Network Size Estimation for LoRa-Based Direct-to-Satellite IOT

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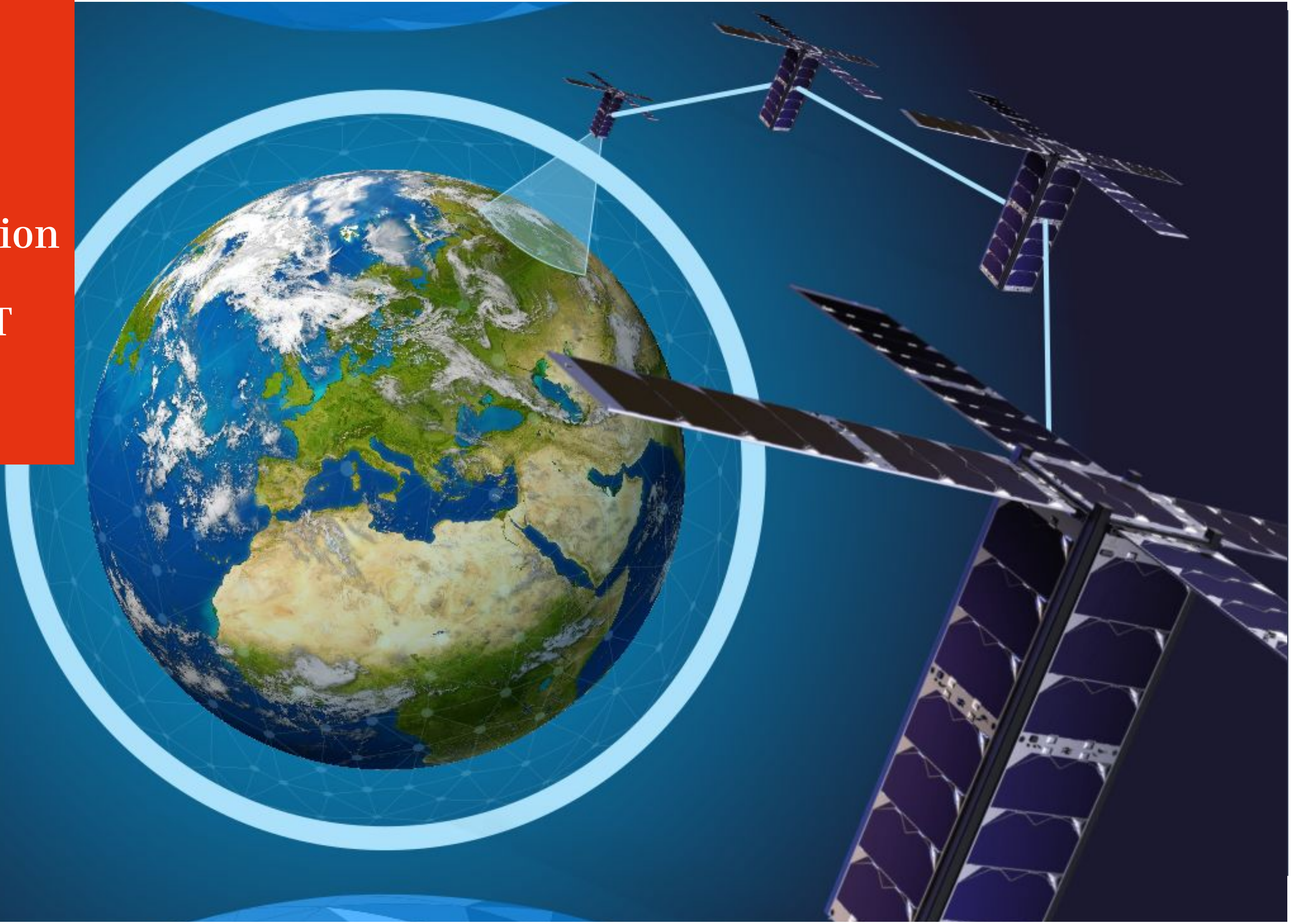
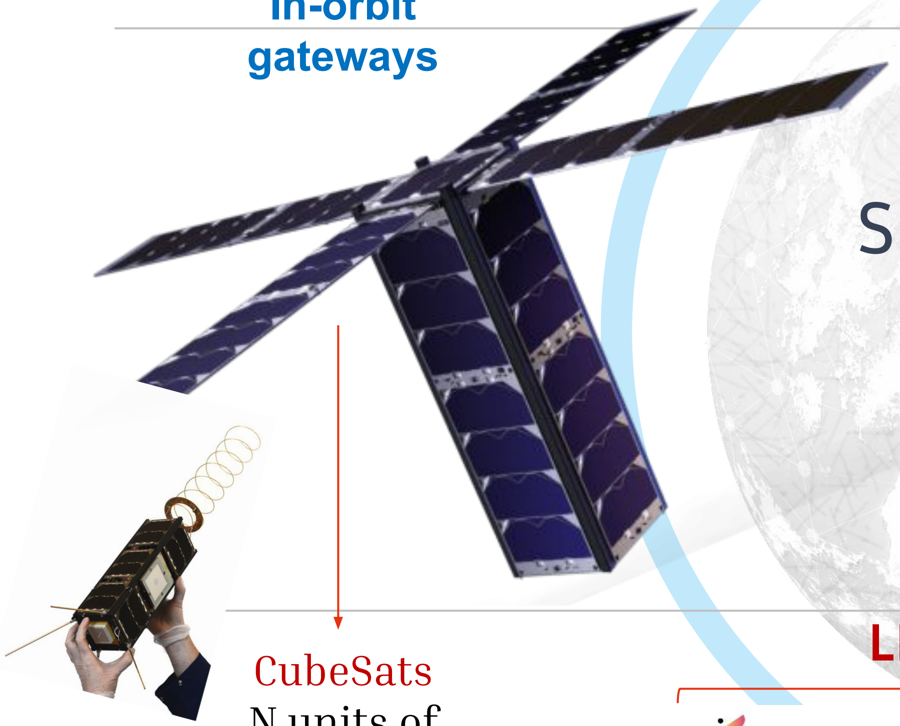


