Automating Reliable and Fault-tolerant Design of LoRa-based IoT Networks

Xiaofan Yu[1], Weihong Xu[1], Ludmila Cherkasova[2], Tajana Šimunić Rosing[1]

[1] University of California San Diego
[2] Arm Research

CNSM 2021

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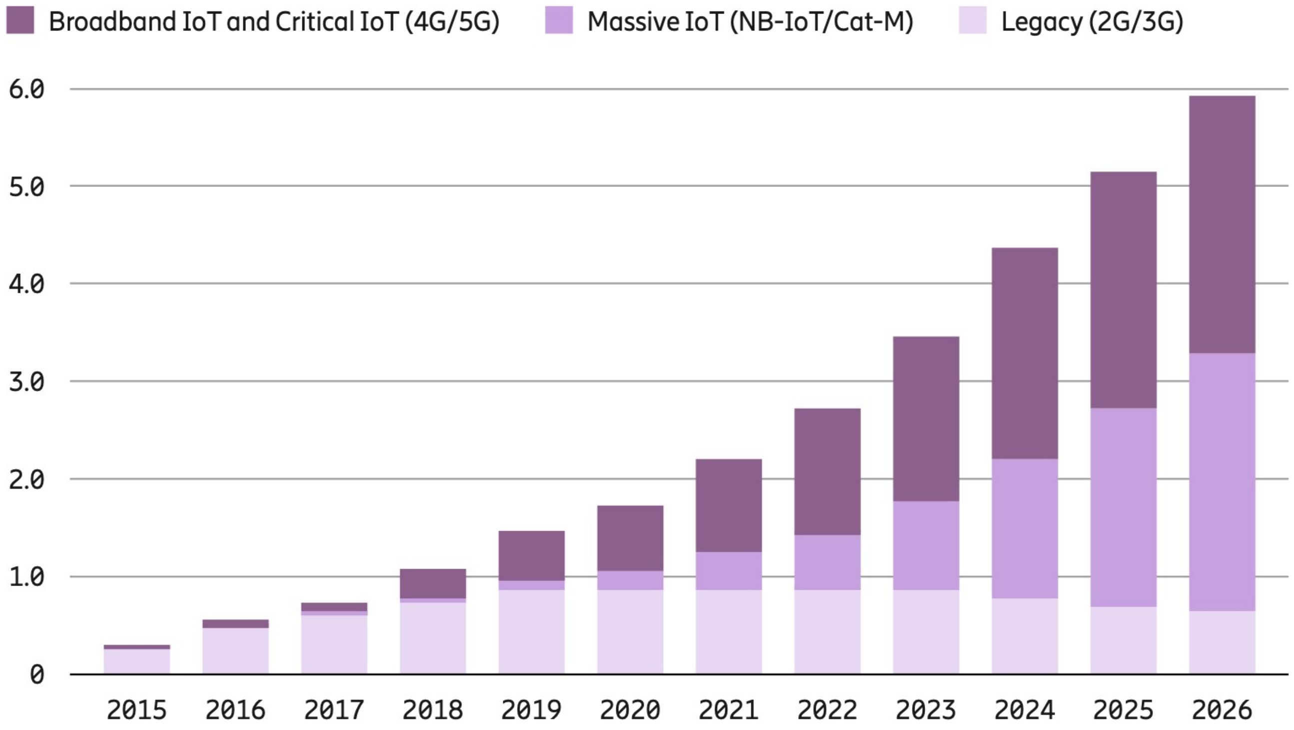
IoT Connections Outlook[1]



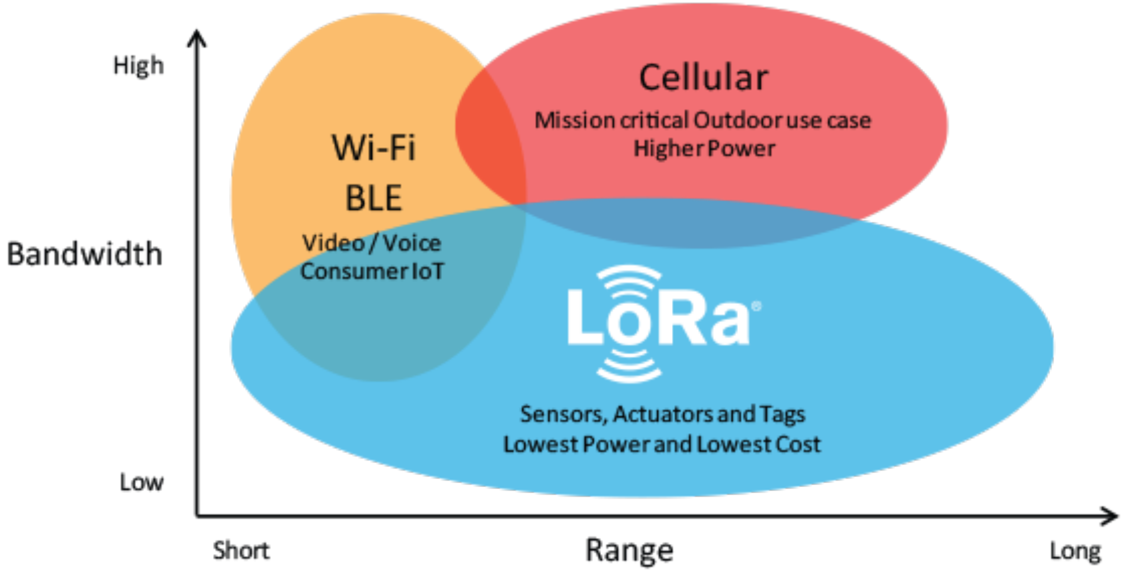
Cellular IoT connections by segment and technology (billion)

