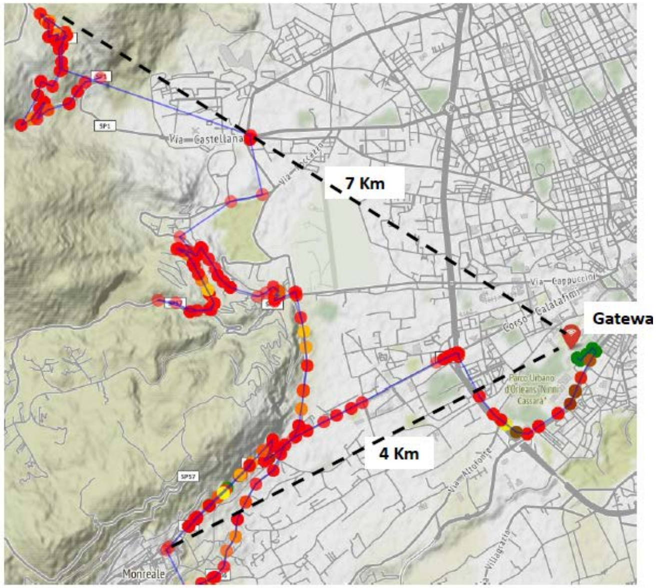
Summary on Data Rates @125 KHz

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

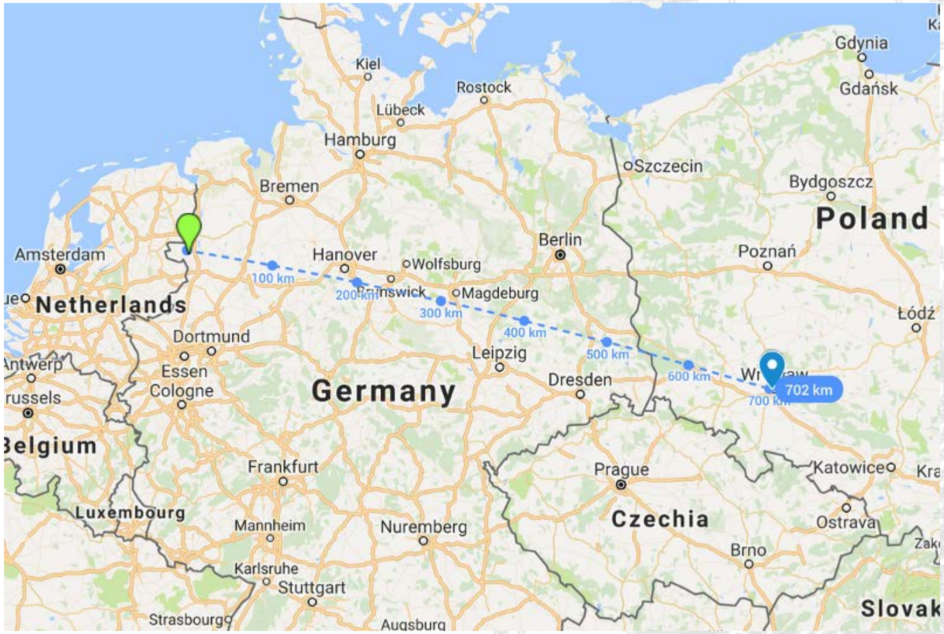
with two additional high-speed channels at 11kbps and 50kbps (FSK modulation)

Coverage

- Different sensitivities map to different distances
  - e.g. from -126.50 dBm for SF7 to -133.25dBm for SF12
  - 7 dB 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 a GW on top of a 3 floor building (SF12)



Up to hundreds of km in Line of Sight!



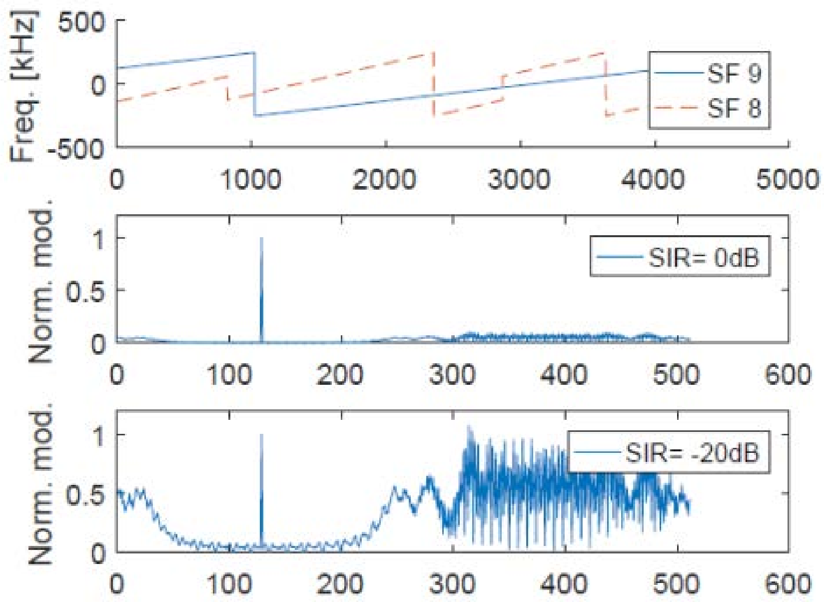
LoRa from a balloon at 38km from the ground

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

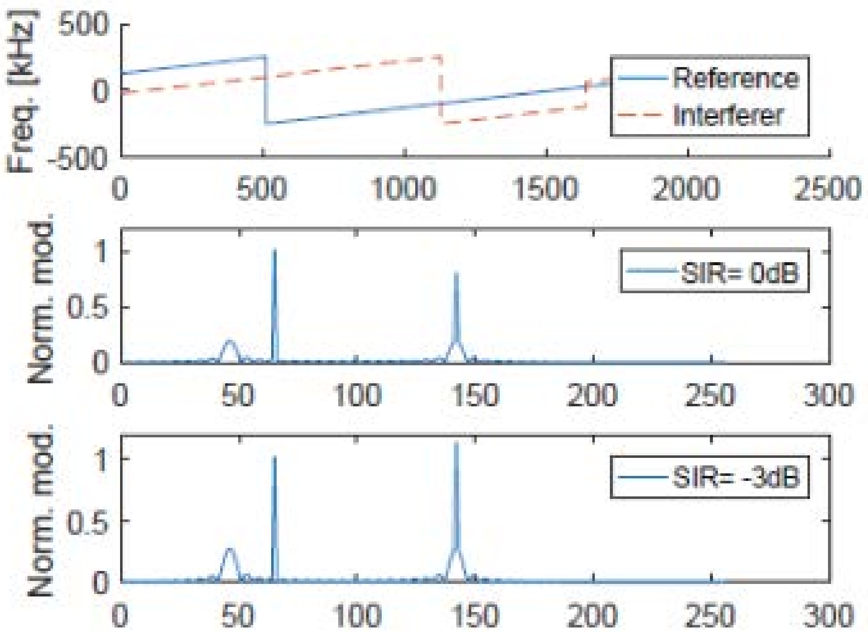
LoRa Inter-SF Interference

- Symbols using different SFs are orthogonal only if perfectly synchronized!
  - In practice, 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