Satellite IoT

Our current focus

In-orbit gateways



Argos, AIS, ADS-B

Space-Terrestrial Integrated IoT

STEREO

On-ground devices

CubeSats
N units of 10x10x10 cm

LPWAN (LoRa, NB-IoT)

kinéis, ECHOSTAR, Lacuna space, Myriota, KEPLER, FLEET, SATELIOT, Wyld

LoRa [1]

Semtech LR1120
LR-FHSS (UL)
(Sub-GHz, 2.4 GHz)

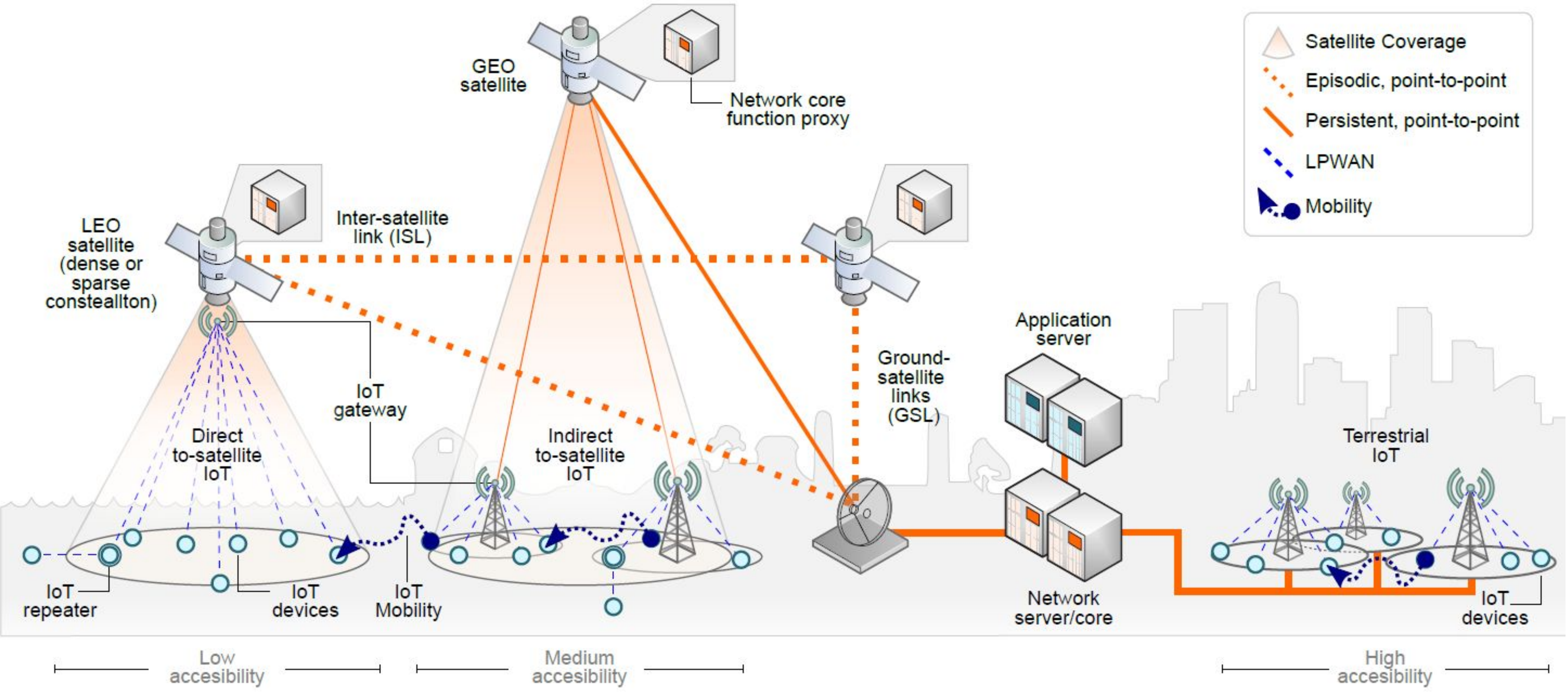
NB-IoT [2]

3GPP 5G NTN:
Rel-17 NB-IoT
(licensed bands)

[1] N. Sornin (Semtech), Extending LoRaWAN Reach (https://youtu.be/pHq7_rgDyFA); Thomas Telkamp (Lacuna) Open satellite LoRaWAN at scale (https://youtu.be/vWkuqVJL1Sg)
[2] L. Ouvry, et al, "An Ultra-Low-Power 4.7mA-Rx 22.4mA-Tx Transceiver Circuit in 65-nm CMOS for M2M Satellite Coms," in IEEE Transactions on Circuits and Systems, May 2018