Figure 15: IoT connections (billion)

IoT	2020	2026	CAGR
Wide-area IoT	1.9	6.3	22%
Cellular IoT[2]	1.7	5.9	23%
Short-range IoT	10.7	20.6	12%
Total	**12.6**	**26.9**	**13%**

1. Ericsson Mobility Report, Nov 2020, https://www.ericsson.com/en/mobility-report/reports/november-2020

Why Long-Range (LoRa)?



- Large coverage
- Ultra-low power
- Multiple access
- Cost effective
- License free

LoRa is suitable for large-scale sensing applications

Smart Environment

Smart City

Smart Agriculture

Smart Electricity Metering

1. Figure source: https://www.semtech.com/lora/why-lora.

Background of LoRa Communication

- LoRa adopts Chirp Spreading Spectrum (CSS) modulation [Liando 2019]

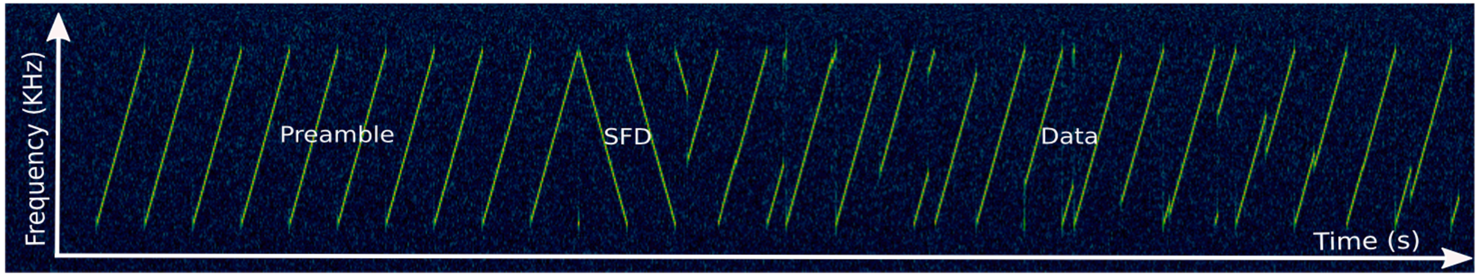
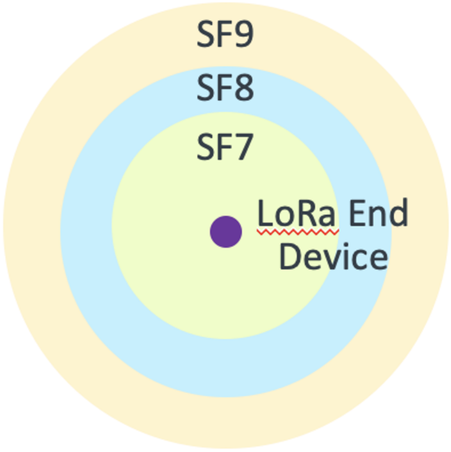
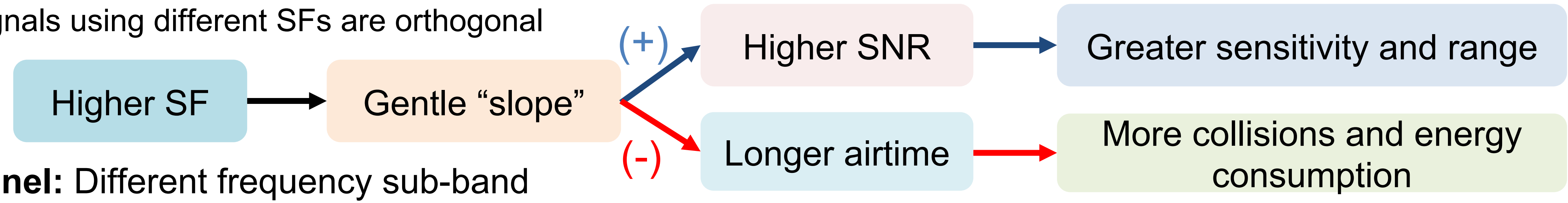


Fig. 1. A snapshot of LoRa transmission that shows up, down, and data chirps as seen on spectrogram.