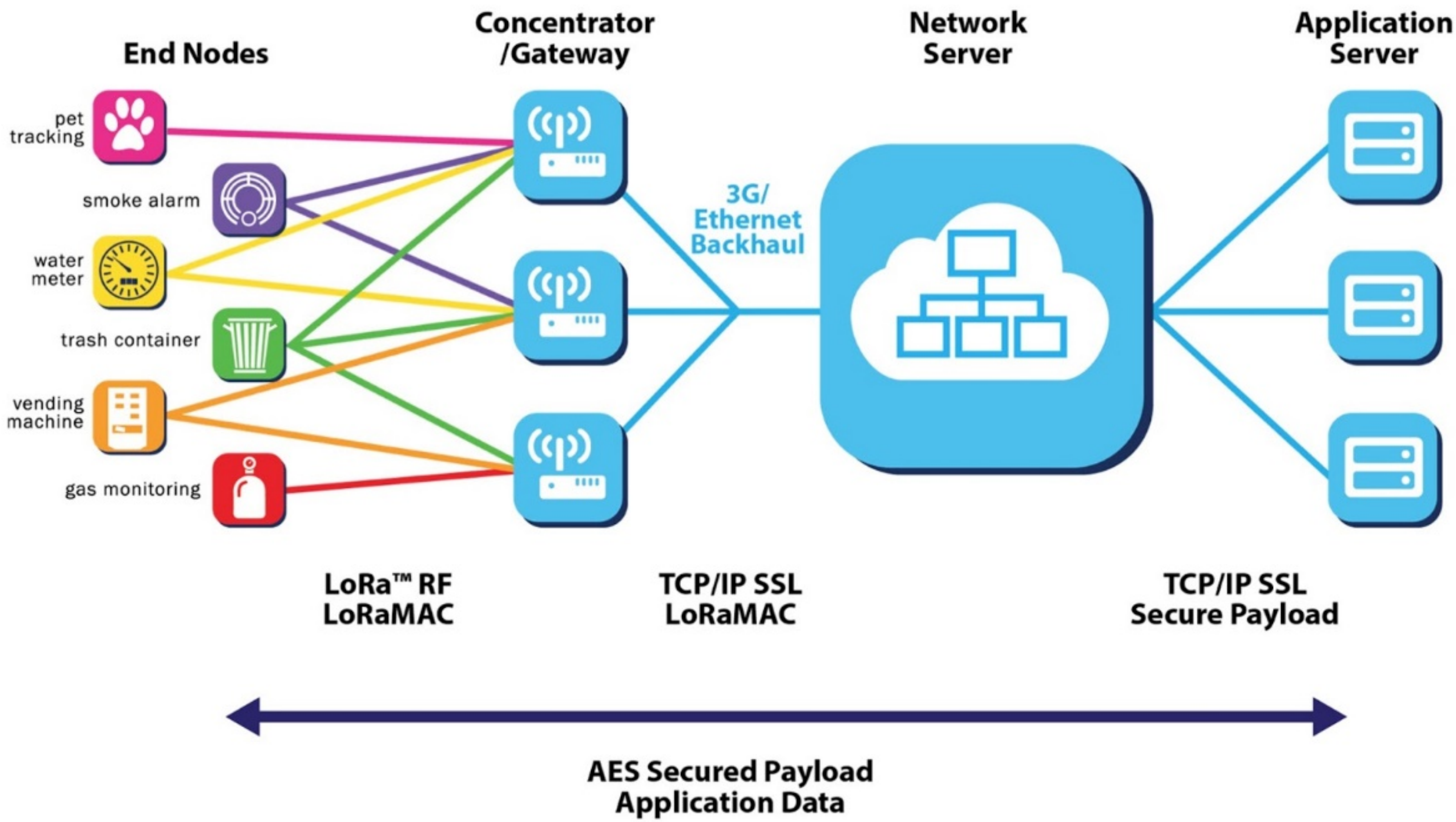


LoRaWAN

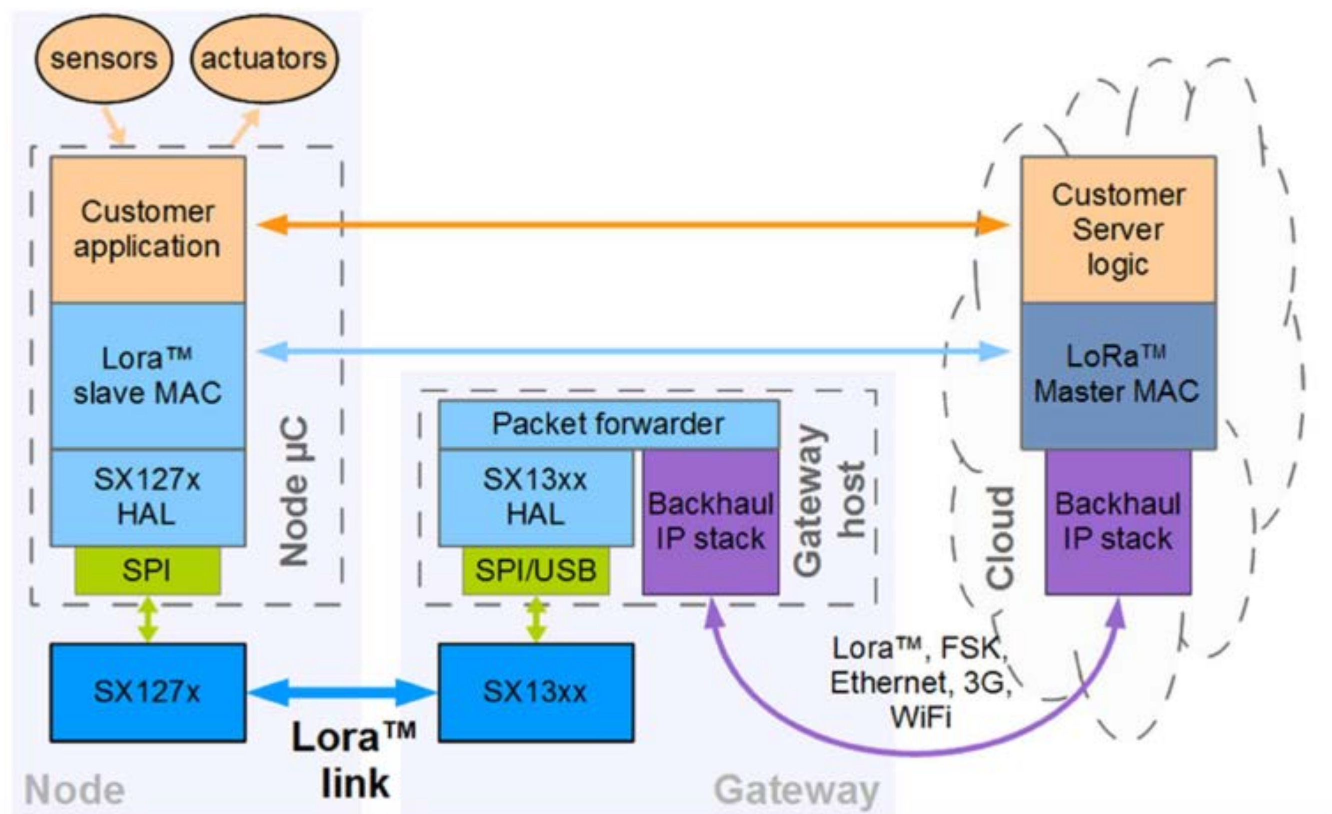
What is LoRaWAN?

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

Network Nodes



LoRaWAN Architecture

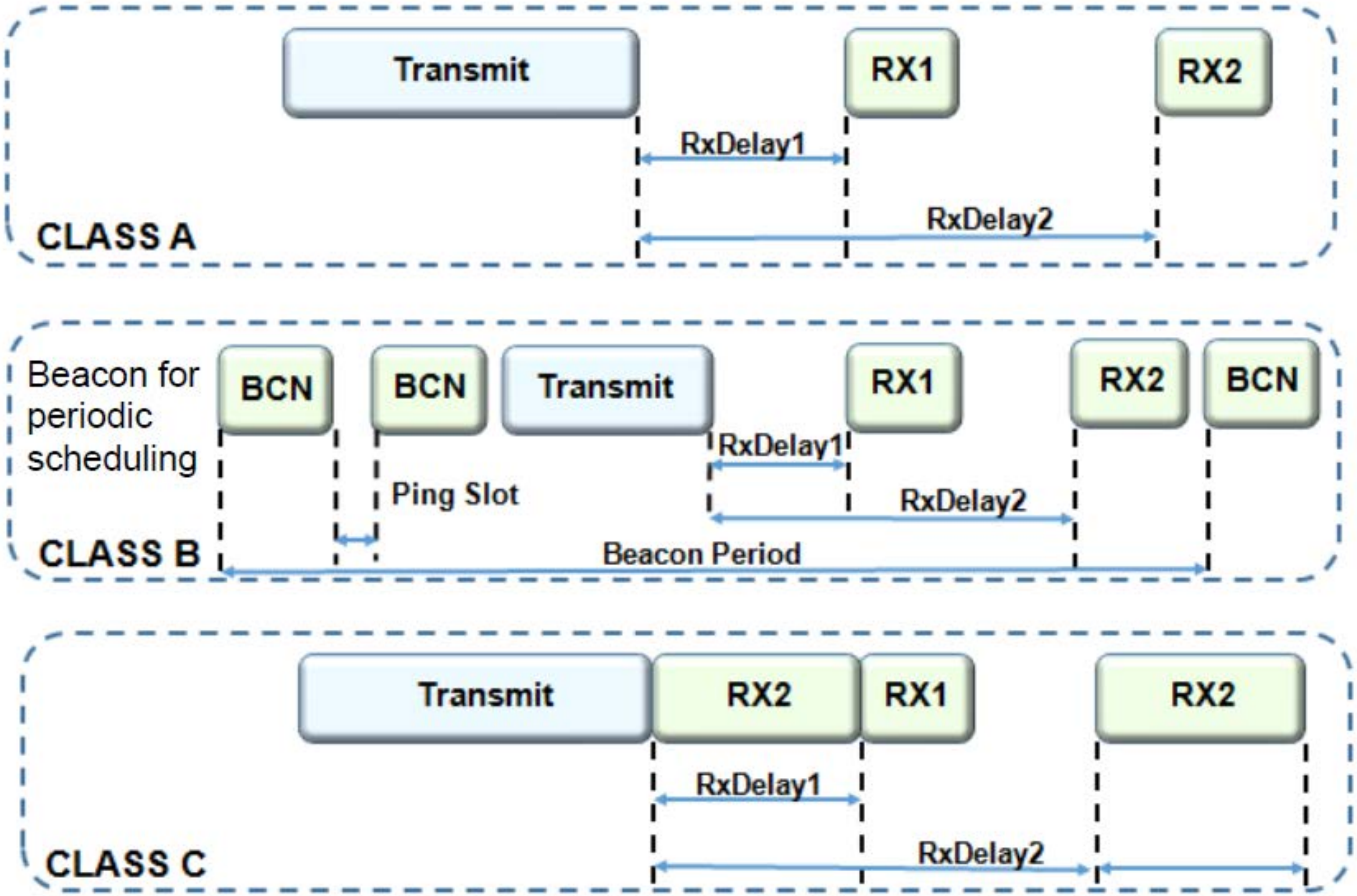


Source: Thomas Telkamp

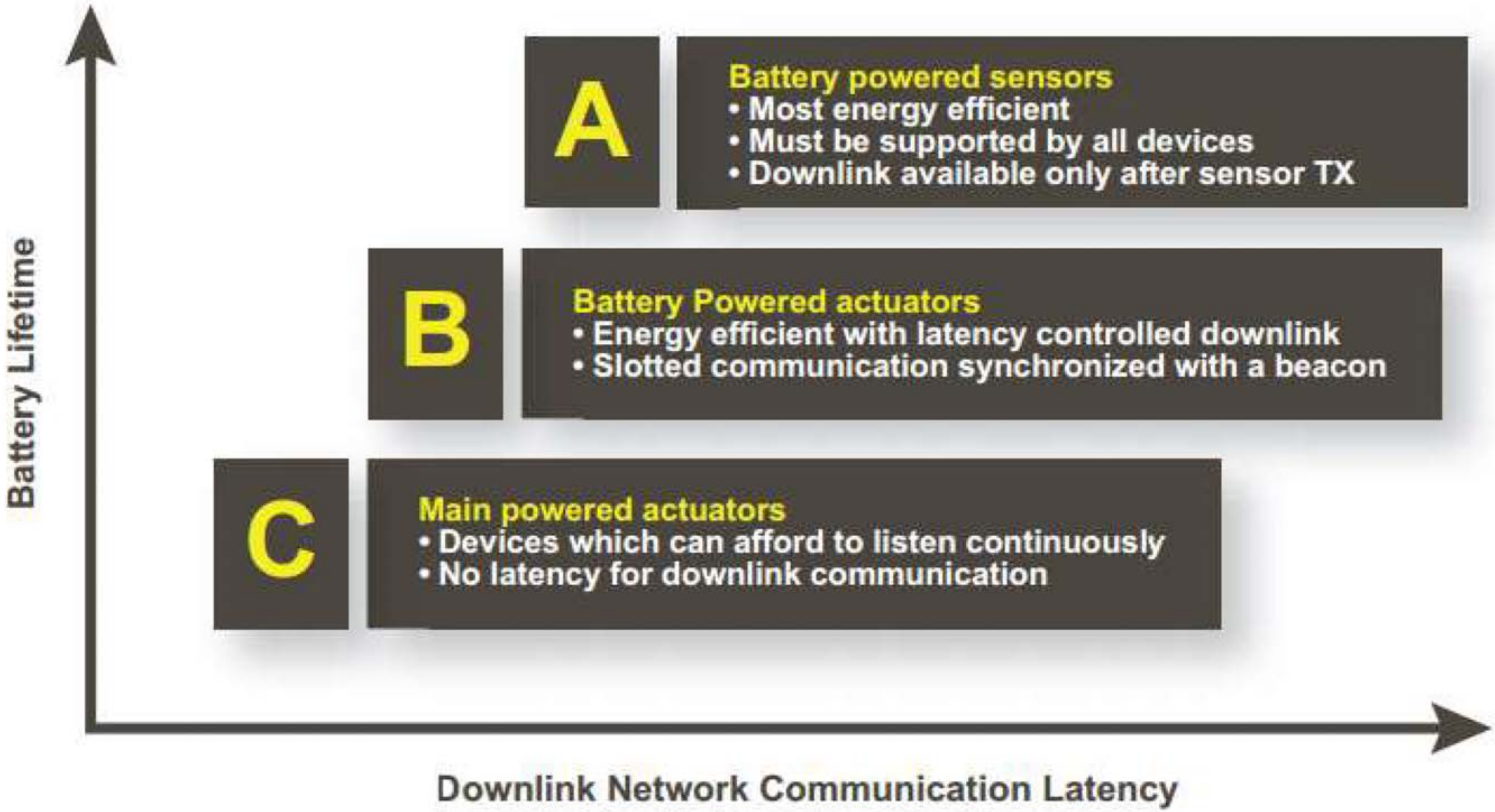
End Devices

- 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



Battery lifetime vs latency



Gateway

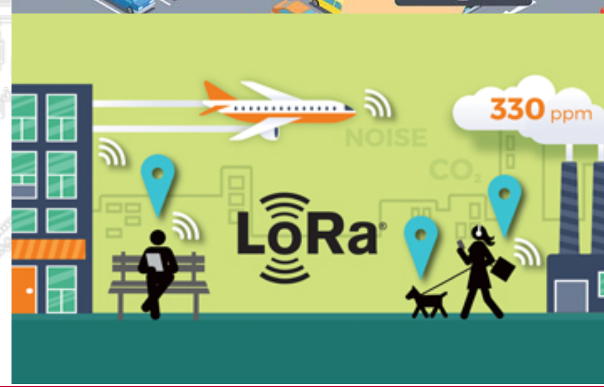
- Collection points deployed on field
  - All GWs receive ALL channels ALL the time
    - ✓ No network controller or reuse planning required
  - Sensors can communicate with any gateway
  - All correctly demodulated packets are forwarded to the network server

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 reference for all gateways
- Low cost gateways, since decisions on network configurations (if any) are taken by the server