Architecture

Space-Terrestrial Integrated IoT



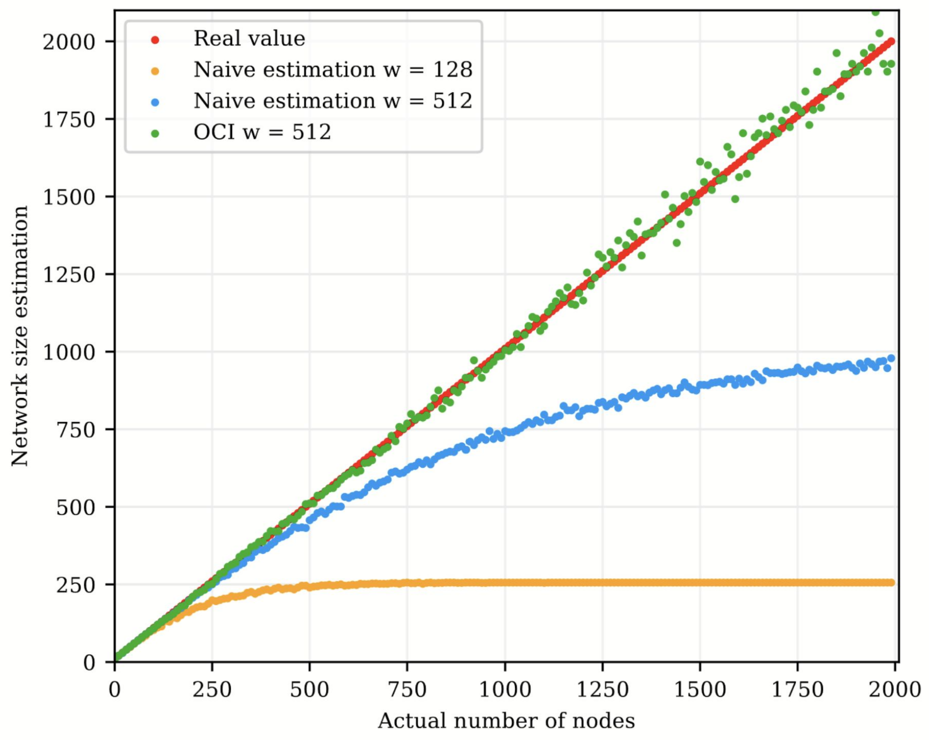
Network size estimation in DtS-IoT

In [3] the authors propose OCI, a network size estimator based on a naive estimation of the number of nodes and a polynomial fit.

The scenario corresponds to a DtS-IoT with Slotted ALOHA protocol.

Model assumptions:

- Stable cluster for each frame
- Time synchronization
- Earth-repeat orbits
- Simple collision model with no capture effect
- All nodes in the cluster will transmit on each frame



[3] Network size estimation with naive approach and OCI

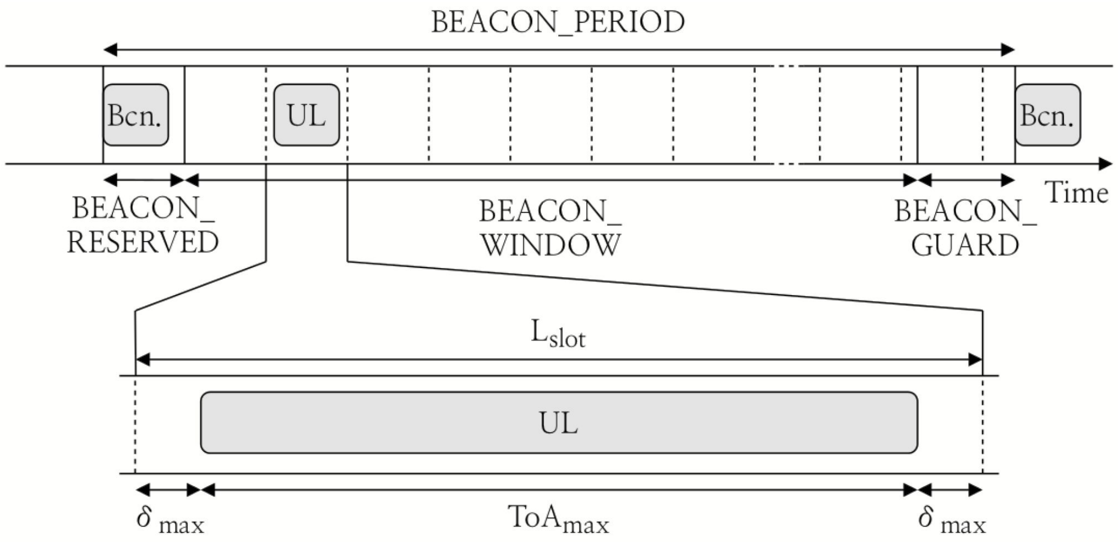
[3] Ilabaca, P., Montejo-Sánchez, S., Fraire, J. A., Souza, R. D., & Céspedes, S. (2022). Network Size Estimation for Direct-to-Satellite IoT. *IEEE Internet of Things Journal*.

LoRa-based Slotted ALOHA scheme

Given the theoretical throughput limit for ALOHA, a slotted approach would be preferred to scale the network.

In [4] the authors propose LoRaSync, a synchronization scheme for LoRa networks

Based on LoRaWAN Class B, it also accounts for clock drift errors to achieve synchronization



[4] LoRaSync beacon period and slot structure

[4] Chasserat, L., Accettura, N., & Berthou, P. (2022). LoRaSync: energy efficient synchronization for scalable LoRaWAN.

L-OCI estimator

OCI network size estimator extended to LoRa-based networks with time-slotted structure

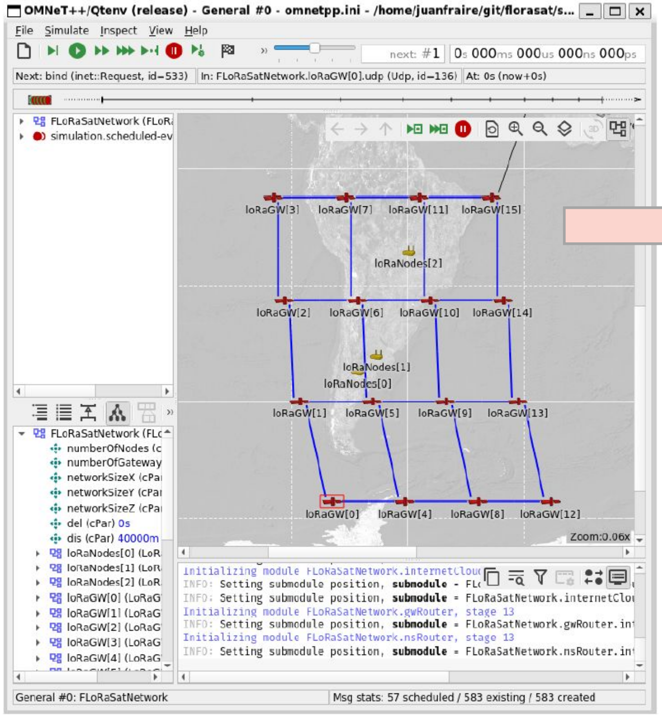
It maintains the same phases as OCI:

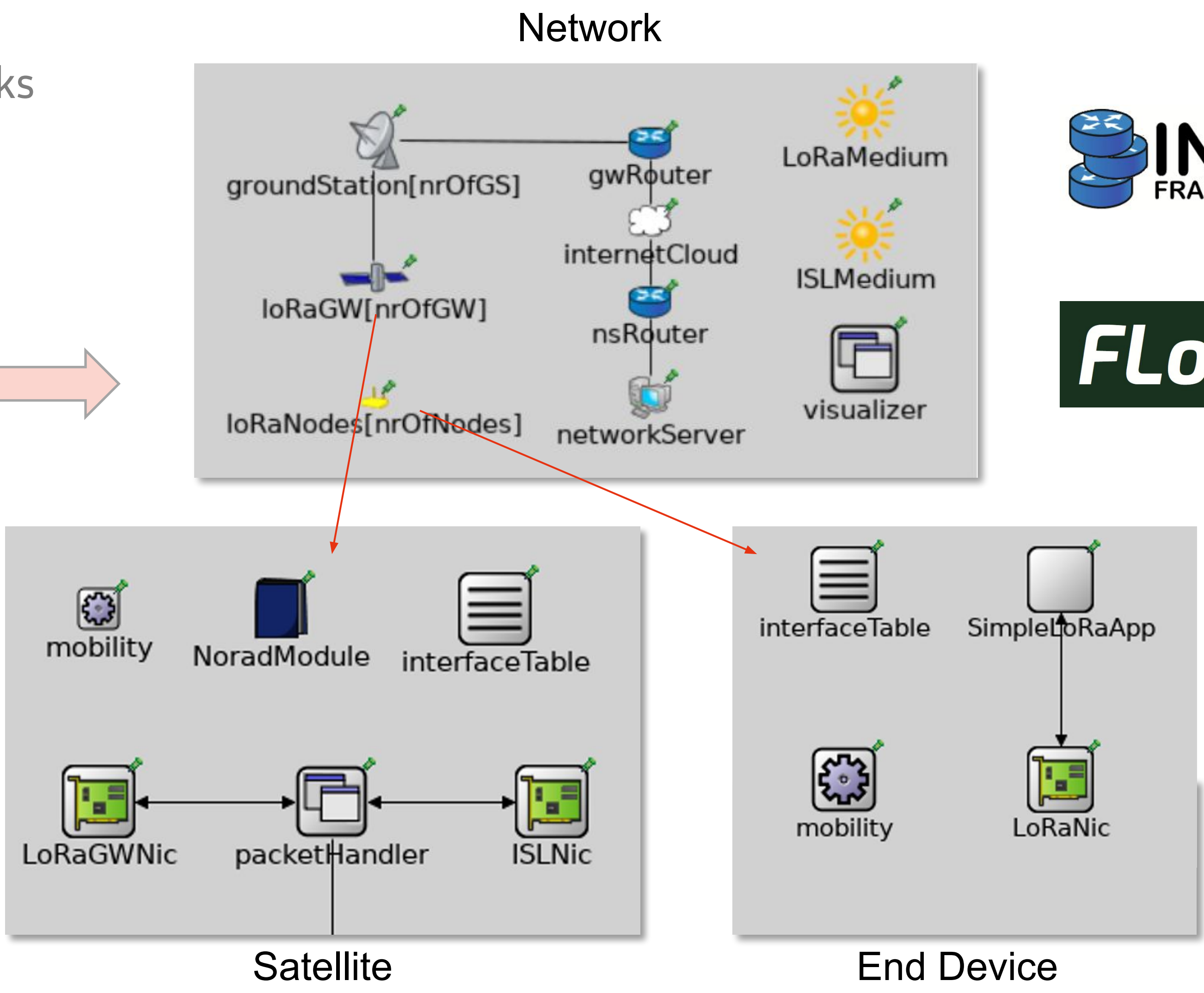
1. Data Collection phase
2. Naive Estimation phase
3. Polynomial Fitting phase
4. Operation phase

Phases 1 to 3 are carried on “offline” (on ground), while phase 4 is executed on board, provided the polynomial obtained from phase 3

FLoRaSat

A simulation tool for DtS-IoT networks





INET FRAMEWORK

FLoRa

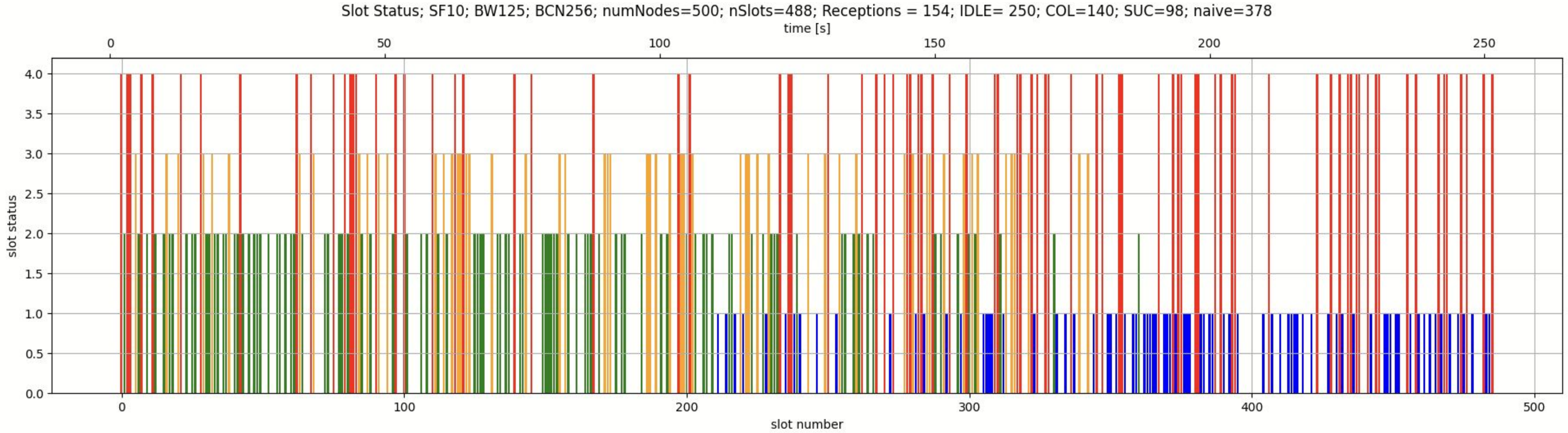
OMNeT++ 6

L-OCI estimator in FLoRASat

How is a slot defined as IDLE, COLLISION or SUCCESSFUL in FLoRaSat?