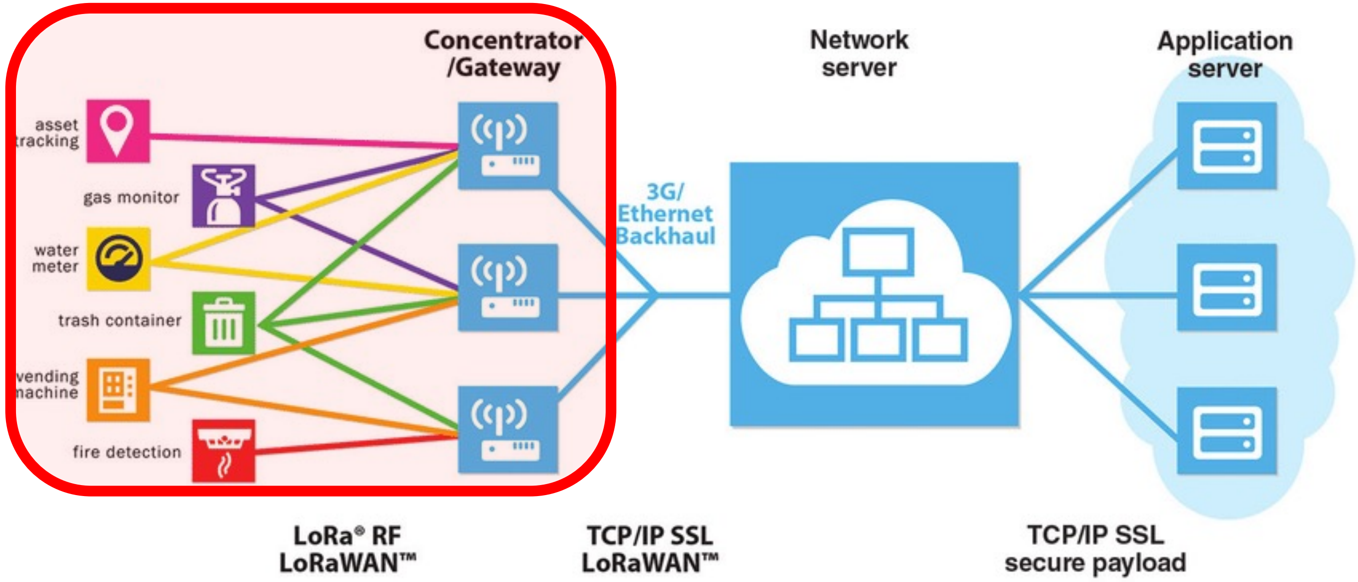


- Important transmission parameters
  - **Spreading Factors (SF)**: Number of bits crammed into a single chirp, “slope” of signal.
    - Signals using different SFs are orthogonal



  - **Channel:** Different frequency sub-band
    - Signals using different channels are orthogonal
  - **Transmission Power (Tx Pow):** Signals with higher Tx Power have higher chances of being received in spite of attenuation

Motivation: Uniqueness of LoRa Networks



- Single-hop network
- No end device-gateway association
- Aloha medium-access mechanism

- Traditional reliability-driven design in IoT networks
  - **M-connectivity:** each node has m **distinct networking paths** to cloud [Gupta 2016]
  - (-) Traditional reliability-driven strategies does not apply to LoRa networks!

Figure source: LoRa Alliance, "A technical overview of LoRa and LoRaWAN", Nov 2020, https://lora-alliance.org/wp-content/uploads/2020/11/what-is-lorawan.pdf

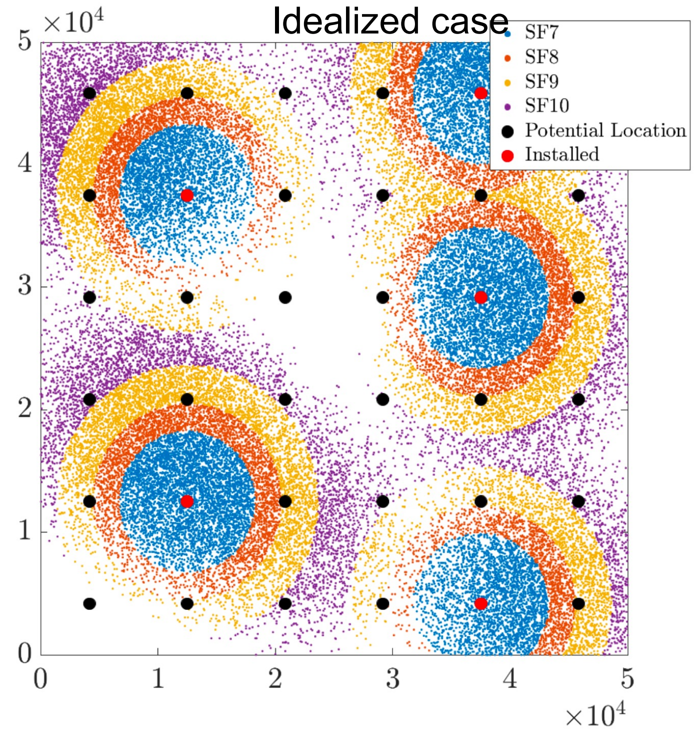
Previous Works

- LoRa networks optimization
  - Assign transmission parameters to maximize transmission reliability (i.e., packet delivery ratio) or energy efficiency [Reynders 2017][Gao 2019]
  - Gateway placement and transmission parameters configuration optimizing for energy efficiency [Ousat 2019] Most related!