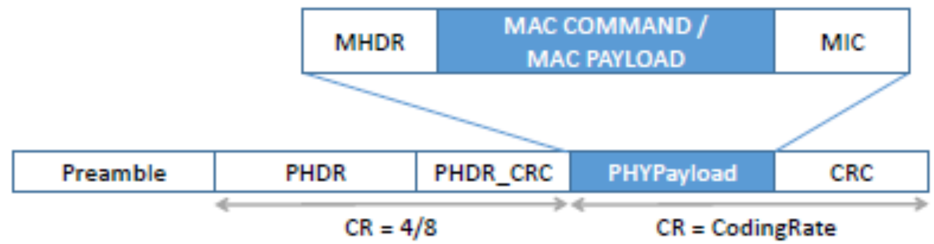
Application Examples

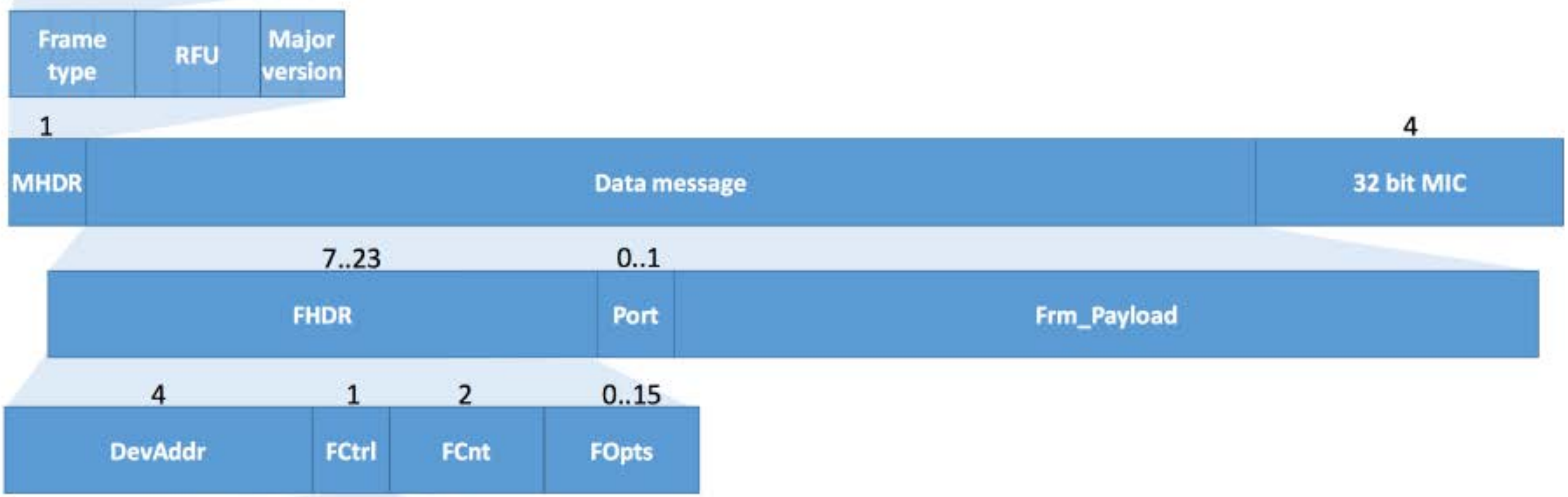
- Agriculture
  - Animal health monitoring
  - Water conservation
- Asset management
  - Utilization of resources
  - Asset tracking
- Smart City
  - Energy conservation
  - Operational efficienty
- Smart Buildings
  - Deep indoor pentratation
  - Safety and security



LoRaWAN Frame

Frame type value $B_7 b_6 b_5$	Description
000	Join Request
001	Join Accept
010	Unconfirmed Data
011	Confirmed Data
011...110	Reserved for future use
111	Proprietary



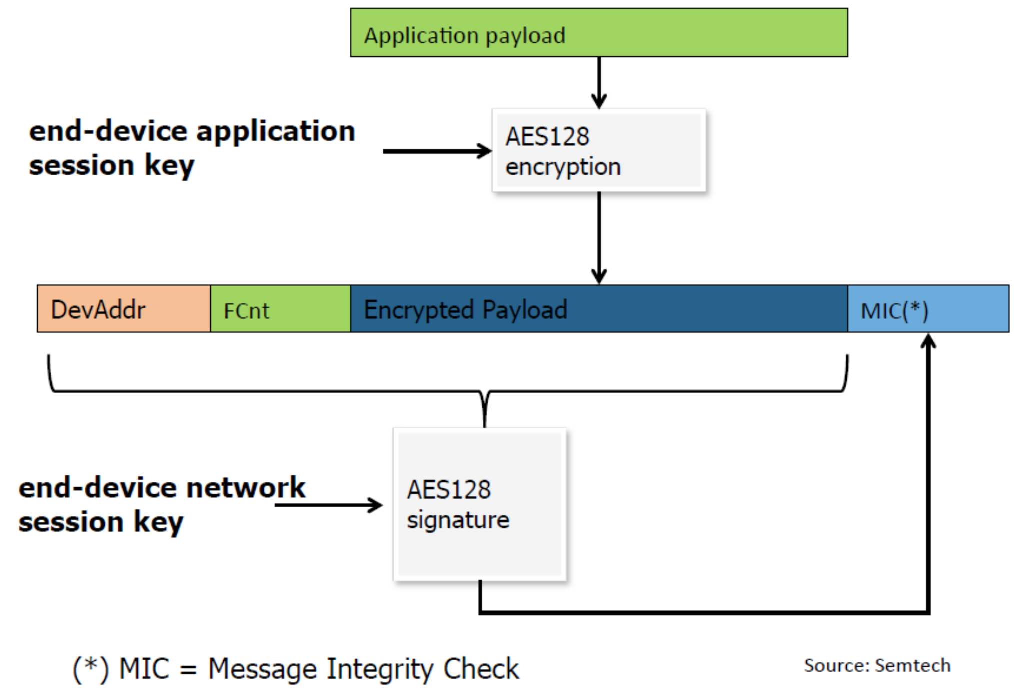


Bits	7	6	5	4	3..0
content	ADR	ADRACKReq	ACK	Frame pending	FOpts Len

Source: Actility

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
- Static activation (pre-configured) or over the air



Over-The-Air-Activation (OTAA)

- Alternative to static activation configuration.
- Join procedure prior to participating in data exchanges with the Network Server
- A node has to go through a new join procedure every time it has lost the session context information.
- Required information prior to OTAA:
  - JoinEUI: global application ID in IEEE EUI64 address space that uniquely identifies the Join Server (for session keys derivation)
  - DevEUI: Globally unique device identifier in IEEE EUI64 space
  - AppKey: root AES-128 encryption key specific for the end-device; extracting the AppKey from a node compromises this node only!
  - NwkKey: root AES-128 key specific to the end-device, but provided by the network operator

Over-The-Air-Activation (OTAA)

ED → NS

Size (bytes)	8	8	2
Join-request	JoinEUI	DevEUI	DevNonce

NS → ED

Size (bytes)	3	3	4	1	1	(16) Optional
Join-accept	JoinNonce	Home_NetID	DevAddr	DLSettings	RxDelay	CFList

(Encrypted with NwkKey)

- NwkSEncKey = aes128_encrypt(NwkKey, 0x04 | JoinNonce | JoinEUI | DevNonce | pad16)
- AppSKey = aes128_encrypt(AppKey, 0x02 | JoinNonce | JoinEUI | DevNonce | pad16)

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
DIChannel	allows to create an asymmetric channel by shifting the downlink frequency band with respect to the uplink one (otherwise they have the same band)

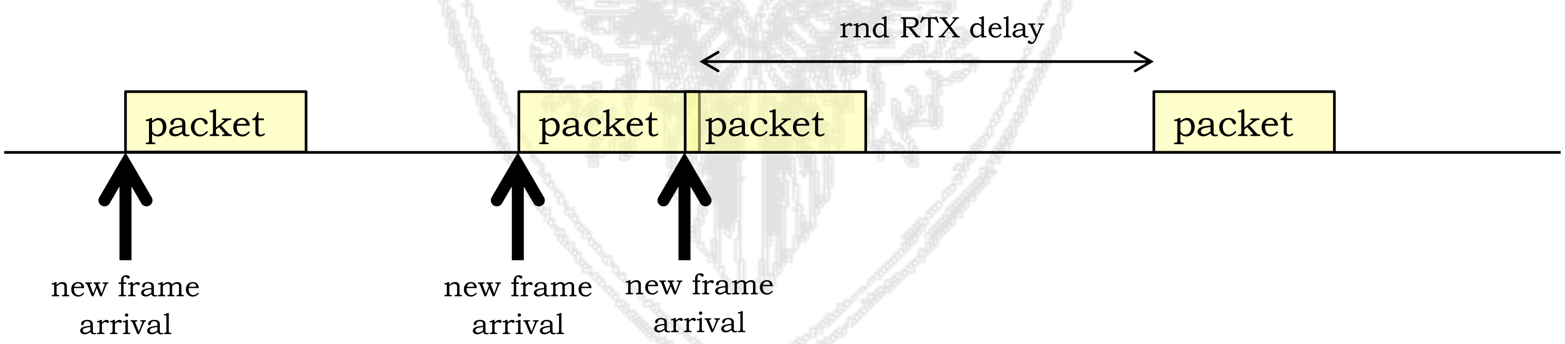
Performance evaluation

Single cell LoRa capacity

- Basically, a pure aloha system
  - Very limited system efficiency 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?