successful == 0	successful == 1

if attempted == 0 then **IDLE** (case 0);
if detectable == 0 then **IDLE** (case 1);
if detectable => 1 then **COLLISION** (case 4);
	if detectable == 1 then **SUCCESSFUL** (case 2);
	if detectable => 2 then **COLLISION** (case 3);



Simulation Scenario

- The satellite has a constant altitude of 600 [km] and a constant speed of 7.56 [km/s] during the beacon period

- Nodes are deployed randomly and uniformly over a circular region of radius Ra centered on the satellite's projection onto the Earth at the beginning of the beacon period

- Ra is selected such as it guarantees all nodes are within the communication range and hence they will all decode the beacon

- All nodes and the gateway use the same modulation parameters for LoRa

Global constants

- Node antenna gain = 5 [dBi]
- Satellite antenna gain = 0 [dBi]
- Node TP = 14 [dBm]
- CF = 863 [MHz]
- CR = 4
- PL = 20 [bytes]
- Beacon reserved = 2.12 [s]
- Beacon guard = 3 [s]
- Max clock drift = 0.01 [s]

Variables:

- sensitivity(SF, BW)
- range(sensitivity)
- airtime(SF, BW)

SF / BW	125 kHz	250 kHz	500 kHz
7	sensitivity = -124 dBm max range = 390 km airtime = 78 ms	sensitivity = -122 dBm max range = 310 km airtime = 39 ms	sensitivity = -116 dBm max range = 155 km airtime = 19 ms
8	sensitivity = -127 dBm max range = 552 km airtime = 140 ms	sensitivity = -125 dBm max range = 438 km airtime = 70 ms	sensitivity = -119 dBm max range = 220 km airtime = 35 ms
9	sensitivity = -130 dBm max range = 779 km airtime = 247 ms	sensitivity = -128 dBm max range = 619 km airtime = 123 ms	sensitivity = -122 dBm max range = 310 km airtime = 62 ms
10	sensitivity = -133 dBm max range = 1100 km airtime = 494 ms	sensitivity = -130 dBm max range = 779 km airtime = 247 ms	sensitivity = -125 dBm max range = 438 km airtime = 123 ms
11	sensitivity = -135 dBm max range = 1386 km airtime = 856 ms	sensitivity = -132 dBm max range = 981 km airtime = 428 ms	sensitivity = -128 dBm max range = 619 km airtime = 214 ms
12	sensitivity = -137 dBm max range = 1744 km airtime = 1712 ms	sensitivity = -135 dBm max range = 1386 km airtime = 856 ms	sensitivity = -129 dBm max range = 694 km airtime = 428 ms

Comparison of SF/BW configurations

Sensitivity to LoRa parameters

The control variables of our study are the spreading factor (SF), the bandwidth (BW) of LoRa in kHz, and the beacon period (BCN) in seconds.

We study the reusability of an L-OCI estimator for test scenarios with a different set of parameters

For all training scenarios the nodes' positions and the selected slot for transmission remains the same

The previous changes for the test scenario

L-OCI training phases:

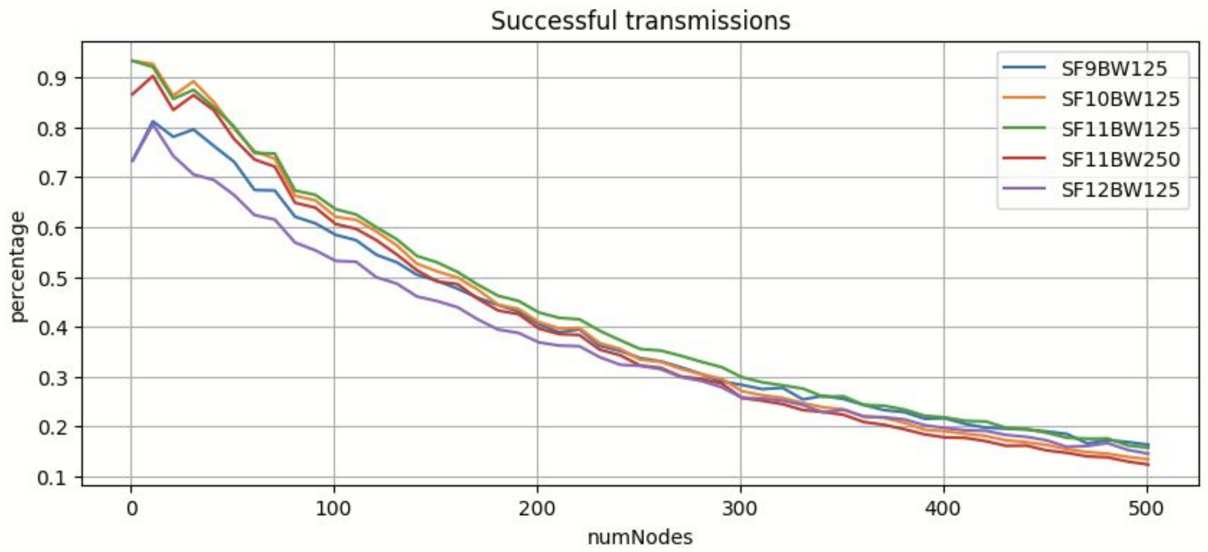
- node number: 1 to 501, step 10
- beacon slots = 167