(+) First to study joint gateway placement and device configuration given sensors' locations

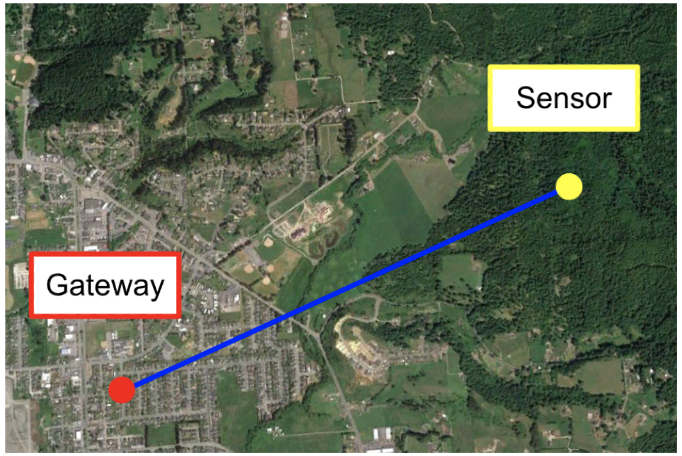
(-) Gateway number needs to be specified
(-) Theoretical path loss models with uniform degradation on various directions

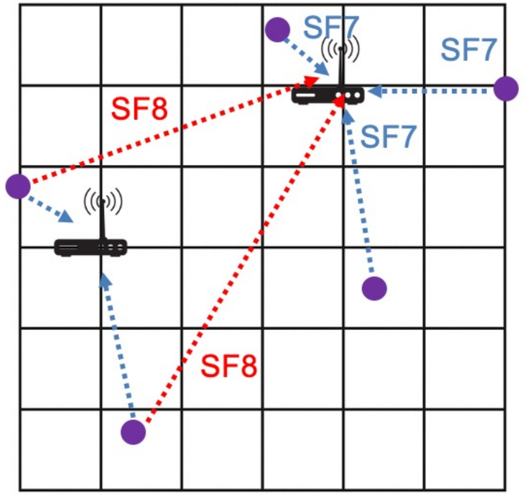
(-) Poor fault tolerance with single connectivity at each end device



Our Contributions: Reliability and Fault Tolerance

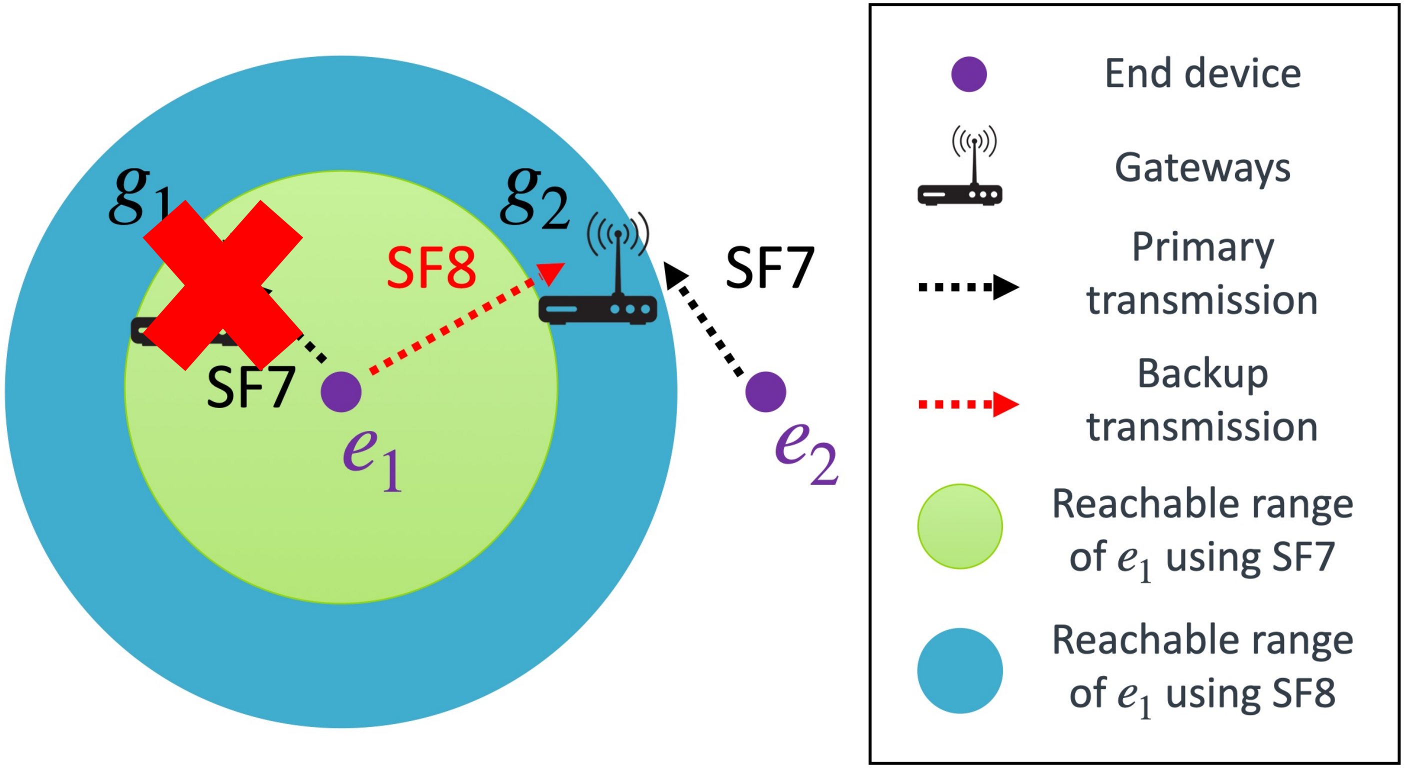
- We introduce m-gateway connectivity to guarantee fault tolerance (against gateway failures and interference) under LoRaWAN protocol
- We leverage land cover-based path loss estimation from remote sensing for practical reliability evaluation
- Given end devices' locations, we formulate an Integer Nonlinear Programming (INLP) for joint gateway placement and resource allocation
  - Optimizing for minimum gateway number
  - Under transmission reliability, fault tolerance and lifetime constraints
- We propose a greedy heuristic, RFT-LoRa, to acquire high-quality solutions for large-scale problems