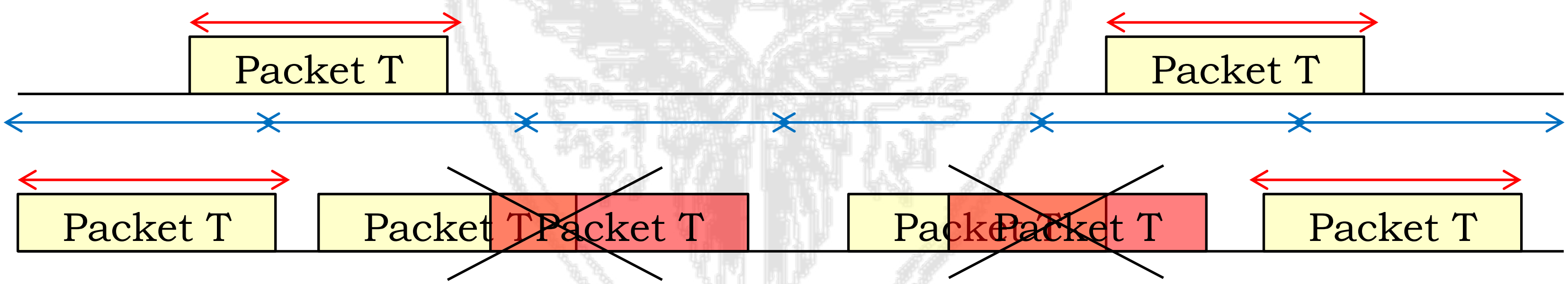
Back to ALOHA

- 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

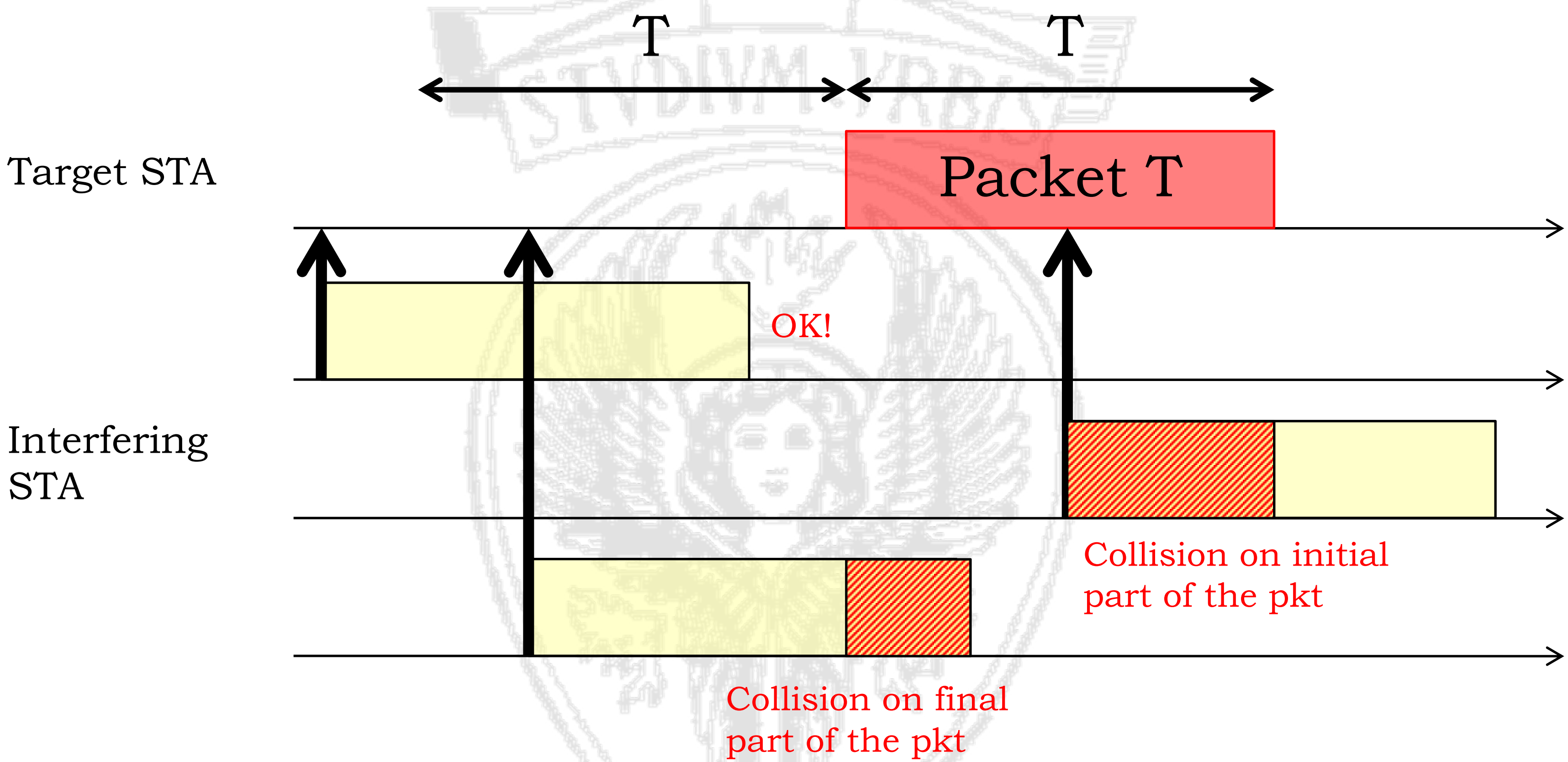


Analysis of Pure ALOHA

- 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 transmissions at time t:

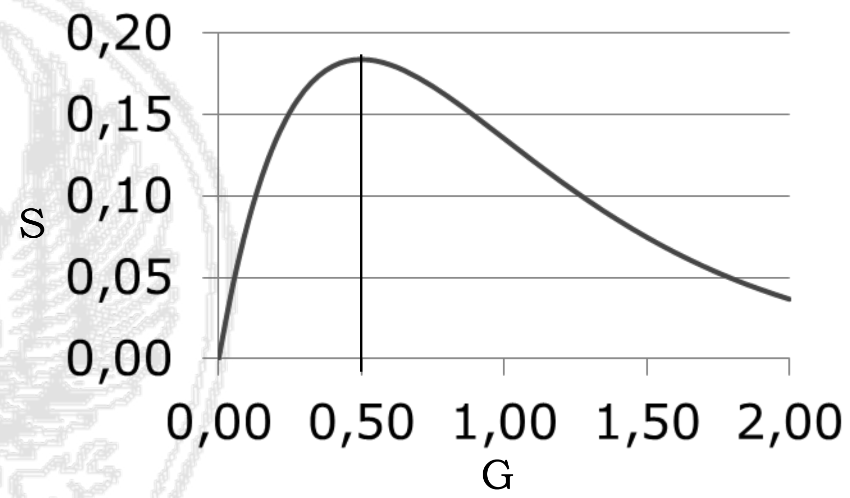
$$P_k(t) = \frac{(\Lambda t)^k e^{-\Lambda t}}{k!}$$

and considering:

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

we have:

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



Maximum Throughput is only 18% of the network capacity!!

Channel captures and ortogonality

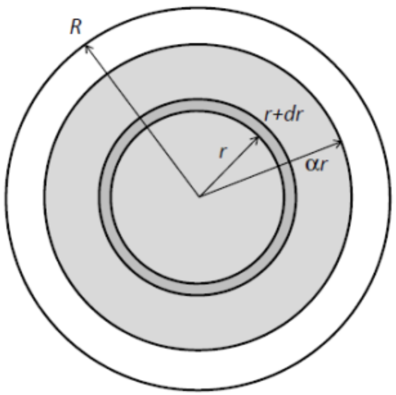
- What happens in case of collision depends on the Signal-to-Interference-Ratio (SIR)
  - if the packets have the same SF → capture effect
  - if packets have different SF → imperfect orthogonality

Minimum **SIR** [dB] that **allows to demodulate the reference signal**

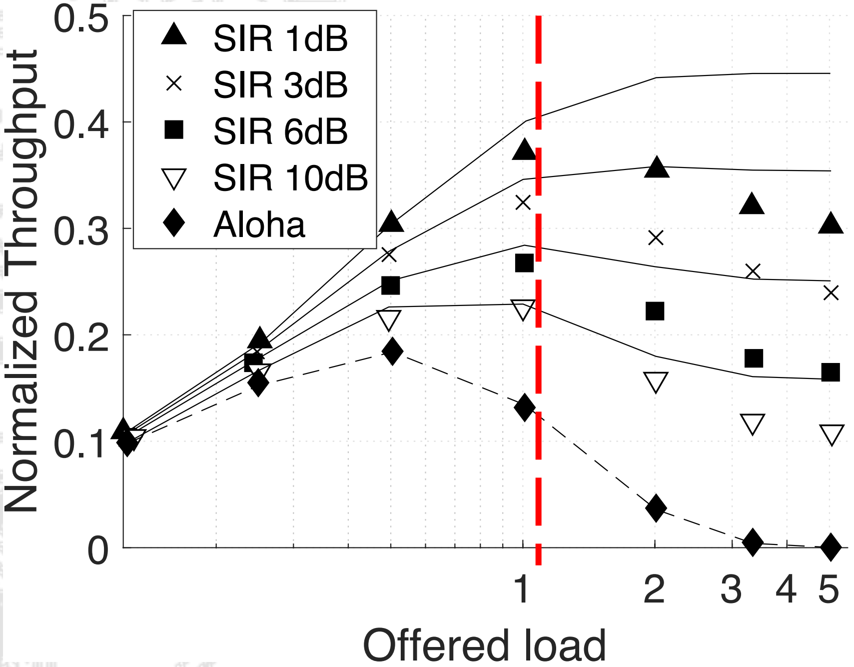
reference \ interferer	7	8	9	10	11	12
7	1	-8	-9	-9	-9	-9
8	-11	1	-11	-12	-13	-13
9	-15	-13	1	-13	-14	-15
10	-19	-18	-17	1	-17	-18
11	-22	-22	-21	-20	1	-20
12	-25	-25	-25	-24	-23	1

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

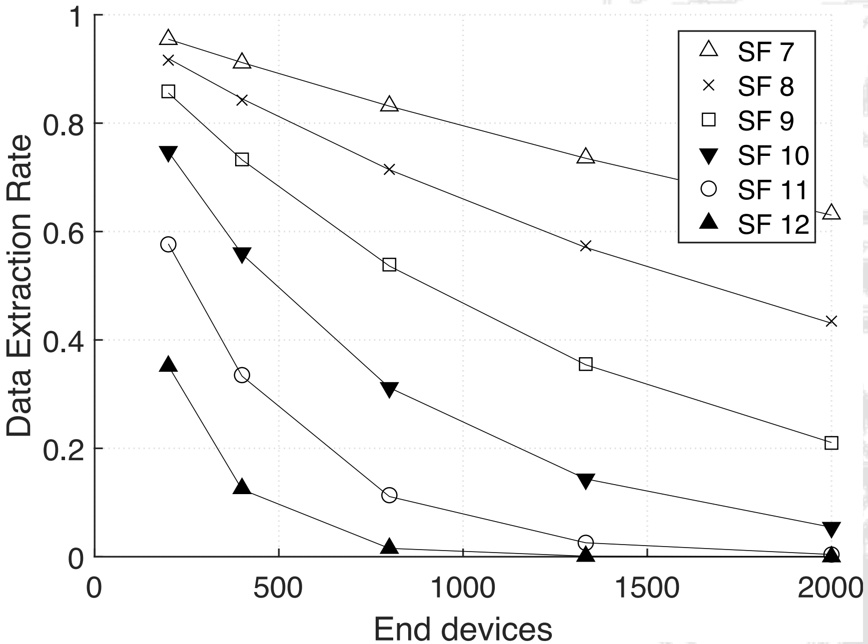


- **Aloha → dashed lines**
- **Our model → solid lines**
- **Simulations → markers**

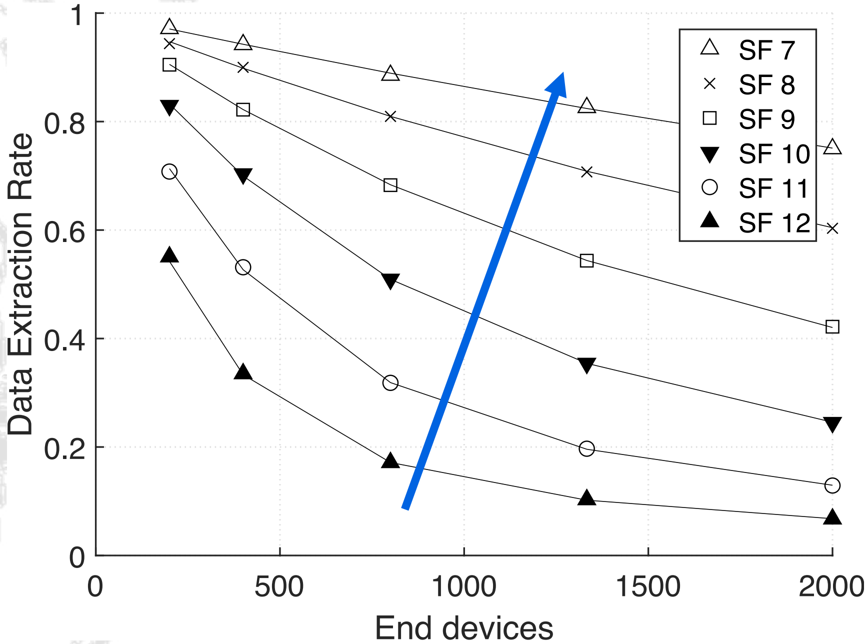
Maximum Throughput can be much higher than 18%!!

