Beyond 5G Low-Power Wide-Area Networks

A LoRaWAN Suitability Study

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Slide 1

HA1 add the meeting/event name

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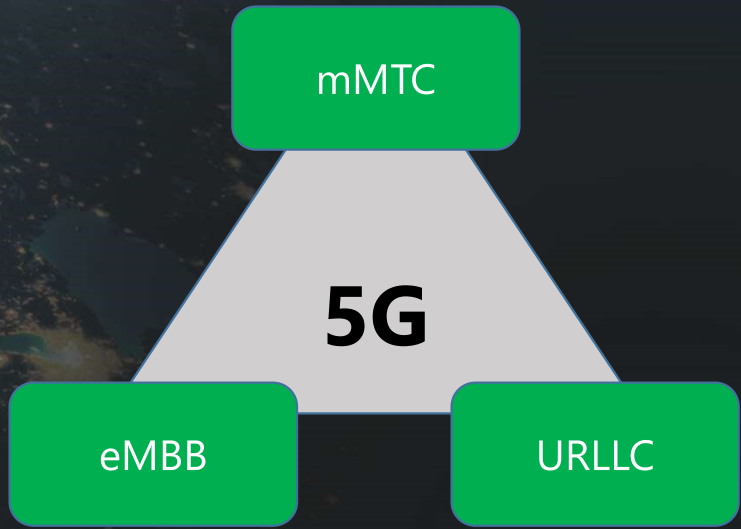
5G systems and beyond

- 5G systems address three types of network services
- eMBB: Enhanced Mobile Broadband
  - Depends on human demand for high bandwidth (e.g., video streaming and video conference applications)
  - 5G boosts it by increasing spectrum efficiency to support more users at higher bit rates.
- URLLC: Ultra-Reliable Low-Latency Communications
  - Although new in the context of cellular networks, relates to a well studied set of critical real-time applications
  - 5G delivers the service by thoroughly planning and managing the resource allocation.
- mMTC: massive Machine-Type Communications
  - Must cope with Ultra-Dense Networks (UDN) of devices with dynamic and sporadic traffic patterns.
  - Poses challenges to delivering massive connectivity with acceptable reliability and promoting efficient resource utilization.