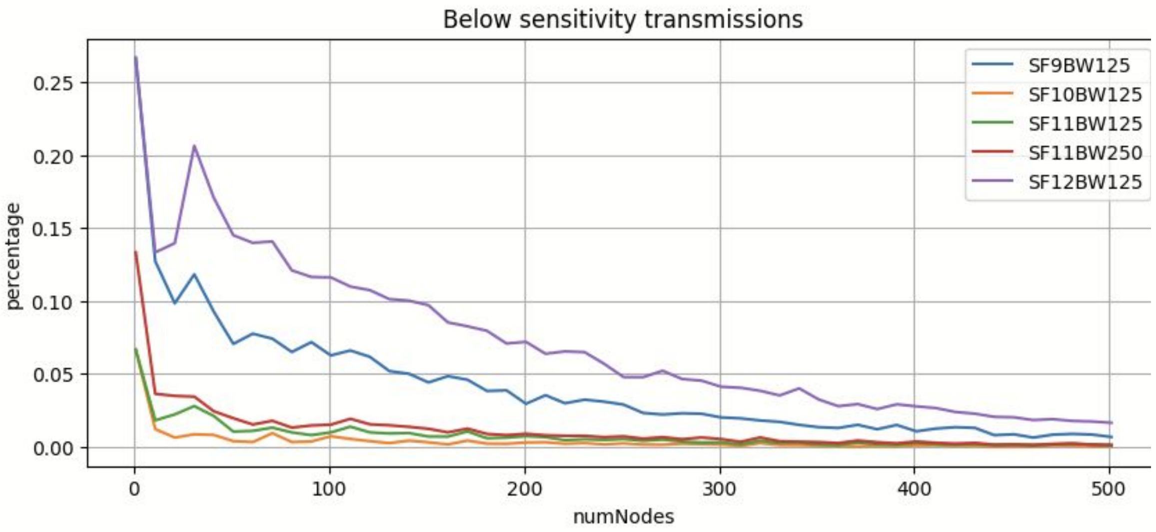
Training scenarios:

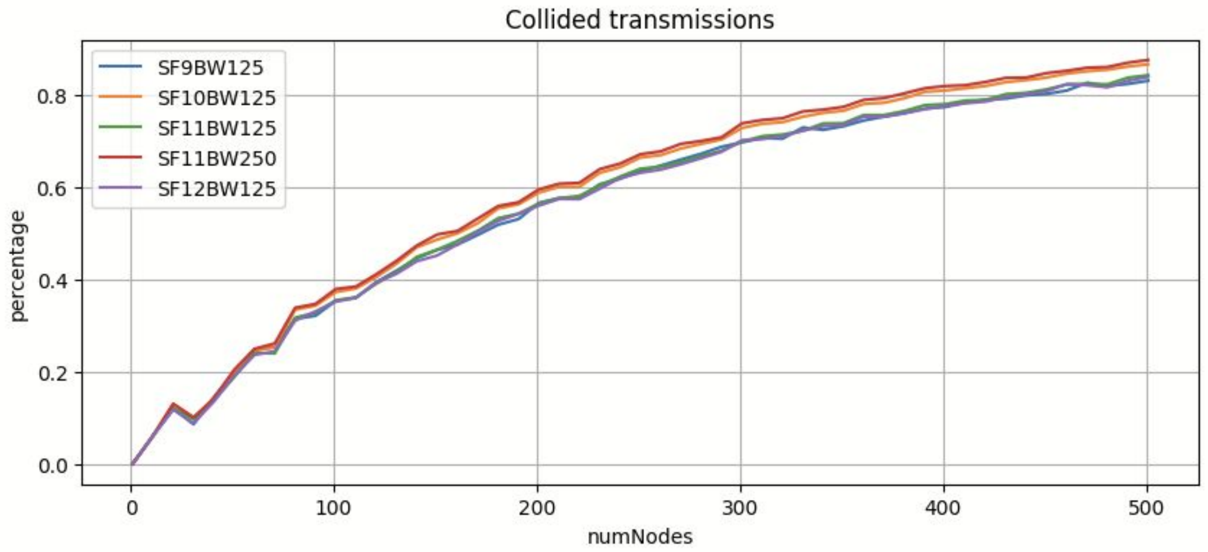
1. SF9 BW125 BCN50
2. SF10 BW125 BCN91
3. SF11 BW125 BCN152
4. SF11 BW250 BCN80
5. SF12 BW125 BCN295