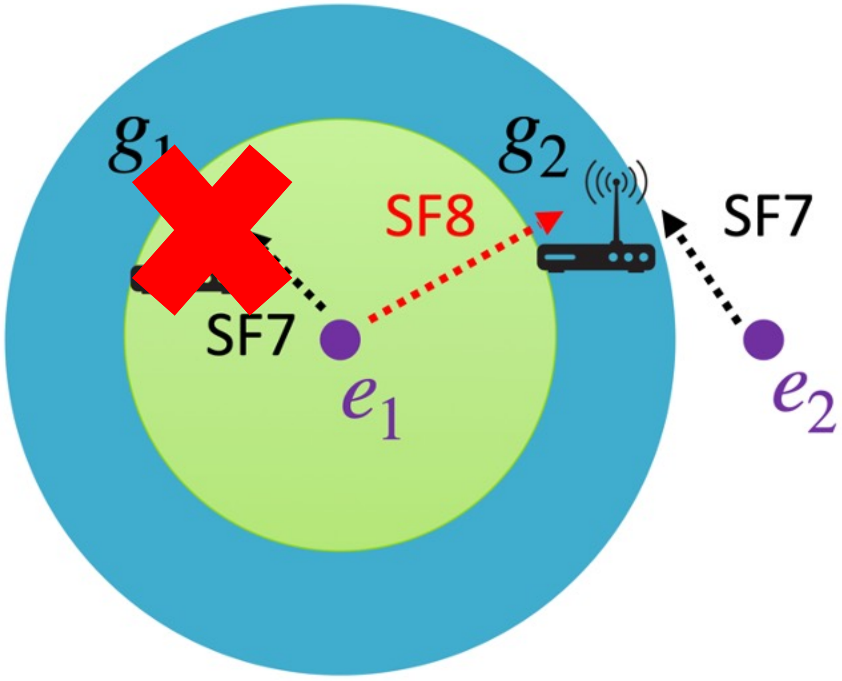
M-Gateway Connectivity for LoRa Networks

- M-connectivity does not apply to single-hop LoRa networks
- We introduce *m-gateway connectivity* to guarantee fault tolerance in LoRa networks
  - ***M-gateway connectivity***: a LoRa end device is able to reach m gateways



M-Gateway Connectivity for LoRa Networks (Cont.)

- Benefits of m-gateway connectivity
  - **Fault tolerance**: Provide backup connectivity in case of gateway failures or strong interferences
  - **Less unnecessary collisions**: Backup gateways are normally not reachable
  - **Savings on total number of installed gateways**: Backup gateways can serve as the primary gateways for other sensors
  - **Enabled automatically with the latest LoRaWAN protocol**



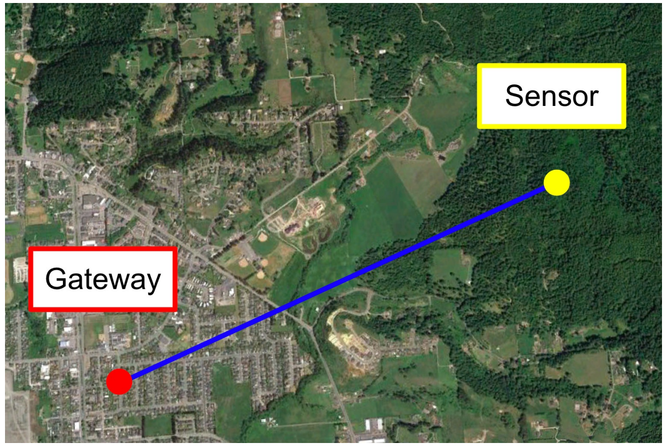
Land Cover-based Path-Loss Model with Remote Sensing