Data Extraction Rate (DER) with captures

Pure Aloha



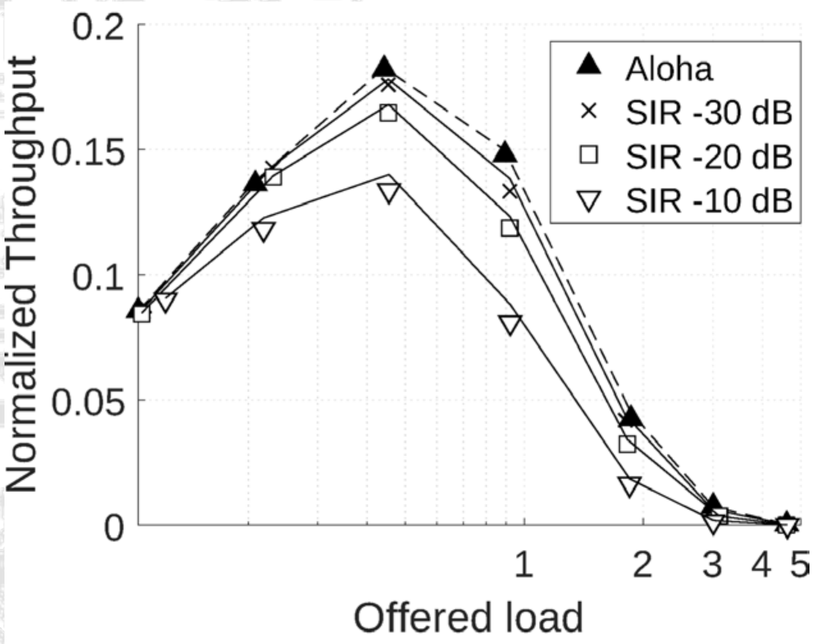
Aloha with captures

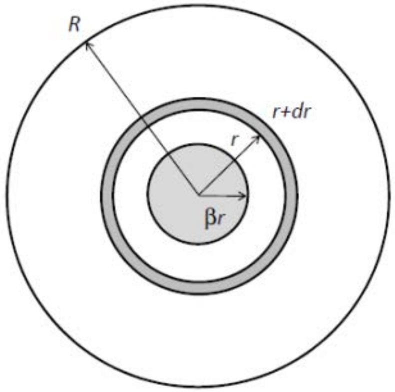


Each device generates a 20 bytes packet every 90 seconds

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

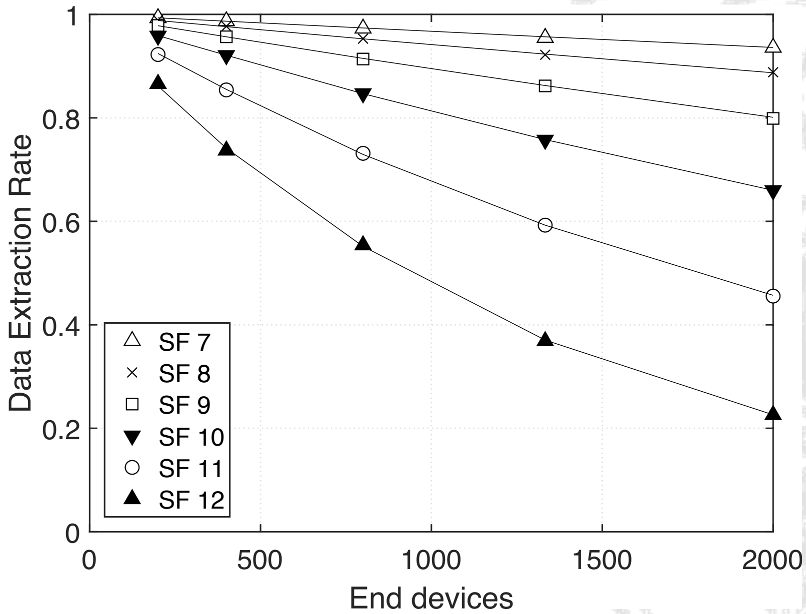




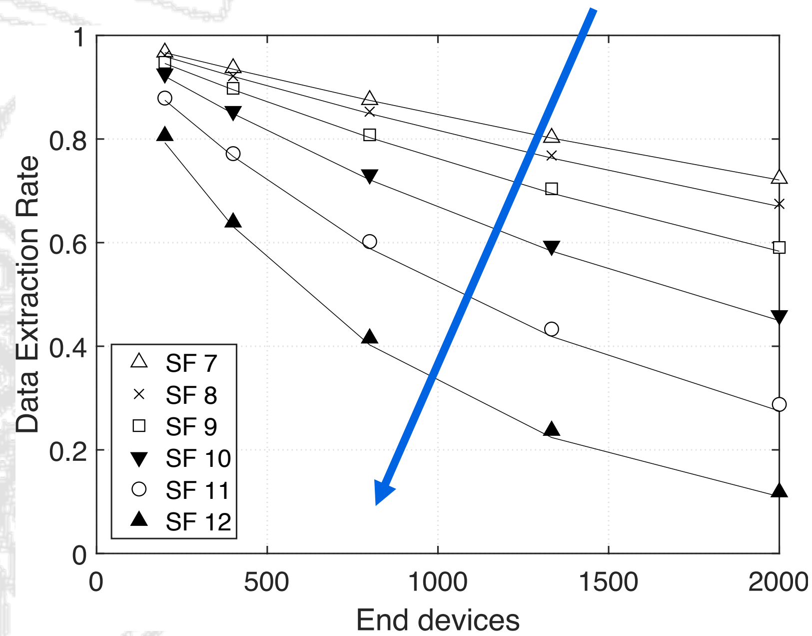
In presence of multiple SFs, maximum throughput of each channel could be lower than 18%!!

DER with inter-SF interferece

Pure Aloha



Imperfect orthogonality

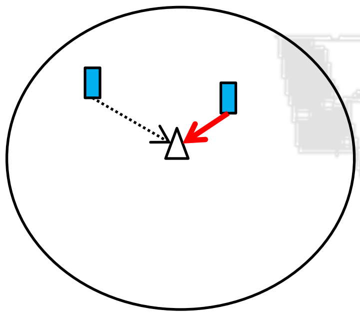


Each device generates a 20 bytes packet every 90 seconds

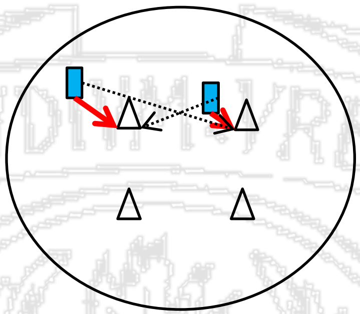
Considerations on Scalability

- 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!

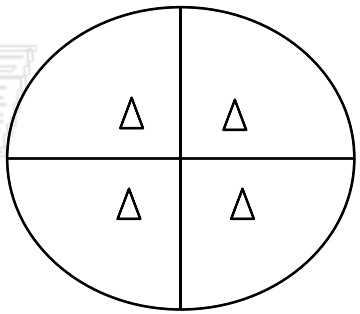
Multi-Gateway Scenario



Capture event: only the closest device is received

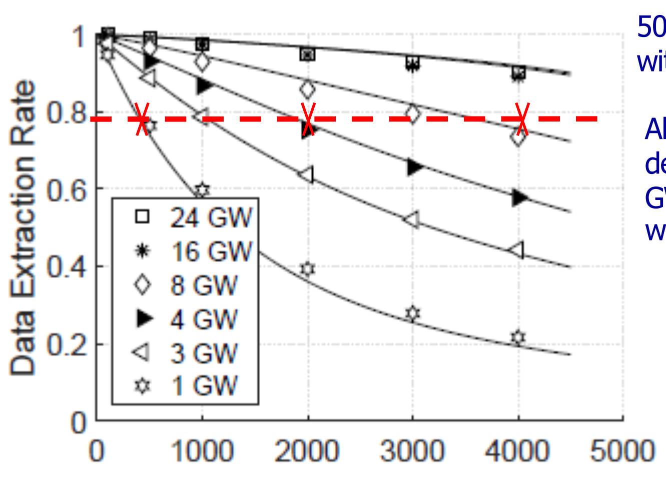


Two correct receptions at two different gateways



With M gateways, system 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

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SF Allocations

SAPIENZA
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Adaptive Data Rate (ADR)

- Basic mechanism: select smallest possible SF for a given SNR/RSSI
  - Highest possible data rate

Received packets

SF = 12
MaxSNR = -10 dB

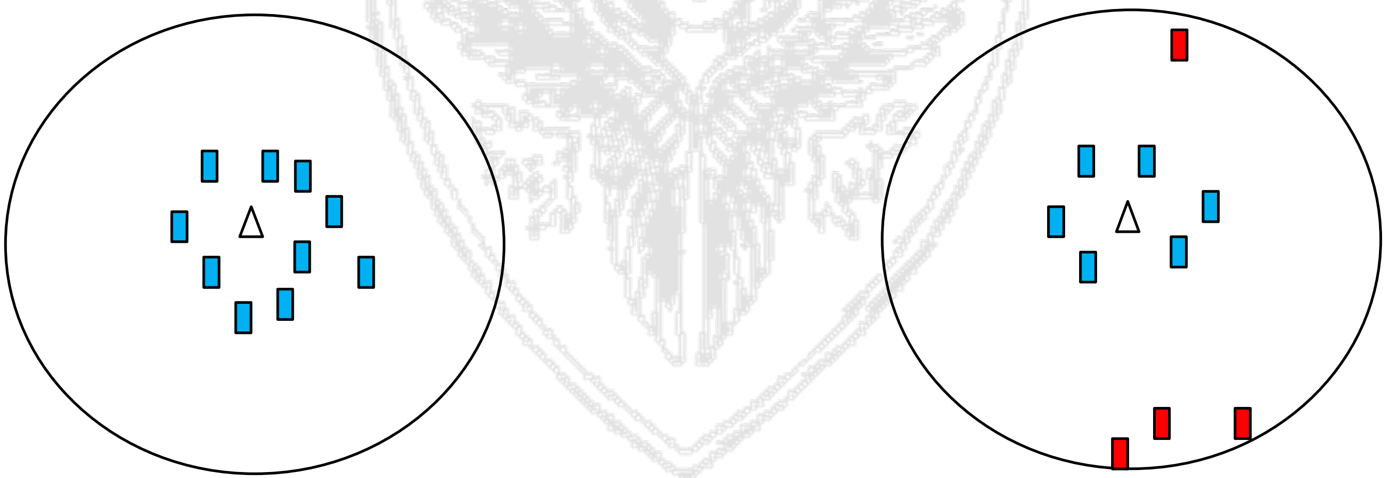
Spreading Factor	SNR limit
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

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

Link ADR request: SF10

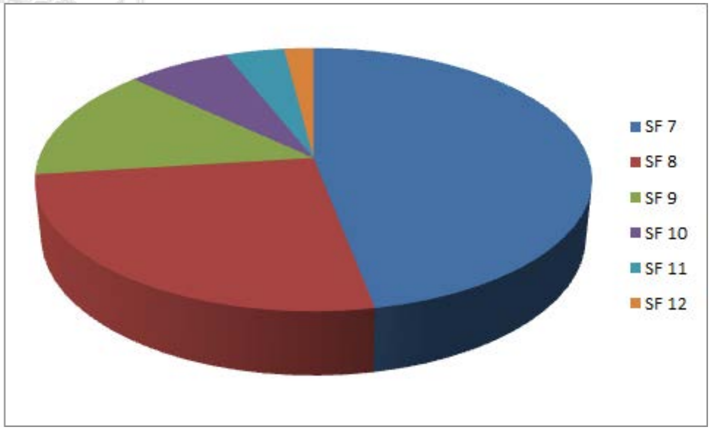
ADR on link-level measurements only?

- 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



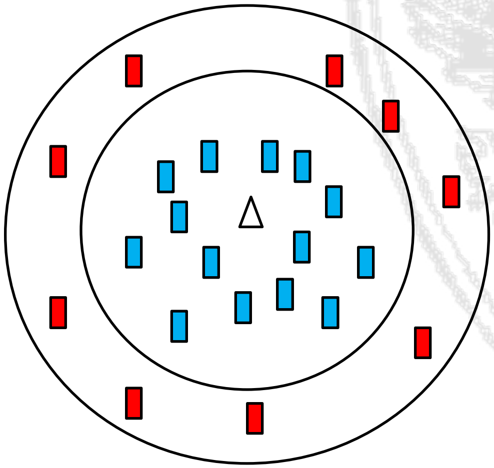
How to balance between SFs?