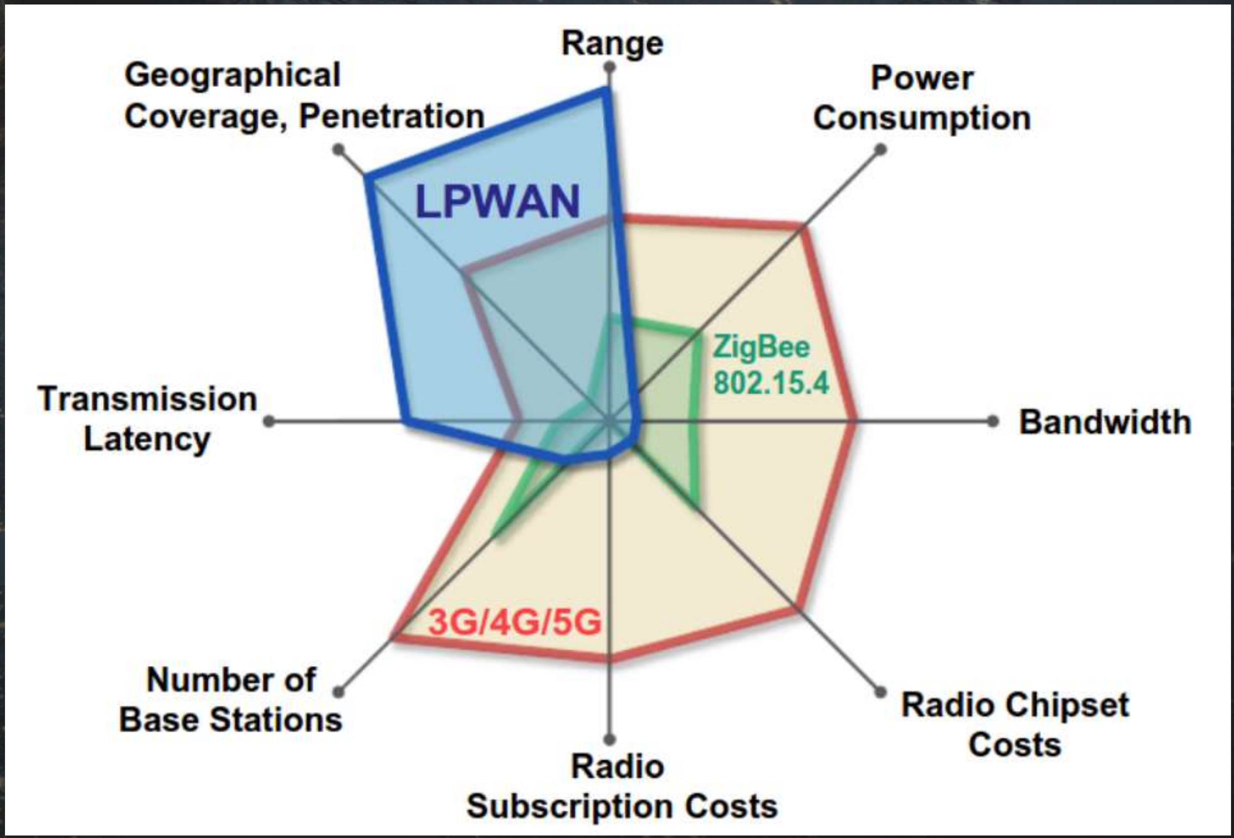
Contextualization

- IoT demands from mMTC
  - to serve *massive numbers of users*
  - with *low-energy consumption*
  - and at *reasonable reliability*
- LPWANs support the first two requirements by design
  - That is usually achieved at the cost of reliability
  - Performance studies of dense LoRaWAN deployments not available
  - Current performance models rely on theoretical or simulation models
- Here, we revisit recent works where we have modeled, analyzed, and simulated the performance of LoRa uplink