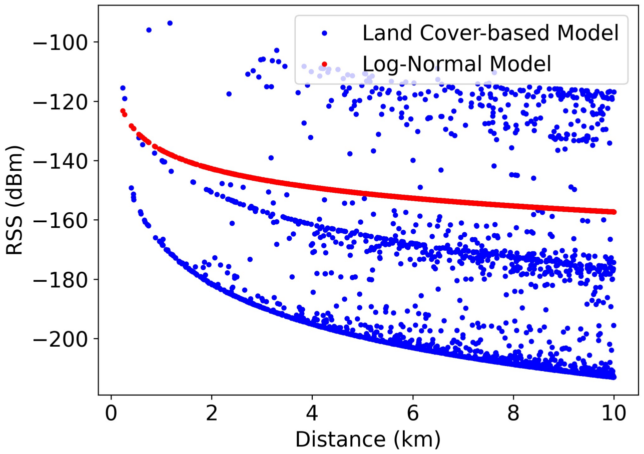
- Previous works optimizing LoRa networks leverage Friis or log-normal path-loss model [Reynders 2017][Gao 2019] [Ousat 2019]

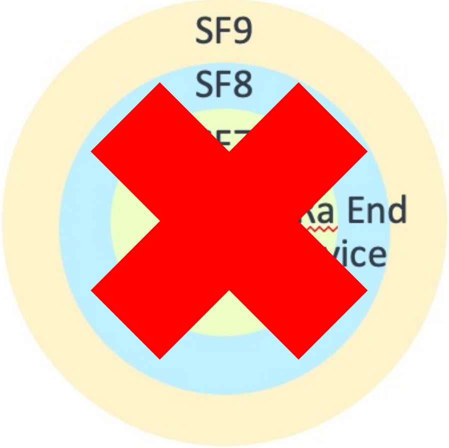
$$PL(d) = \overline{PL(d_0)} + 10n\log\left(\frac{d}{d_0}\right) + N_\sigma$$

d: tx distance, d_0: reference distance, n: path loss exponential, N_σ: zero-mean Gaussian noise

- Path loss over different land covers (e.g., buildings, forests) can be largely different
- We leverage the remote sensing-based model in [Lin 2020]
  - Fit n, σ for different land covers through real-world experiments
  - Propose path-loss estimation algorithm based on remote sensing







Problem Formulation: Reliability and Fault Tolerance

- Given
  - A set of end devices and path-loss matrix
- Variables
  - Gateway placement
  - Transmission parameters allocations, i.e., SF, channel, TX Power
- How to deploy <u>minimum</u> gateways while satisfying
  - Transmission reliability constraint
  - Lifetime constraint
  - M-gateway connectivity constraint

Integer Nonlinear Programming (INLP)

N, PL

$$g_j = \begin{cases} 1 & \text{if a gateway is placed at } j \\ 0 & \text{otherwise.} \end{cases} \quad \forall j \in G$$

$$sf_i \in SF, \quad \forall i \in N, \quad SF = \{0,1,2,3\},$$
$$ch_i \in CH, \quad \forall i \in N, \quad CH = \{0,1,2,3,4,5,6,7\},$$
$$tp_i \in TP, \quad \forall i \in N, \quad TP = \{0,1,2,3,4,5\}.$$

(P)
$$\min_{g,sf,ch,tp} \sum_{j \in G} g_j \tag{5a}$$
s.t.
$$PDR_i(g, sf, ch, tp) \geq PDR_{th}, \quad \forall i \in N \tag{5b}$$
$$L_i(sf_i, tp_i) \geq L_{th}, \quad \forall i \in N \tag{5c}$$
$$\sum_{j \in G} g_j c_{ij} \geq M, \quad \forall i \in N \tag{5d}$$
$$g_j \in \{0,1\}, \quad \forall j \in G \tag{5e}$$
$$sf_i \in SF, \ ch_i \in CH, \ tp_i \in TP, \quad \forall i \in N \tag{5f}$$

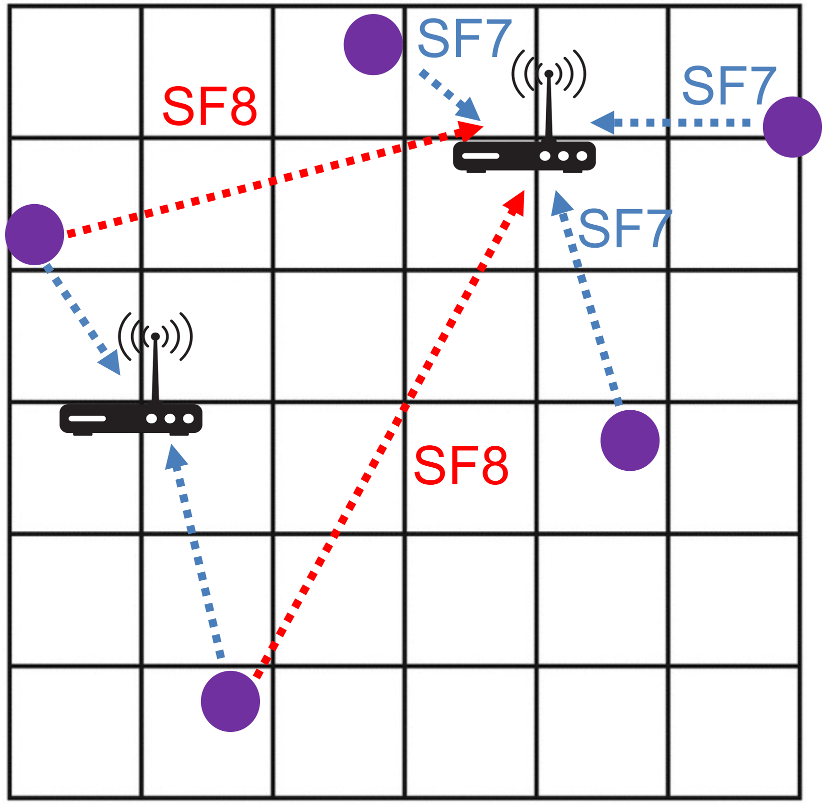
Reliable and Fault-Tolerant LoRa Networks (RFT-LoRa)