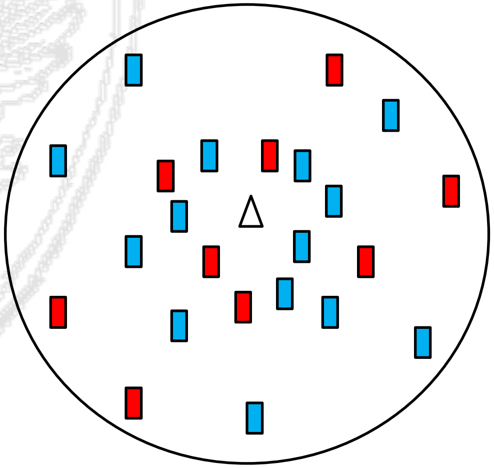
- Airtimes at each SF are not equal
  - Roughly, transmissions times are in the ratio T(SF12)=2 T(SF11)=4 T(SF10)=...=32 T(SF7)
- With uniform application rates, load balancing requires different nodes on each SF
  - More nodes with lower transmission times
    - ✓ 47%, 26%, 14%, 7%, 4%, 2%
    - ✓ Only a few nodes on SF12



And which distribution within the cell?

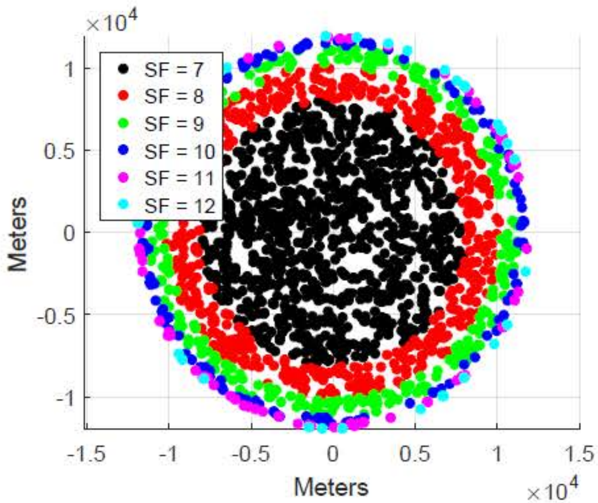
- Consider two SFs only
- Assume all the nodes can be served with smallest SF
- Which allocation is better?
  - Different circular rings or uniform spreading?

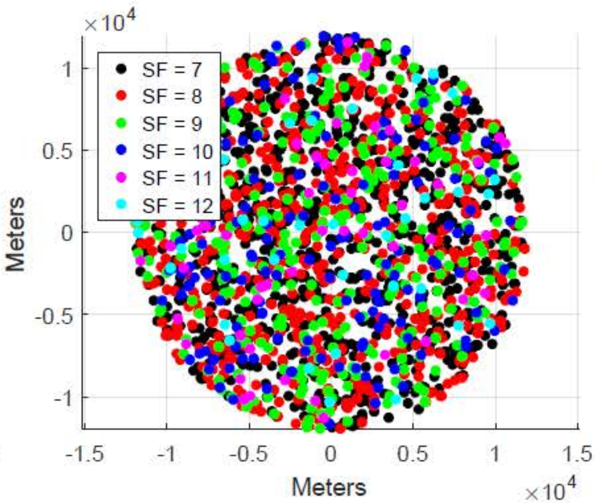


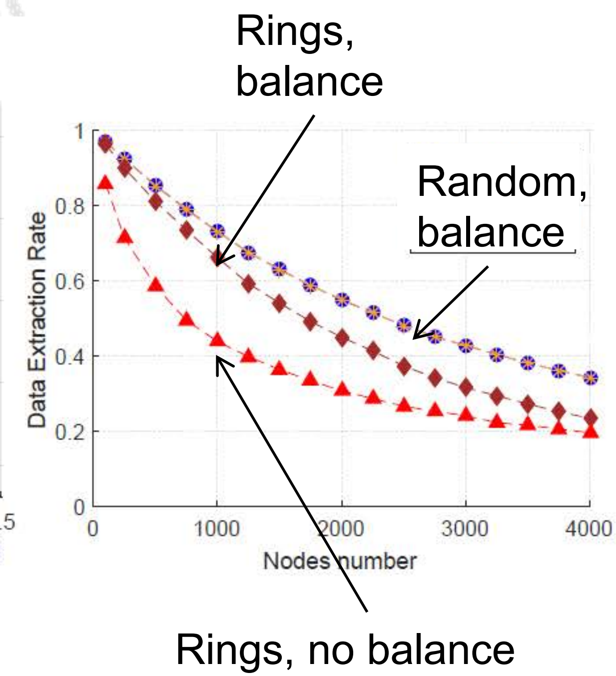


Some Performance Results

- 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!

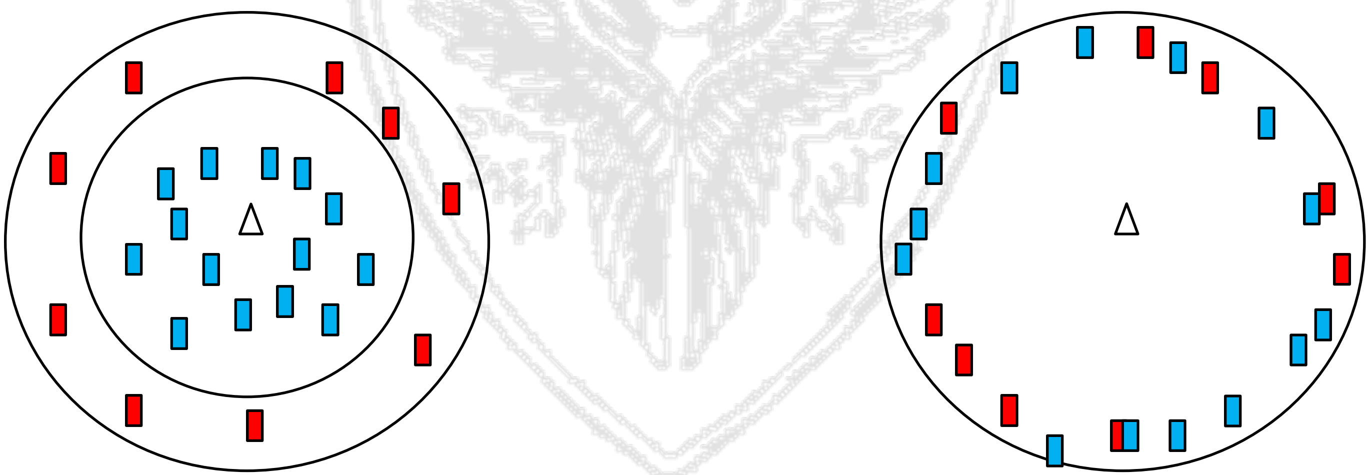






Power Control to mitigate interference?

- Inter-SF interference can be avoided using power control, but…
- No real benefit, because it destroys capture opportunities!
  - Equivalent to move nodes to the same distance from the gateway



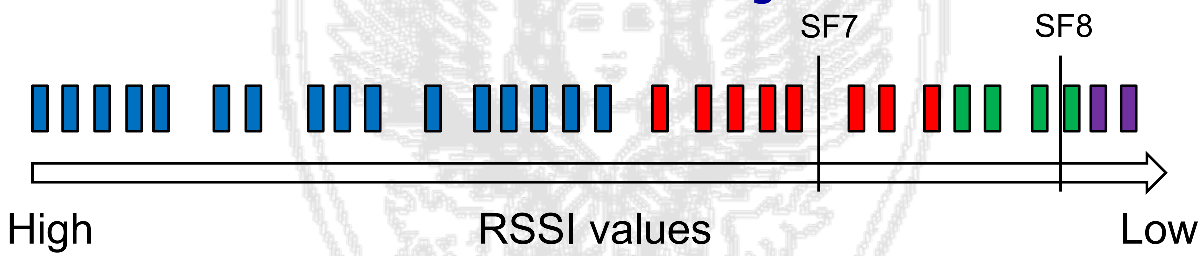
Mapping to SF Allocations: EXPLORA

Basic Principles

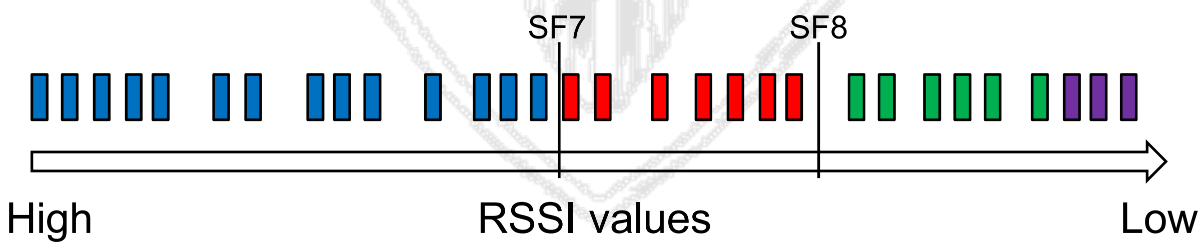
- Take into account RSSI limits
  - Only a portion of nodes can work on higher data rates
- Balance traffic among SFs
- Increase capture probility
  - By distributing users working on the same SF in the total coverage area

Sequential Waterfilling (Single Cell)

- RSSI limits & Load Balancing
  - Users are ordered as a function of their RSSI from the gateway
  - SFs are allocated in proportion, starting from SF7
- Example:
  - 30 Nodes, 16@SF7, 8@SF8, 4@SF9, 2@SF10
  - Cell size allows using SF9 and SF10 everywhere, while SF7 and SF8 have the limits shown in the figure

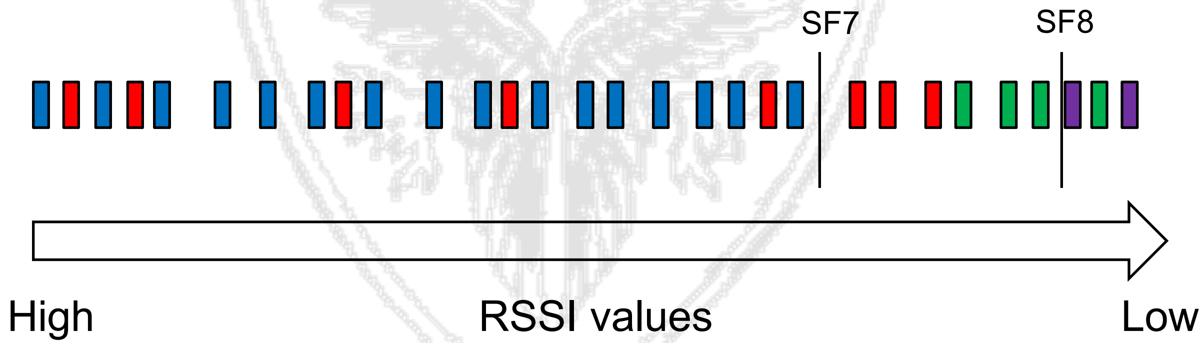


  - In some cases, budget limits can prevent perfect balancing



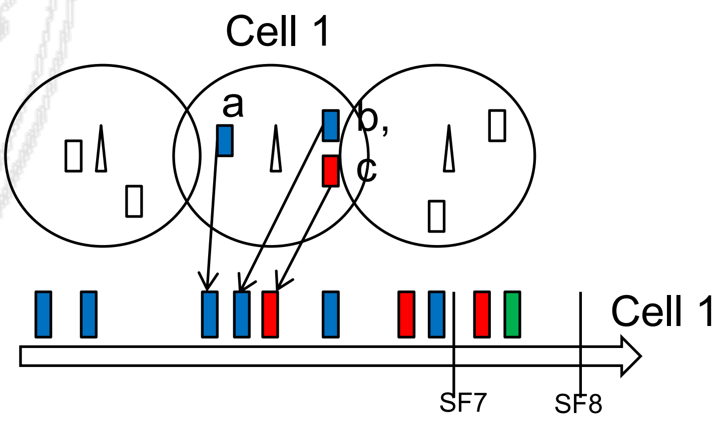
Can we do better?