- This allows us to understand some characteristics of LoRa networks and, through extrapolation, other LPWAN.

Low-Power Wide-Area Networks

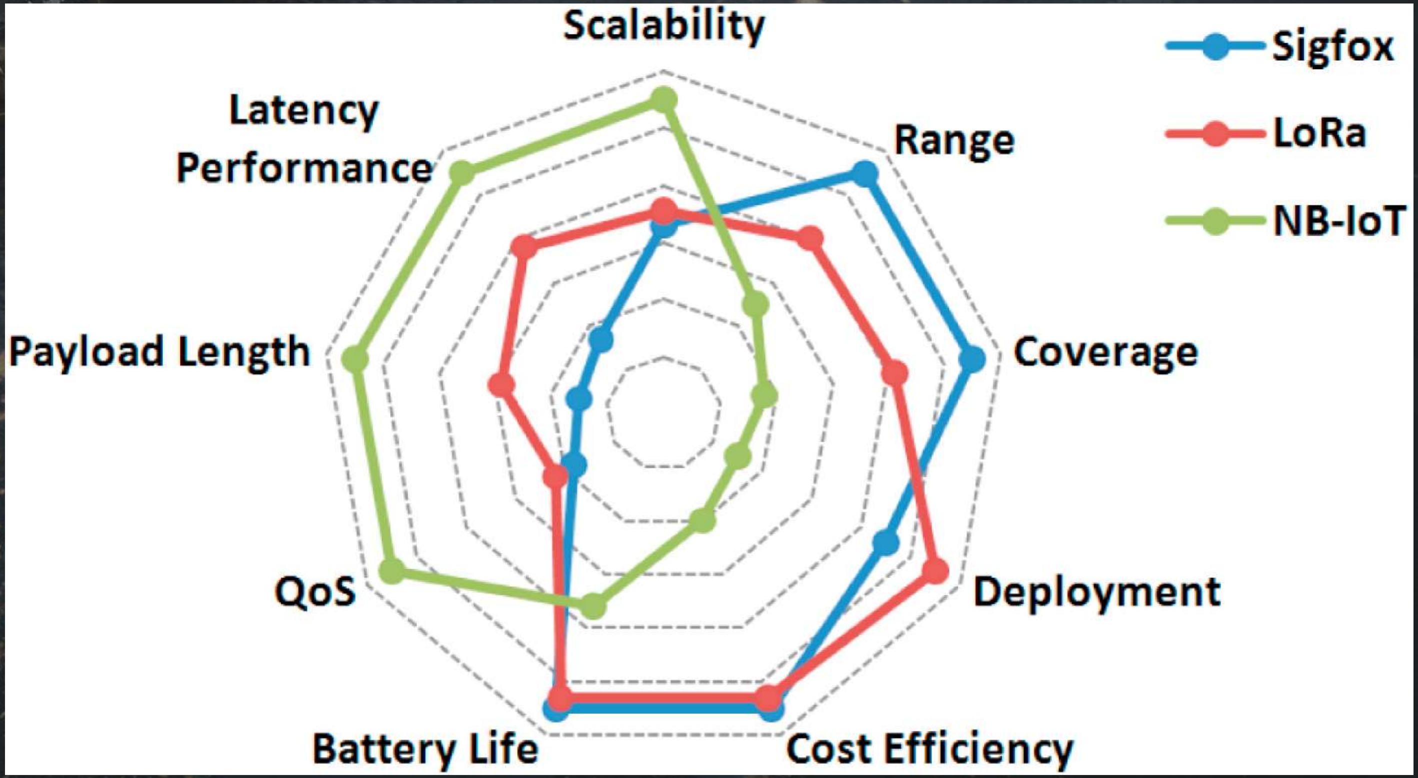
- Communication channels with low energy consumption, reaching long distances
  - Sub-GHz central frequency
  - (Ultra-)Narrow bandwidths, usually bellow 250kHz
  - High link budgets, at about 150±10dB
- Massive numbers of devices on short duty cycles
- Use low complexity MAC algorithms (e.g., ALOHA)
- (Very) Low bit-rates (from several bps to a few kbps)
- Examples: LoRaWAN, SigFox, NB-IoT.