Sensitivity to LoRa parameters

Transmissions outcome normalized by the number of nodes







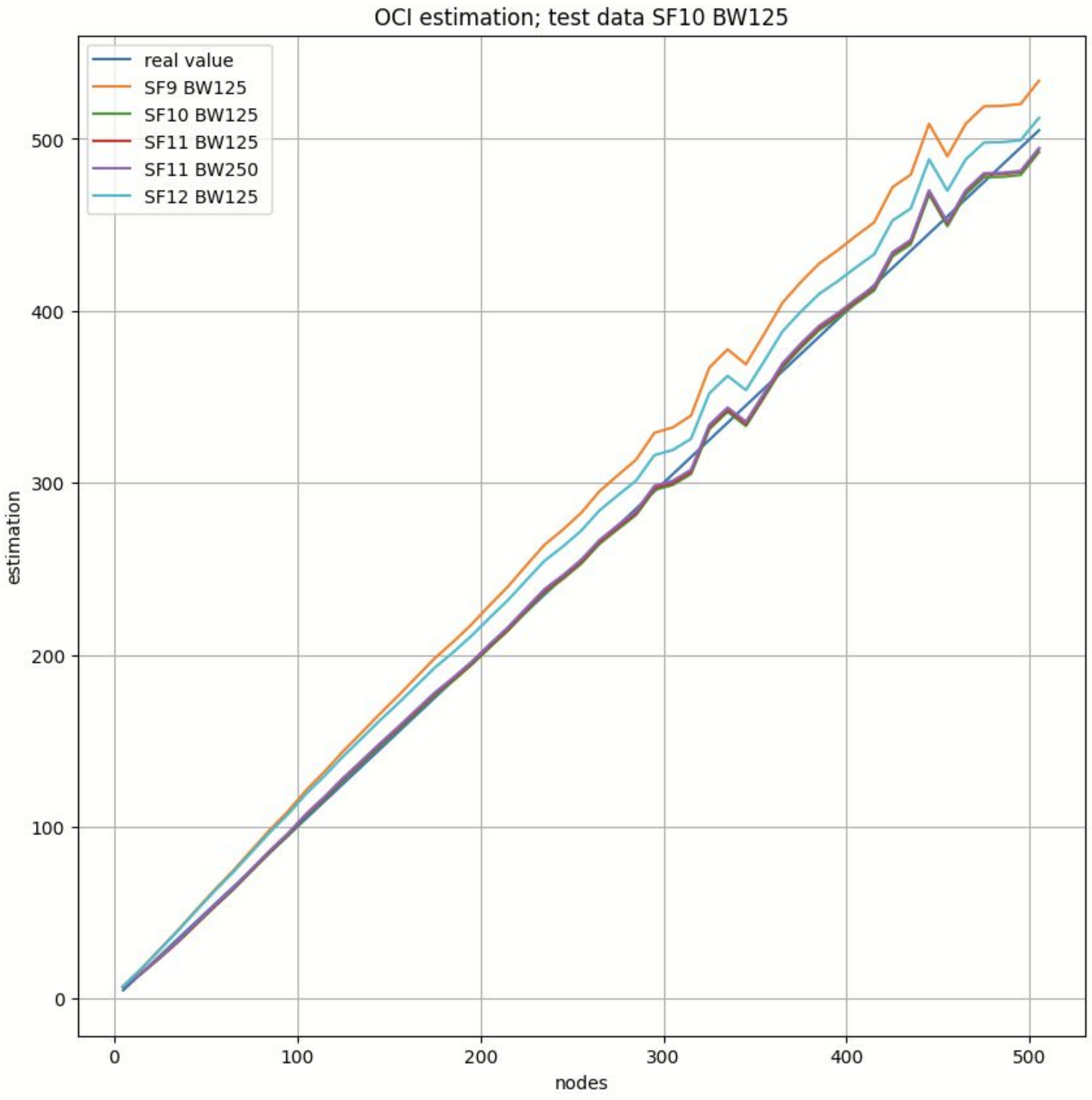
Sensitivity to LoRa parameters

L-OCI test phase:

- node number: 5 to 505, step 10
- SF 10
- BW 125 kHz
- Beacon period = 91 s
- range = 1100 km
- airtime = 494 ms
- beacon slots = 167

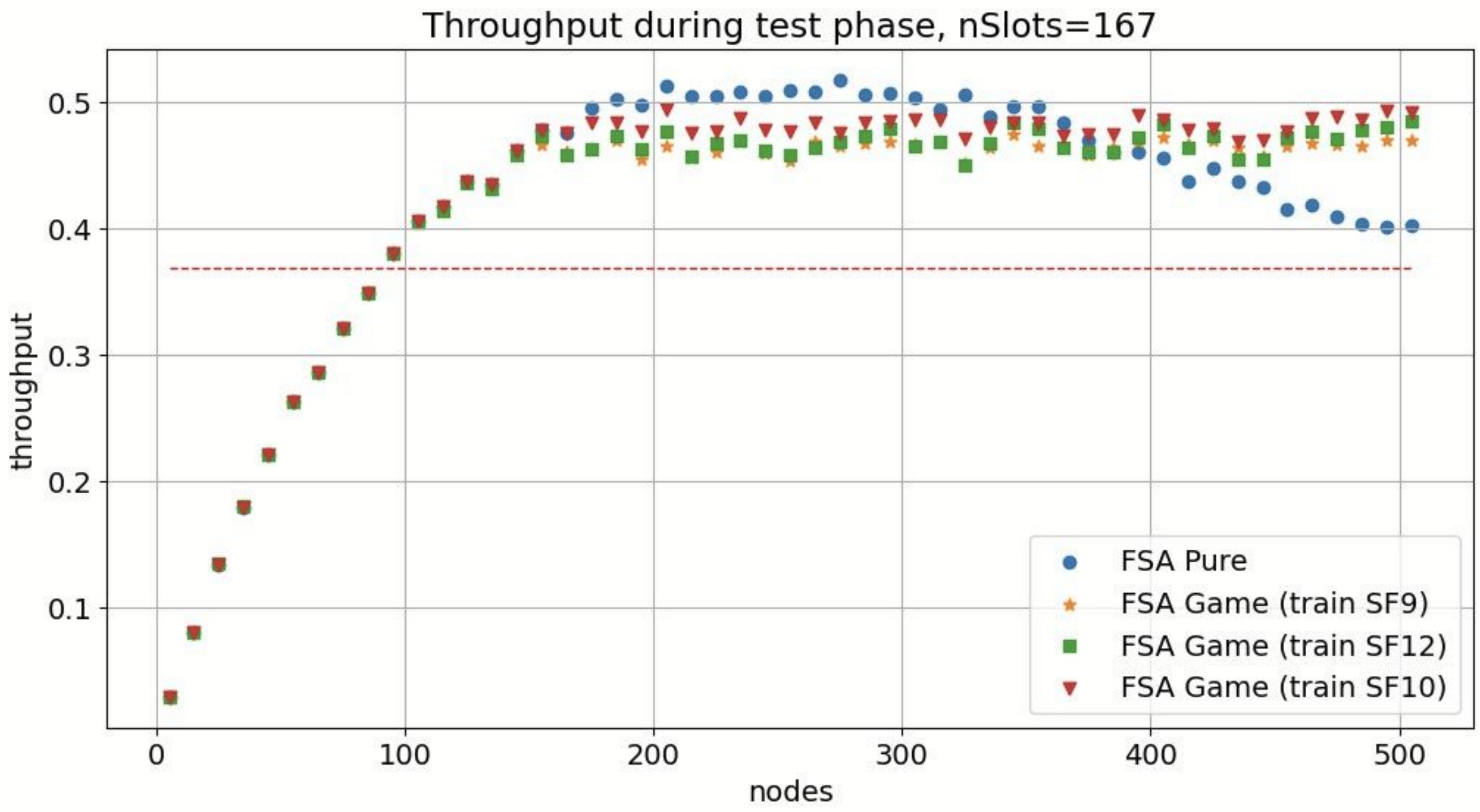
RSME test phase error:

- SF9 BW125 = 29.693
- SF10 BW125 = 5.556
- SF11 BW125 = 5.586
- SF11 BW250 = 5.747
- SF12 BW125 = 17.909



Impact on Throughput

the previous L-OCI network size estimations obtained are fed to the Slotted ALOHA Game protocol [5]



[5] B. Zhao, G. Ren, and H. Zhang, "Slotted aloha game for medium access control in satellite networks," in 2019 IEEE/CIC Int. Conference on Communications in China (ICCC). IEEE, 2019, pp. 518–522.

