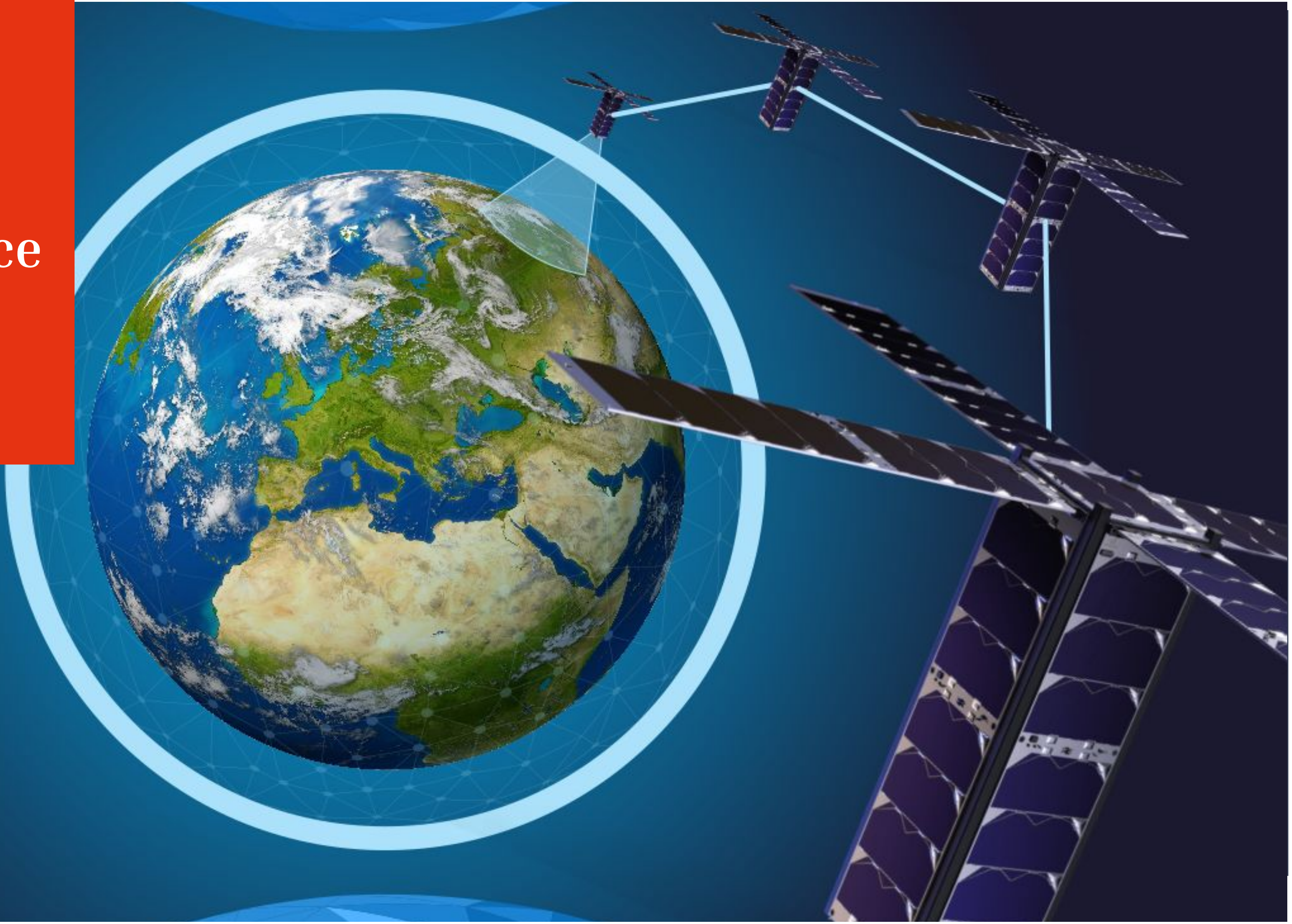
LoRa CSS and LR-FHSS Resource Allocation in Dts IoT Scenarios