LPWAN within the IoT landscape



Souce: Egli, 2017.
http://peteregli.ch/content/iot/iot.html

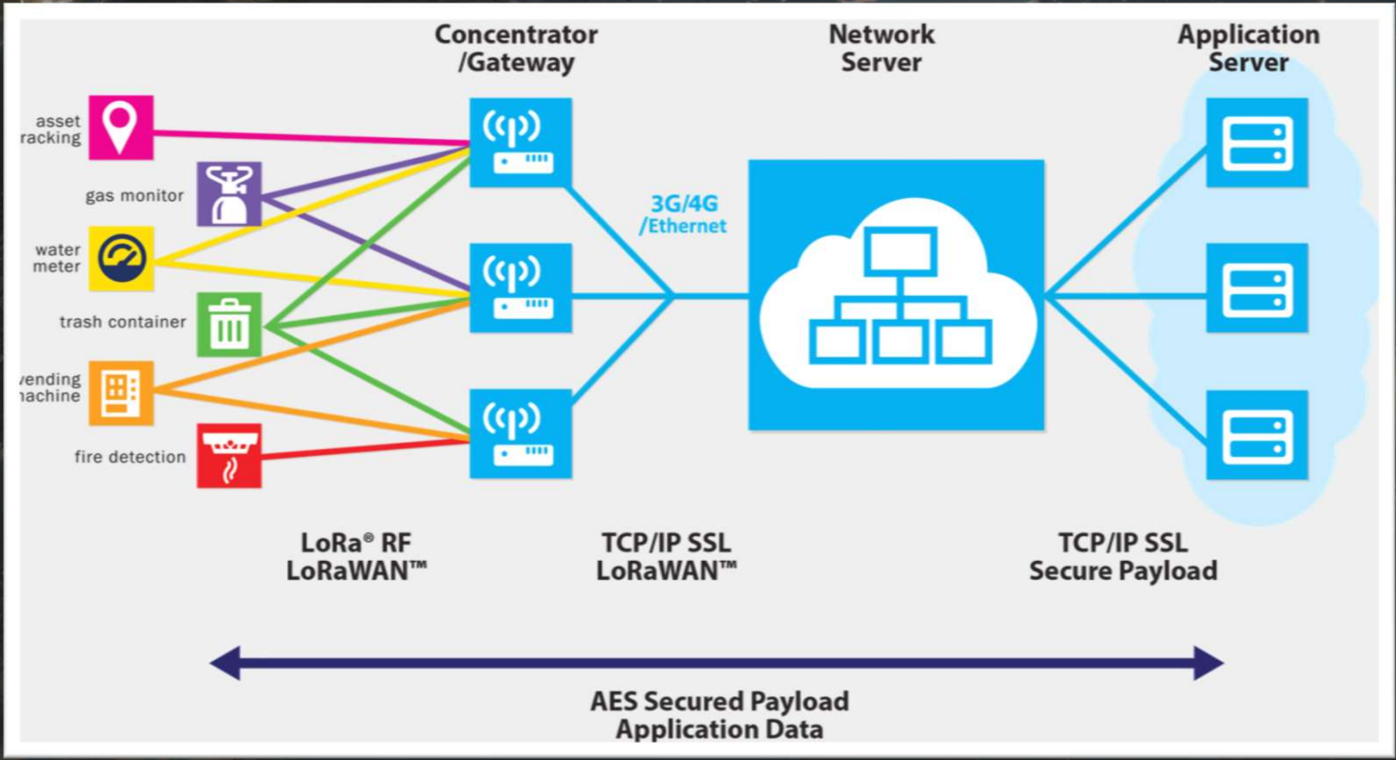
Different LPWAN technologies



Souce: Mekki *et al.*, 2019.
https://doi.org/10.1016/j.icte.2017.12.005

LoRaWAN Overview

- LoRaWAN specifies a protocol stack that forms a star topology of IoT devices using the ALOHA MAC



Souce: LoRa Alliance, 2015.
https://lora-alliance.org/resource-hub/what-lorawanr

LoRaWAN PHY configurations

- Chirp Spread Spectrum
- Spreading Factor (SF) impacts symbol length
- E.g., LoRa packet (9/13-bytes payload/header)

SF i	**Time-on-Air** t_i **(ms)**	**Tx Rate** R_b **(kbps)**	**Rx Sensitivity** S_i **(dBm)**	**SNR threshold** ψ_i **(dB)**
7	56.58	5.47	-123	-6
8	102.92	3.12	-126	-9
9	205.83	1.76	-129	-12
10	370.69	0.98	-132	-15
11	659.46	0.54	-134.5	-17.5
12	1318.92	0.29	-137	-20