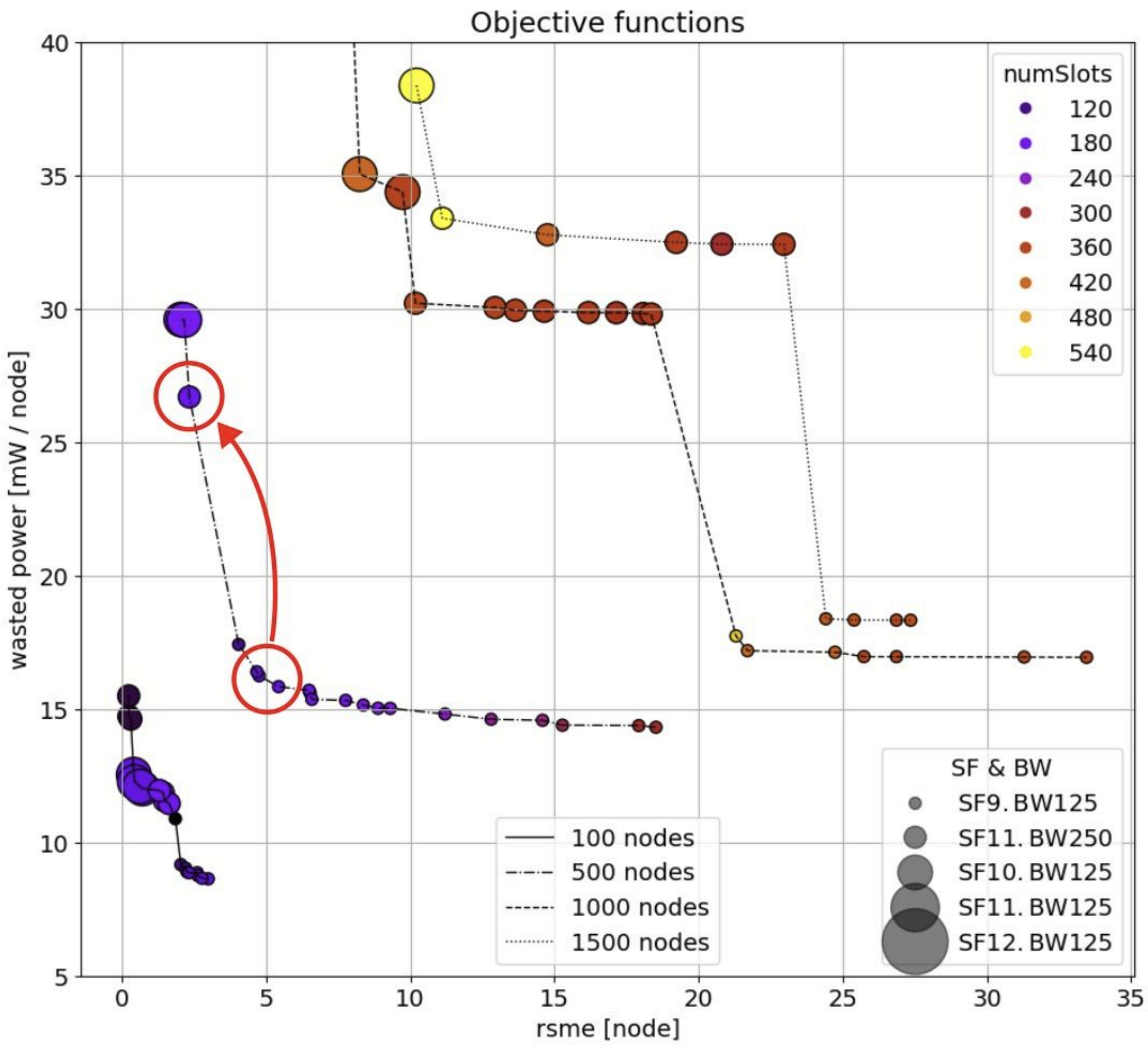
Error and Energy Trade-off

Multi-objective Optimization Problem

- F1 - wasted energy [nW / node]: energy expensed in low sensitivity and collided transmissions during OCI estimation phase

- F2 - RSME [node]: estimation error during OCI test phase

- Algorithm: MOEA/D (multiobjective evolutionary algorithm based on decomposition) [6]



[6] Q. Zhang and H. Li, “Moea/d: A multiobjective evolutionary algorithm based on decomposition,” IEEE Transactions on evolutionary computation, vol. 11, no. 6, pp. 712–731, 2007.

Discussion

- The OCI estimator maintains its declared performance when implemented on top of LoRa (L-OCI)
- The L-OCI estimator depends heavily on the network parameters (LoRa, satellite orbit and node deployment region parameters)
- Because of the previous, it is not guaranteed a single L-OCI estimator can achieve low error estimation on a test phase operating under a different set of parameters
- L-OCI cannot estimate a network size beyond the training set
- L-OCI breaks down when including repeated naive estimations in its training set
- L-OCI has a sharp compromise between the wasted power during estimation phase and its error during test phase
- We proved it can estimate up to 5000 nodes, though this number could be higher

Merci!

FLoRaSat: https://gitlab.inria.fr/jfraire/florasat/