- In each iteration, RFT-LoRa attempts to place a gateway at every unoccupied location, and **greedily** assigns SF, channel, and Tx Power to all end devices based on the current deployment
- Pick the location with the most "benefit"
- Repeat until *m-gateway connectivity* is met

Sensor nodes | Candidate gateway locations

LoRa Transmission | Placed LoRa Gateways

2-gateway connectivity



Reliable and Fault-Tolerant LoRa Networks (Cont.)

- Benefit of each candidate gateway location:

$$B = \sum_{i \in N} \omega_1 \underline{PDR_i} + \omega_2 \underline{L_i} + \min\left(\underline{Conn_i - M}, 0\right).$$

Benefit on transmission reliability

Benefit on Lifetime

Penalty for unsatisfied m-gateway connectivity

- Time complexity of RFT-LoRa is $O(M|N|^3|G|^2)$
  M: m-gateway conn., N: given end devices locations,
  G: candidate gateway locations

Simulation Setup

- We implement our algorithms in Python 3.7[1] and evaluate in ns-3, with open-source LoRaWAN module [Magrin 2019]
- Baselines
  - **EE-LoRa** [Ousat 2019]: energy efficiency-driven gateway placement and resource allocation
  - **$\text{OPT}_{\text{relax}}$**: relaxation with continuous variables, solved optimally with SNOPT[2]
- Three evaluating scenarios:

Scenario	End devices	Candidate gateways	Area	Path loss model
Small region	100 randomly initialized devices	25	30 km × 30 km	Log-normal
Large region	264 devices from PurpleAir[3]	216	60 km × 100 km in Southern California	Land cover-based
Scalability study	Up to 5K randomly initialized devices	64	50 km × 50 km	Log-normal

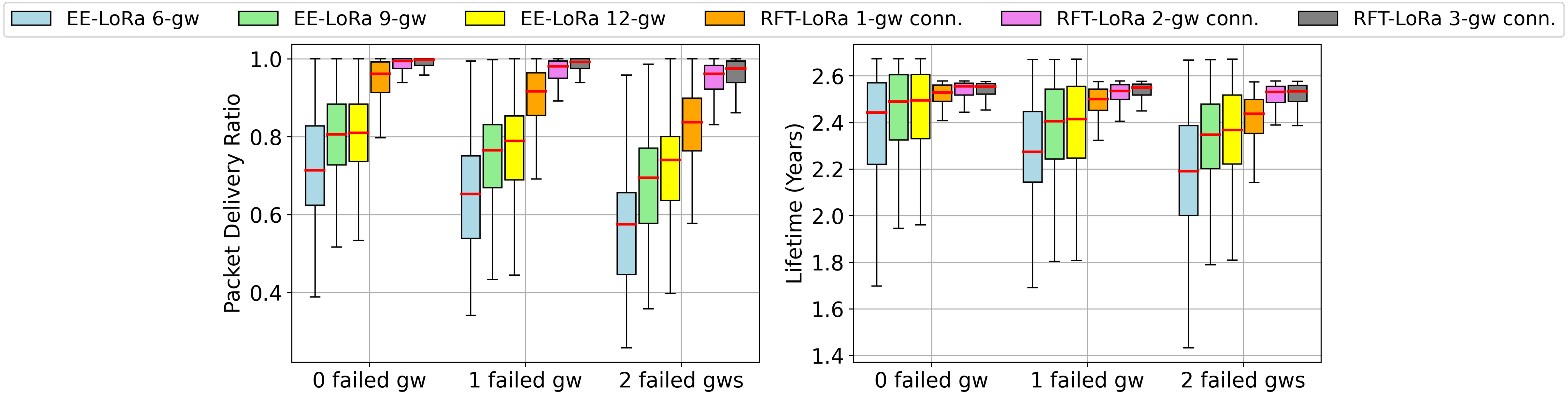
1. Source code is available at https://github.com/Orienfish/robust-lora
2. SNOPT 7.7, https://ccom.ucsd.edu/~optimizers/static/pdfs/sndoc7.pdf
3. PurpleAir: real-time air quality monitoring, https://www2.purpleair.com/

Simulation Results on the Small Region

Method	Gateway Number	Min PDR	Min Lifetime (Year)	Execution Time (Sec)
Relaxed Opt.	**2.92**	**0.76**	**1.9**	2953
EE-LoRa	3	0.55	1.6	**0.3**
RFT-LoRa	3	0.73	1.8	1.8

- Take average results after 5 trials of random end-device initializations
- RFT-LoRa approximates the relaxed gateway number with similar packet delivery ratio (PDR) and lifetime, and executes **1640x** faster on this toy example
- EE-LoRa takes less than a second to finish but has the worst PDR because EE-LoRa only proportionally distributes the available resources without performance guarantees