- We should distribute as much as possible users working on the same SF for increasing captures!
  - Distance between consecutive nodes
    - ✓ If RSSI differ from previous node more than 3dB, keep SF
    - ✓ Otherwise, use a different SF (compatible with link budget)
- Example:
  - 30 Nodes, 16@SF7, 8@SF8, 4@SF9, 2@SF10



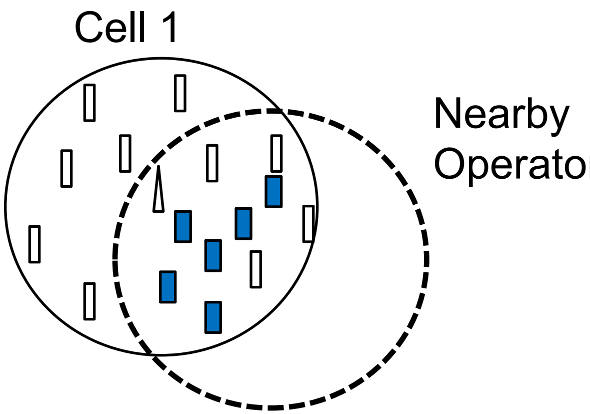
Sequential Waterfilling (Multi Cell, M GWs)

- Nodes are divided into M sets
  - Nodes are assigned to the closest gateway
- Each gateway assigns SFs keeping the proportions
  - Interference between cells is proportional on each SF in absence of link constraints
- Distance between nodes is generalized, taking into account the set of visible GWs
- Example: 3 cells in a row
  - 6@SF7, 3@SF8, 1@SF9 in each cell
  - nodes a and b are 'distant' because they see different GWs, while nodes b and c are close

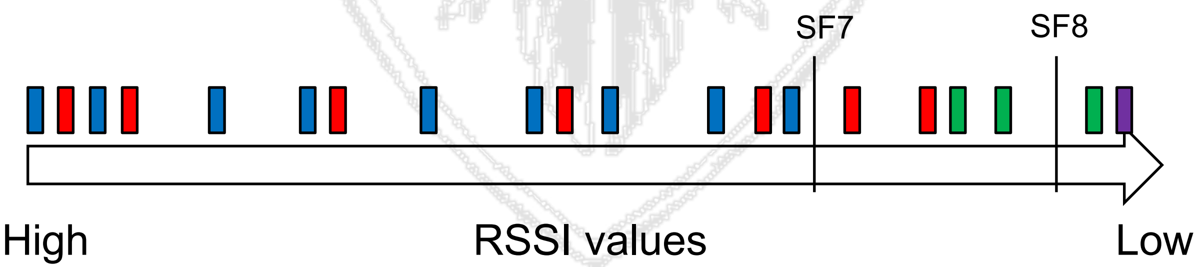


Sequential Waterfilling (Multi Cell, Multi ISP)

- If some nodes are controlled by a different operator?
- Each GW computes the 'residual' proportion for each SF and runs the algorithm with the new budgets!



- Example: 1 nearby operator
  - Interference only @SF7
  - Assuming 20 nodes, proportions become:
    - ✓ (16-6)@SF7, 8@SF8, 4@SF9, 2@SF10
    - (being 4 the 'equivalent' number of devices)



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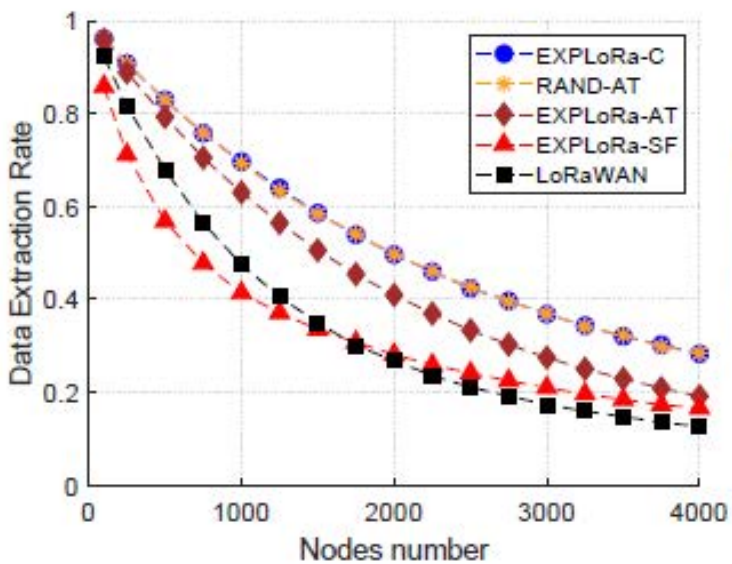
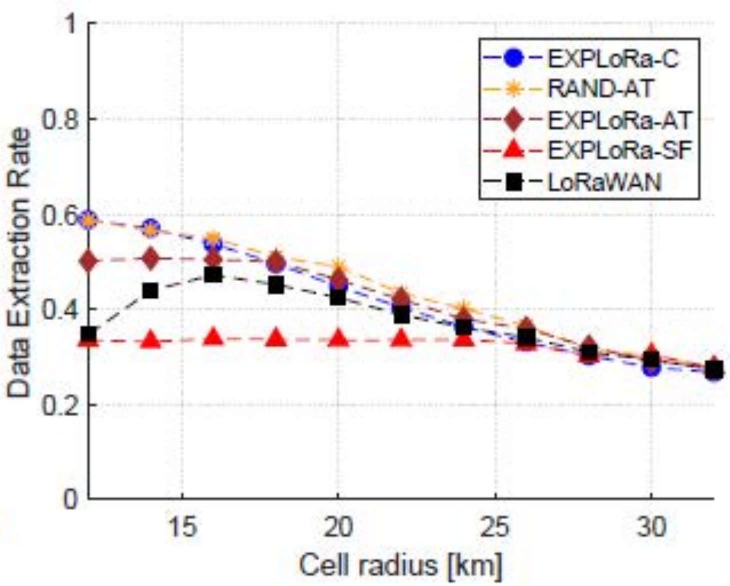
Some Results



No link budget constraints



With link budget constraints and bigger cells

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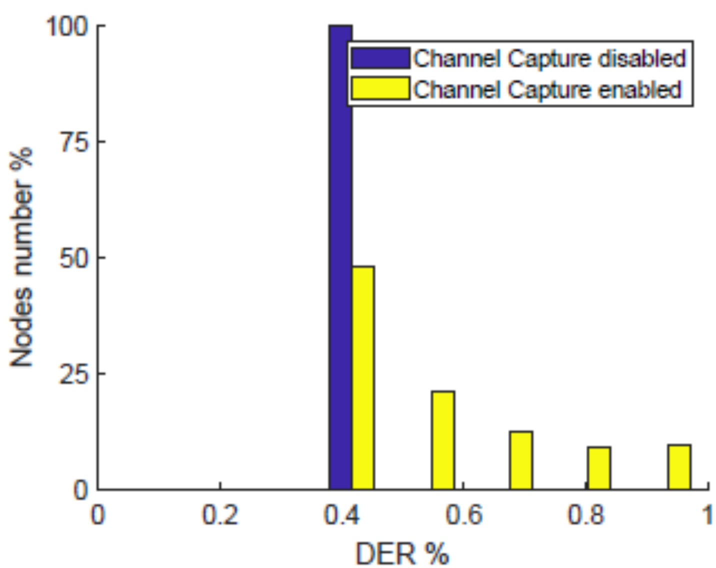
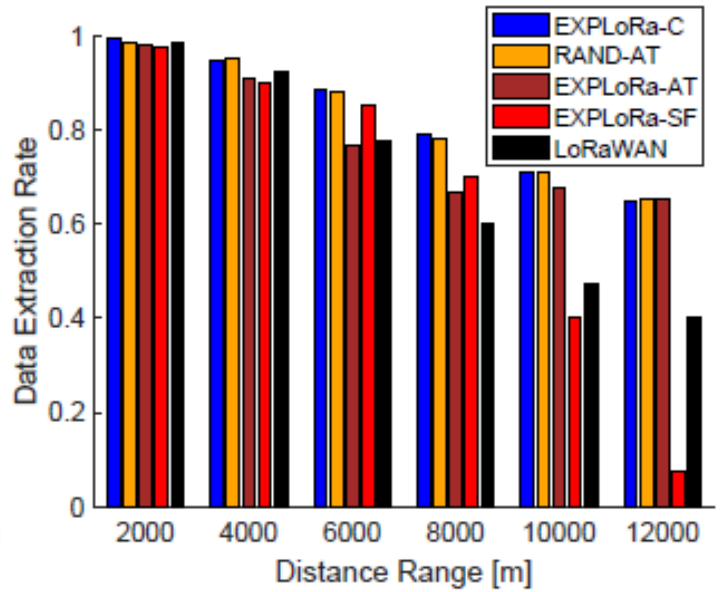
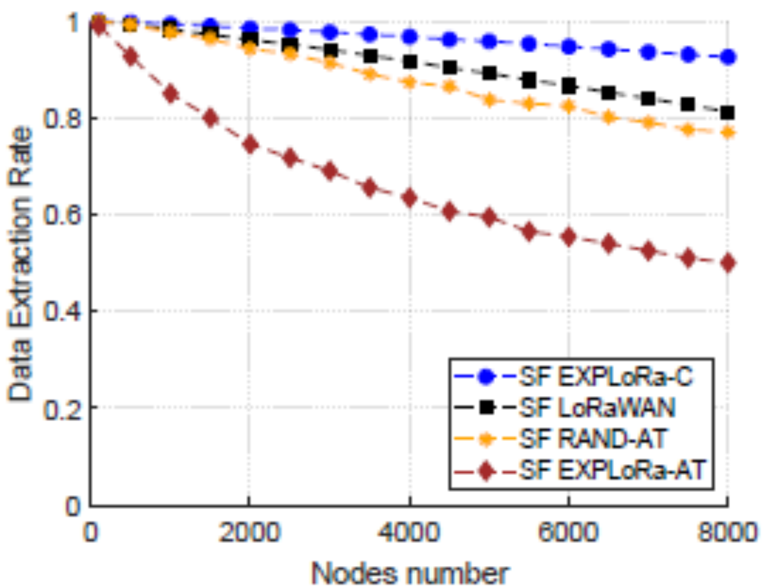
Is it fair in presence of captures?

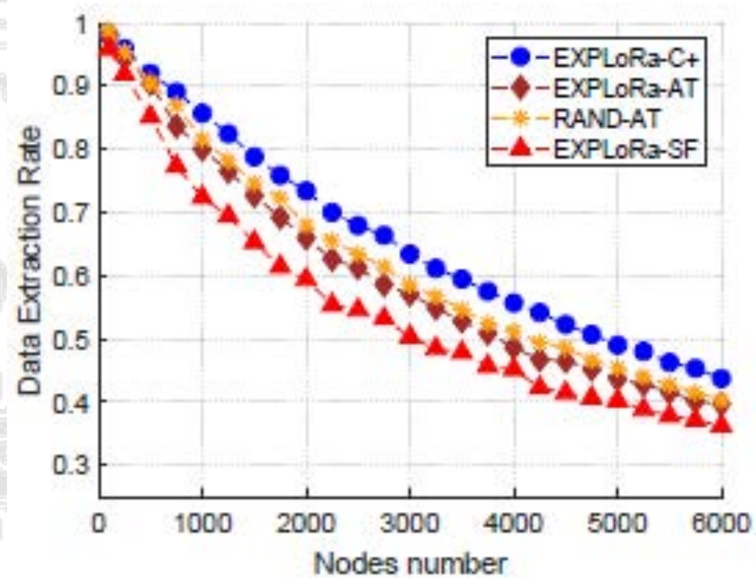




Is it enough to go random?