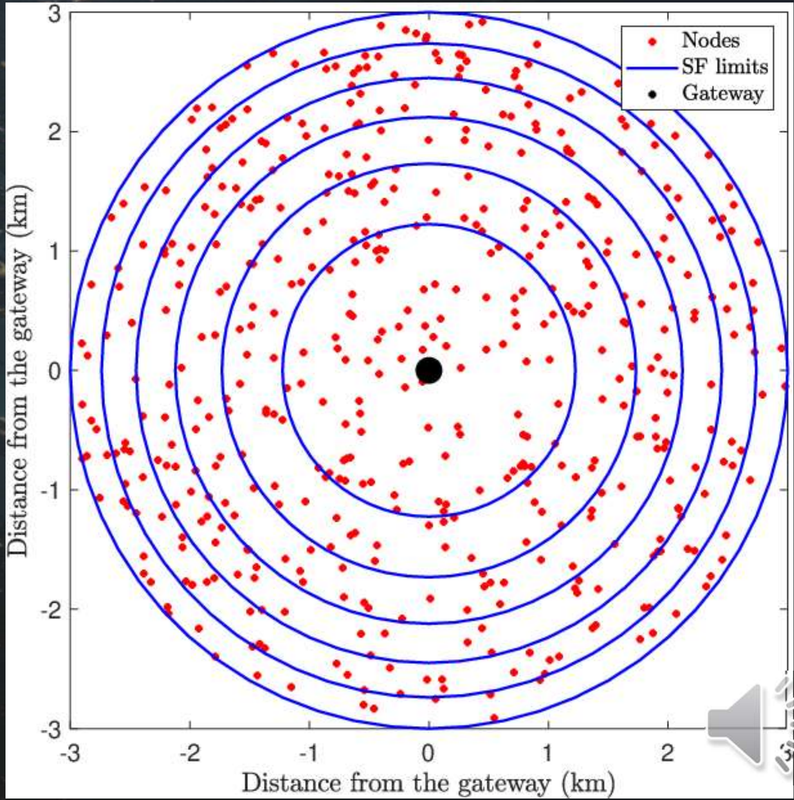
LoRaWAN Performance Evaluation

- Performance evaluation in two previously published works dealing with single-gateway LoRaWAN cells
- Analytical model for the coverage probability
  - A. Hoeller, R. D. Souza, H. Alves, O. L. Alcaraz López, S. Montejo-Sánchez and M. E. Pellenz, "Optimum LoRaWAN Configuration Under Wi-SUN Interference," in IEEE Access, vol. 7, pp. 170936-170948, 2019.
  - doi: 10.1109/ACCESS.2019.2955750
- Simulation model for throughput and PDR
  - J. Markkula, K. Mikhaylov and J. Haapola, "Simulating LoRaWAN: On Importance of Inter Spreading Factor Interference and Collision Effect," 2019 IEEE International Conference on Communications, Shanghai, China, pp. 1-7, 2019.
  - doi: 10.1109/ICC.2019.8761055

Analytical LoRa Uplink model

- LoRa devices usually employ the Adaptive Data Rate mechanism to set the devices' SF according to the channel condition measured at the gateway
- Since the channel condition depends on the communication distance, analytical models adopt a ring-based network topology
- Nodes distributed uniformly
- Equal-area SF rings/allocation
- Activity modeled by a PPP (Φ)
- ALOHA, duty-cycle
- All nodes use same Tx Power
- Free-space pathloss $g_k = \left(\frac{\lambda}{4\pi d_k}\right)^\eta$
- Interference over a finite area

$$r_1 = \sqrt{P_{tx} g_1} h_1 * s_1 + \sum_{j \in S} \sum_{k \in \Phi_j} \sqrt{P_{tx} g_k} h_k * s_k + w$$



Coverage Probability

- The coverage probability (C_1) is the product of the noise-dependent connection probability (H_1) and the interference-dependent capture probability (Q_1)

$$C_1 = H_1 Q_1$$

- Connection probability considering zero-mean AWGN and Rayleigh fading

$$H_1 = \mathbb{P}\left(\mathrm{SNR} > \gamma_i\right) = \mathbb{P}\left(\frac{P_{tx} g_1 |h_1|^2}{\sigma_w^2} > \gamma_i\right) = \exp\left(-\frac{\gamma_i \sigma_w^2}{P_{tx} g_1}\right)$$

- Where i denotes the SF ring of the typical node
- Capture probability with both intra-SF and inter-SF interference sources. We first analyze it separately for each SF ring j. Averaged for the PPP and the Rayleigh fading of all nodes yields

$$P_{SIR_j} = \mathbb{P}(\mathrm{SIR}_j > \delta_{ij}) = \exp\left\{-\pi\alpha_j\left[l_j^2\,{}_2F_1\left(1, \frac{2}{\eta}; 1+\frac{2}{\eta}; -\frac{l_j^\eta}{d_1^\eta \delta_{ij}}\right) - l_{j-1}^2\,{}_2F_1\left(1, \frac{2}{\eta}; 1+\frac{2}{\eta}; -\frac{l_{j-1}^\eta}{d_1^\eta \delta_{ij}}\right)\right]\right\}$$

- Where j denotes the SF of the interference sources.
- The probability that a collision does not occurs is

$$Q_1 = \exp\left(\sum_{j \in S} P_{SIR_j}\right)$$

LoRaWAN Simulator

- Based on Riverbed Modeler network simulator
  - Pathloss based on the Hata Rural model
  - Models inter- and intra-SF interference
  - Pure-ALOHA – Class A LoRaWAN end-devices
  - duty cycle limitations for frequency channels
  - channel hopping
  - uplink and downlink transmission functionalities
- Three packet collision models
  - B(P): baseline (pessimistic), all concurrent transmissions are lost
  - IC: intra-SF collisions with capture effect. With perfect inter-SF isolation
  - IIC: considers imperfect inter-SF orthogonality with capture-effect

Simulation setups

- N1 case
  - All devices use SF7
  - B(P) and IC collision models considered
  - Reporting the average of 100 two-hour-long simulations
- N2 case
  - Devices operated with randomly allocated SF7-SF12
  - 50 devices per SF
  - B(P), IC, and IIC collision models considered
  - Reporting the average of 100 five-hour-long simulations
  - Devices distributed in a circular area with random radius from 0 to 13 km
  - Gateway at the center of the area
  - PDR close to 100% if there are no collisions.
  - Devices transmit LoRaWAN packets with 8-byte application payload
  - Traffic follows Poisson distribution with particular mean varying from 0.1 to 1 erlang (E).