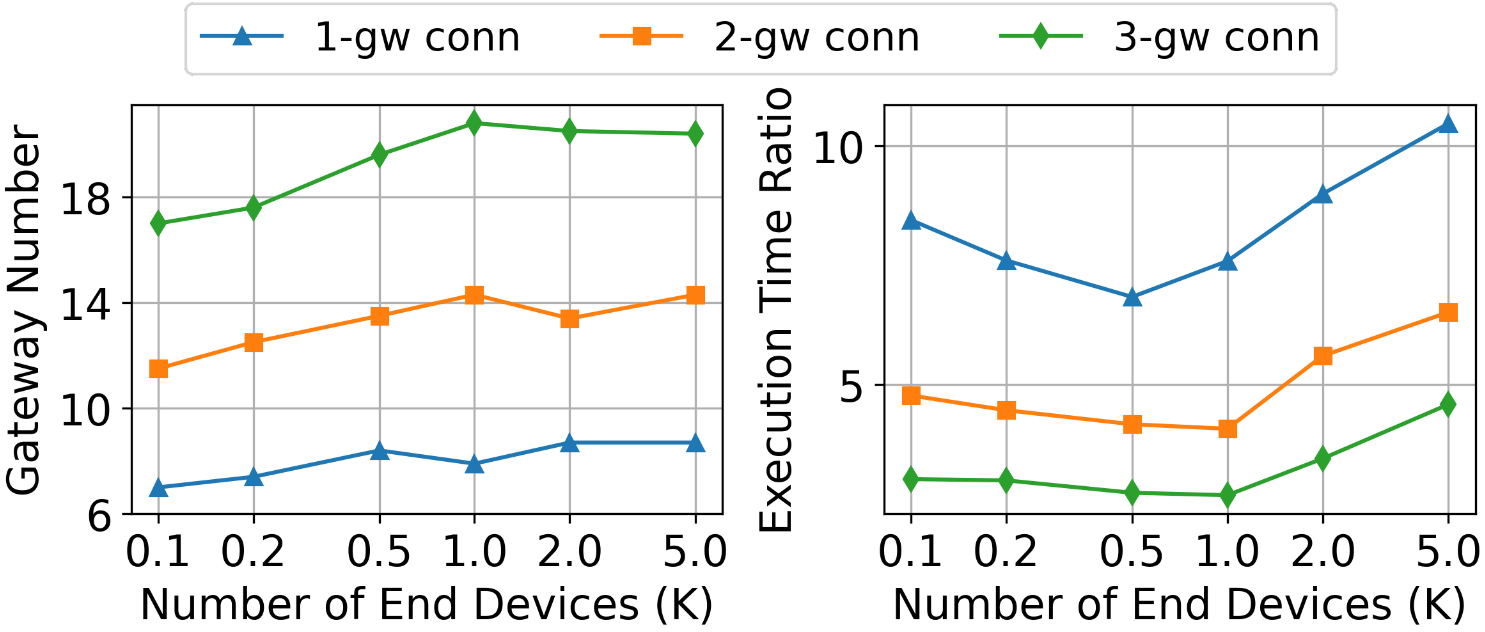
Simulation Results on the Large Region in ns-3



- RFT-LoRa places 6, 9 and 12 gateways under *1-, 2- and 3-gateway connectivity*
- RFT-LoRa enhances 22%-106% on packet delivery ratio, 4%-10% on lifetime compared with EE-LoRa (w/ same gateway number) during gateway failures and interferences

Scalability of RFT-LoRa on Large Problems

Average placed gateway number of RFT-LoRa



Execution time ratio between RFT-LoRa and EE-LoRa

- Take average results after 10 trials of random end-device initializations
- RFT-LoRa requires only 1.2x - 1.5x more gateways instead of 2x when switching from *1-* to *3-gateway connectivity*
- RFT-LoRa takes at most 38 minutes for 5K end devices while EE-LoRa consumes only 10 minutes

Conclusion

- We propose new approach to design reliable and fault-tolerant LoRa networks
  - Reliability: we use land cover-based path-loss model based on remote sensing
  - Fault Tolerance: we introduce m-gateway connectivity for LoRa networks
- We formulate INLP to minimize the number of gateways through strategic gateway placement and resource allocation, while satisfying reliability, fault tolerance and lifetime constraints
- A greedy heuristic RFT-LoRa is proposed to search high-quality solutions in large-scale problems
- Simulation results show that RFT-LoRa approximates the gateway number of the relaxed problem with similar reliability, executing 1640x faster.
  RFT-LoRa presents better fault tolerance than existing works during gateway failures and interferences.

References

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Traditional vs. New Long-Range Communication Technologies[1]

	Traditional Wireless Technology	New Long-Range Technology	
	Wi-Fi, BLE	LoRaWAN, NB-IoT, LTE-M	
< 100 m	← Short Distance	Long Distance →	5-10 km
~10 Mbps	← High throughput	Low throughput →	~100 kbps
~100 mW in avg.	← High Power Consumption	Low Power Consumption →	~1 mW in avg.

1. Data source: [Lee 2007], [Ghena 2019]