Multi-gateway

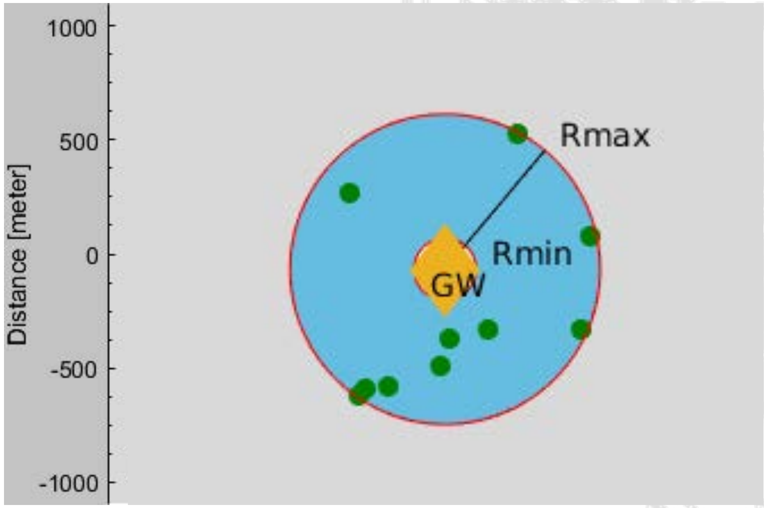


Multi-gateway, multi-operator

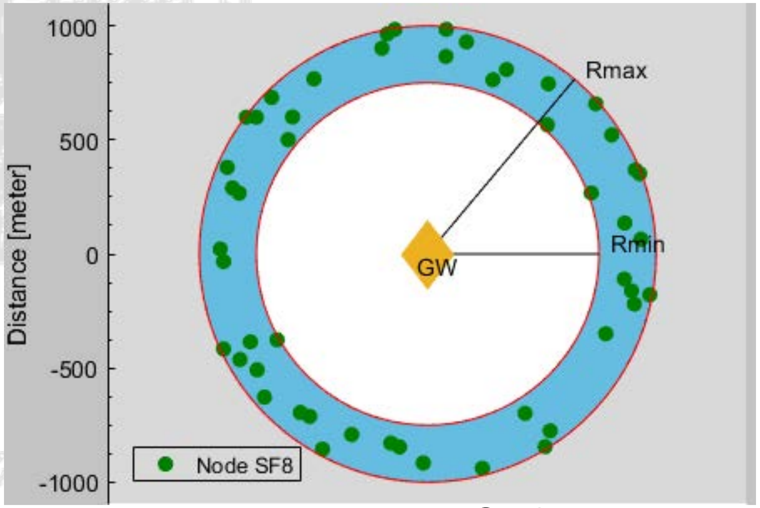
Open Issues

1) Experimental Studies

- How to do experiments with thousands of nodes?
- Possible idea: work on traffic emulator, given:
  - # of nodes, source rates and SF allocation
  - Position of the nodes (Rmin and Rmax)
- Schedule transmissions (including collisions) and generate aggregated signal to transmit via software radios (e.g. USRP)

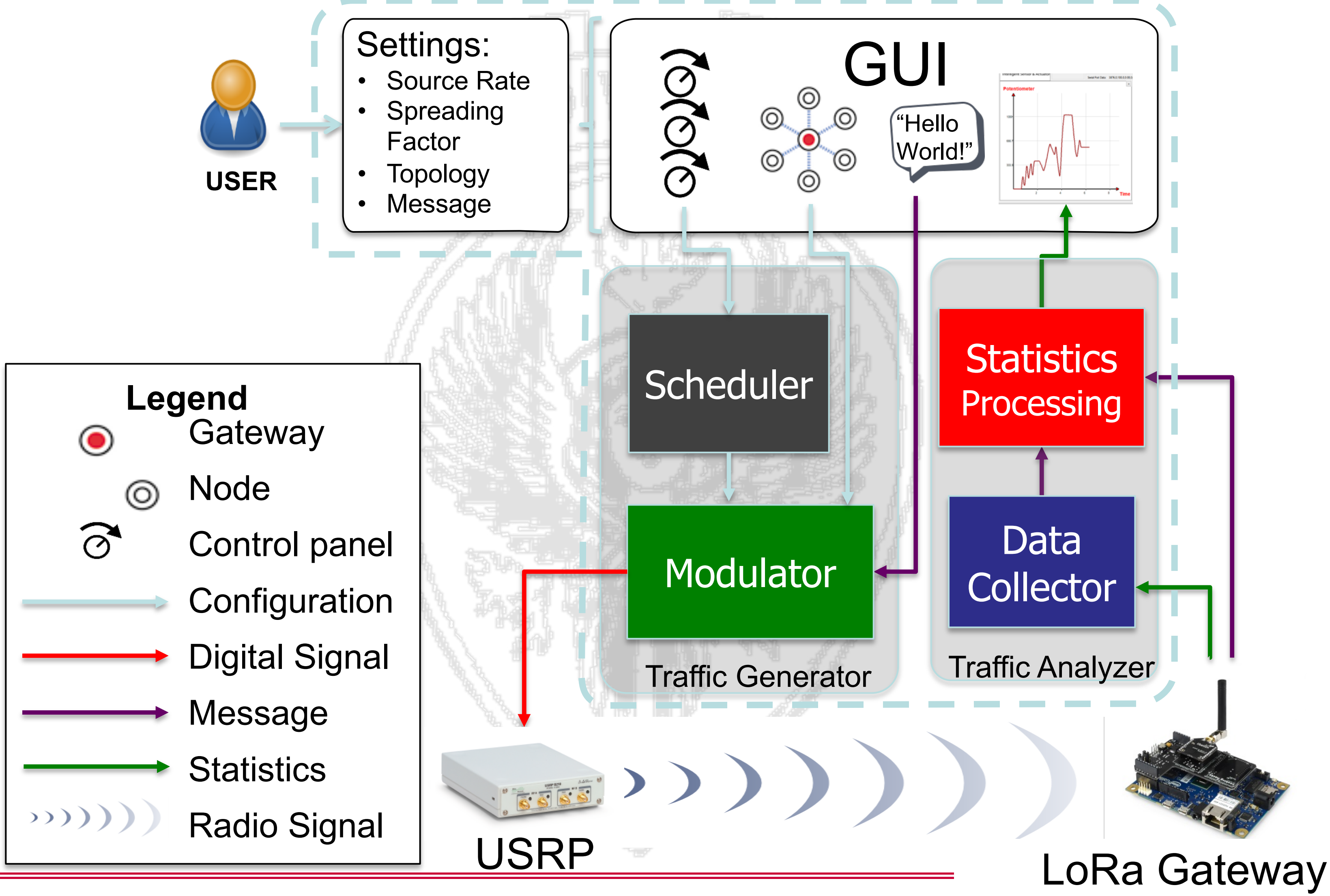


Nodes with SF7



Nodes with SF8

Emulator architecture

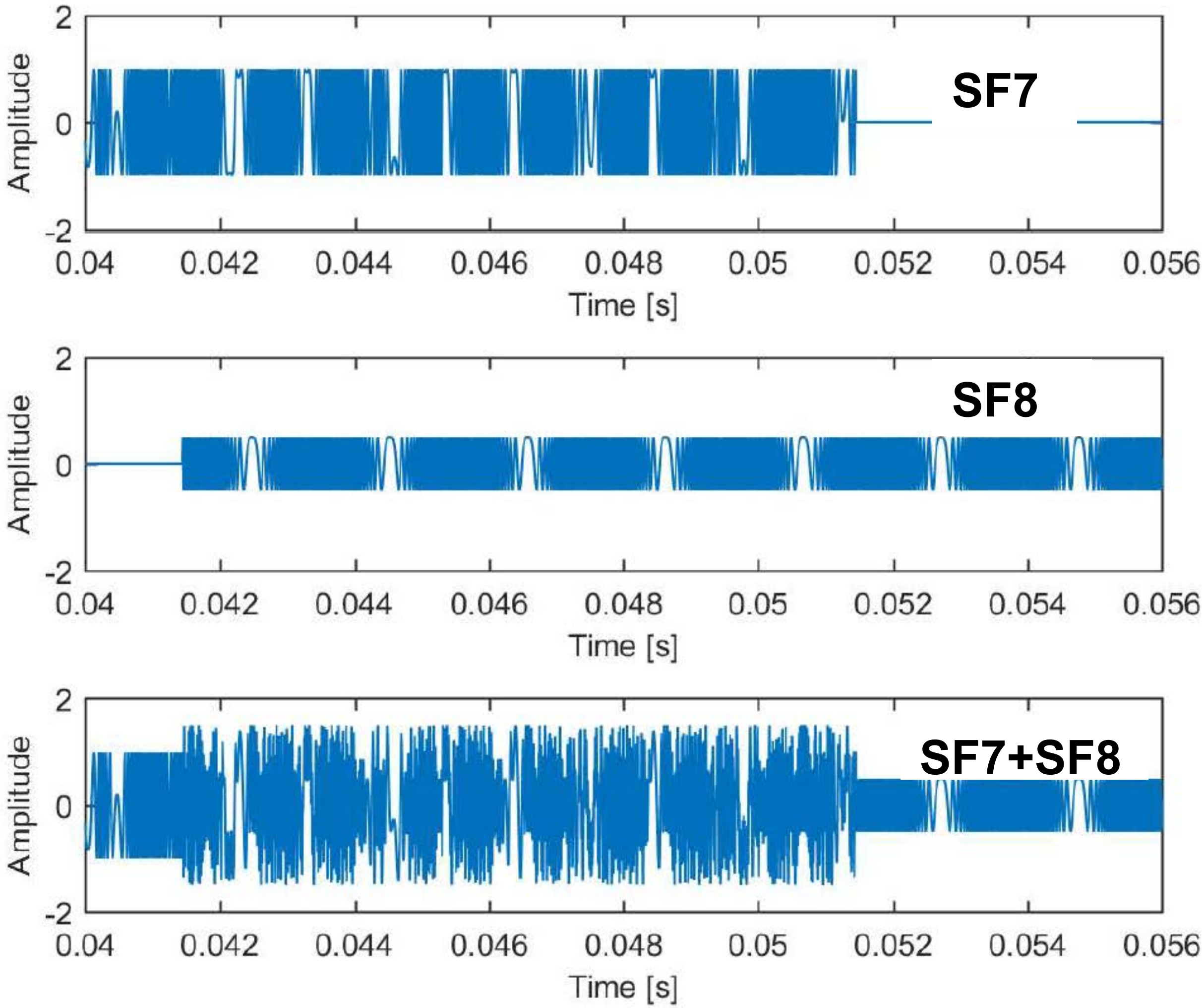


An example of aggregated trace

Ch1

Ch2

On Air



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
- Special cases: anomaly detection, network re-start…

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…

Conclusions

- Pros:
  - Outdoor, indoor and deep indoor connectivity
  - Low cost of ownership with private or public networks
  - Scalable architectures robust to interference
  - Strong ecosystem of partners and applications
  - Active research area & open source community
- Cons:
  - ISM band = no performance guarantees
  - Difficult to optimize
- IoT is a competitive market!
  - SigFox, LoRa, NB-IoT, LTE-M, etc.
  - Somehow complementary (performance vs. costs)

References

- Do LoRa Low-Power Wide-Area Networks Scale?
  - Martin Bor, Utz Roedig Lancaster University, Thiemo Voigt Uppsala University and SICS, Juan M. Alonso Nac. de San Luis, Argentina
- LoRaWAN specification
  - N.Sornin , M. Luis , T. Eirich , T. Kramp , and O. Hersent , LoRa Alliance Inc., San Ramon, CA, Ver. 1.0., January 2015
- 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
- Long-Range IoT Technologies: The Dawn of LoRa
  - L. Vangelista, A. Zanella, M. Zorzi, in Future Access Enablers of Ubiquitous and Intelligent Infrastructures, pp. 51–58, Springer, 2015
- Extending the performance of LoRa by suitable spreading factor allocations
  - F. Cuomo, M. Campo, A. Caponi, G. Bianchi, G. Rossini and P. Pisani, WiMob 2017
- LoRaSIM simulator
  - https://github.com/adwaitnd/lorasim

Thank you!

Questions?