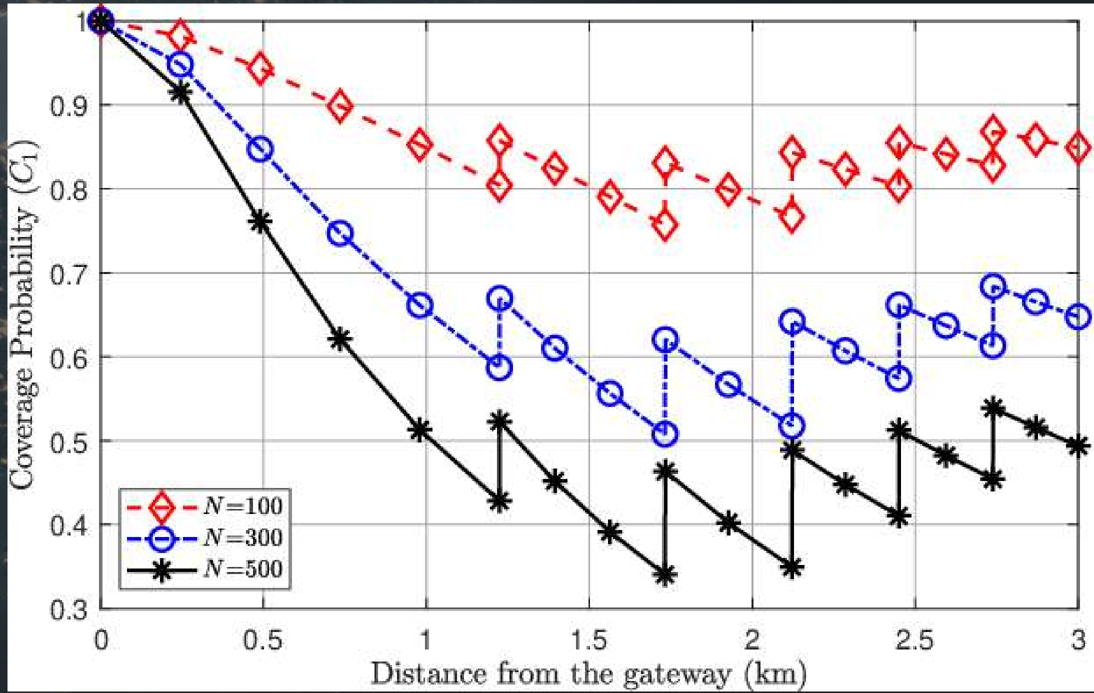
Parameter	Value
Number of nodes	300 (end-device), 1 (gateway)
End-device traffic	0.1, 0.2, ..., 1 E
Spreading factor	7 (N1 case), 7, 8, ..., 12 (N2 case)
Duty cycle	1%
Channel band width	125 kHz
Base frequency	868.1
Transmission power	14 dBm
Tx antenna gain	0 dBi
Antenna height	3 m (end-device), 24 m (gateway)
MAC	ALOHA, random frequency channel
Channel hopping	Disabled
Retransmissions	
Downlink transmissions	
ADR and power control	
Activation:	by personalization

Numerical results – Coverage Probability

- Theoretical coverage probability for a single frequency channel
- Assume typical EU configurations
  - 868MHz ISM band
  - 125 kHz bandwidth
  - FEC rate of 4/5
  - Transmit power 14 dBm
- We also assume
  - The path loss exponent 2.75
  - Interferers' duty cycle at 1% (p=0.01)
  - AWGN power -117 dBm
  - Receiver noise figure of 6 dB

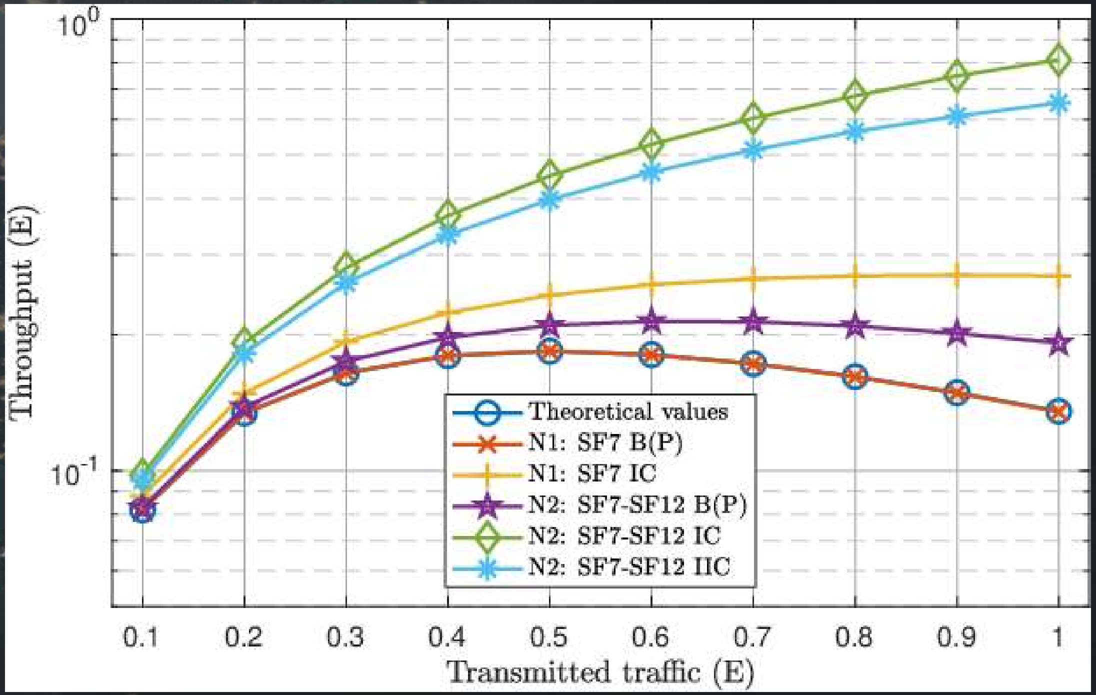
Numerical results – Coverage Probability

- Q_1 has a high impact on C_1
- Higher SF increases C_1
- Inside SFs, C_1 drops due to path loss
- Equal-area SF rings have more stable performance in our model
  - It equalizes interference in all SF rings
  - Happens here because we do not consider a specific application
  - If network usage changes with SF, interference equalization will depend on the on-air packet time for each SF



Numerical results – Simulations

- Throughput as function of traffic
- Baseline theoretical values consider pure-ALOHA
- Packet on-air times
  - In N1 (all using SF7), 46.3 ms
  - In N2, the average packet duration is 399.5 ms
- B(P) for N1 matches with the theoretical results
- IC more than doubles the throughput, especially because of the capture effect
- IC increases the maximum throughput for the N2 case compared to B(P)
- IIC has lower performance than IC because of inter-SF interference



Discussions and Outlook

- Current LPWANs offer at least two clear benefits
  - Less signaling
    - Has a positive impact on latency, energy consumption, and device complexity and cost when network traffic is low or moderate
    - As we have shown, there is a drawback: in heavy-loaded networks, without efficient signaling, interference becomes a critical limiting factor for scalability
  - LPWAN does not implement handover mechanisms
    - Positive impact on the scalability and reliability of multi-gateway networks (to be considered in further works)
    - However, it introduces extra load to the backbone network and servers, implying additional costs

Discussions and Outlook

- Future IoT applications
  - Number of active devices is expected to increase drastically
  - Interference will become a significant limiting factor
  - Reduced signaling of LPWAN technologies like LoRaWAN and SigFox can become a bottleneck
  - Investment in backbone infrastructure to support this huge number of devices will increase
- Such limitations are considered in recent research
  - More efficient and lightweight access control
  - Adapting current cellular technologies like NB-IoT to the unlicensed spectrum
  - Simplify the signaling for particular data transfers in cellular technologies in licensed bands (e.g., the almost ALOHA-like EDT for NB-IoT)
- Post-5G LPWAN connectivity will likely
  - feature operations in both licensed and unlicensed bands
  - employ time- and frequency-division combination
  - use both ALOHA-like and grant-based channel access

Kiitos!

Thanks!

Obrigado!

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