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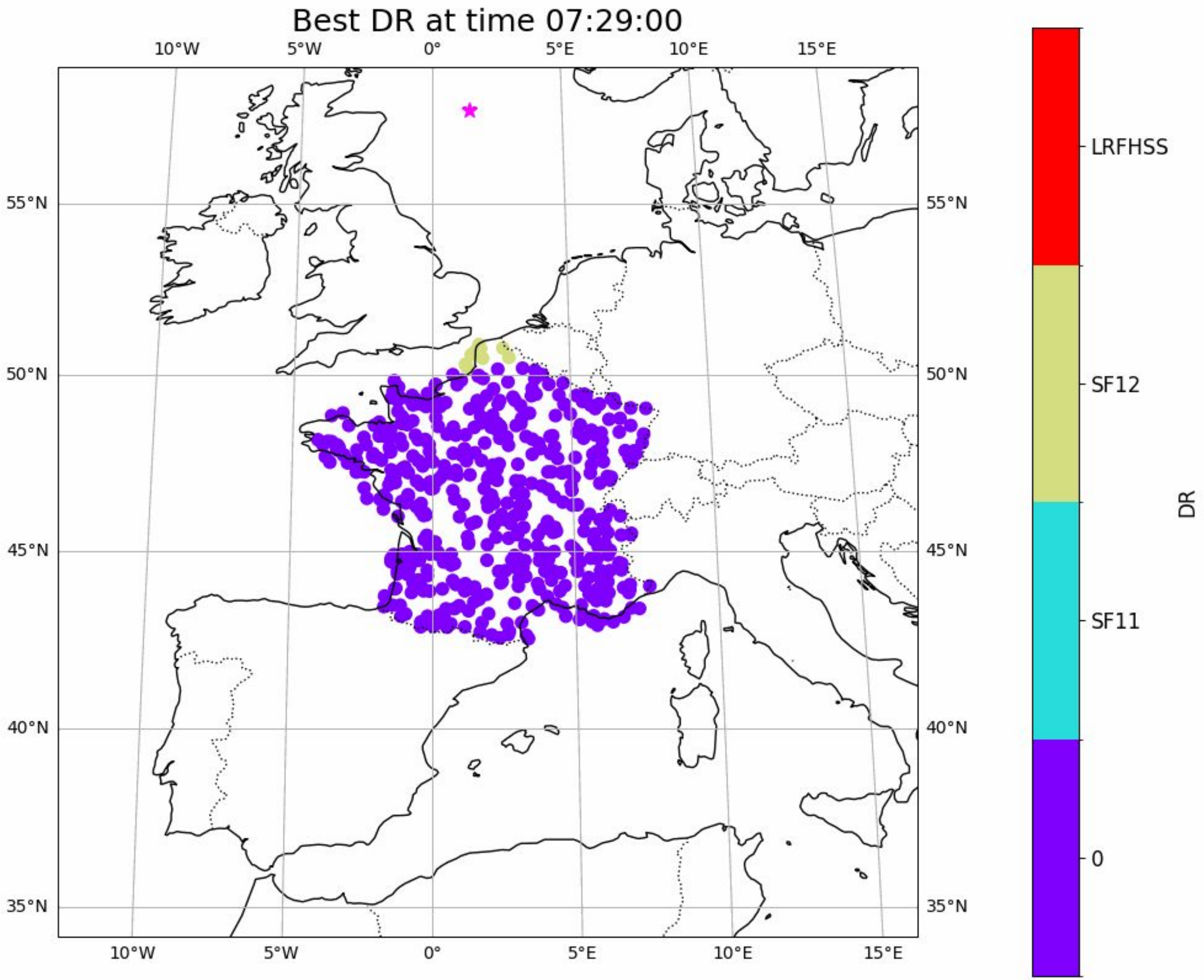
STEREO Workshop 2025, Toulouse

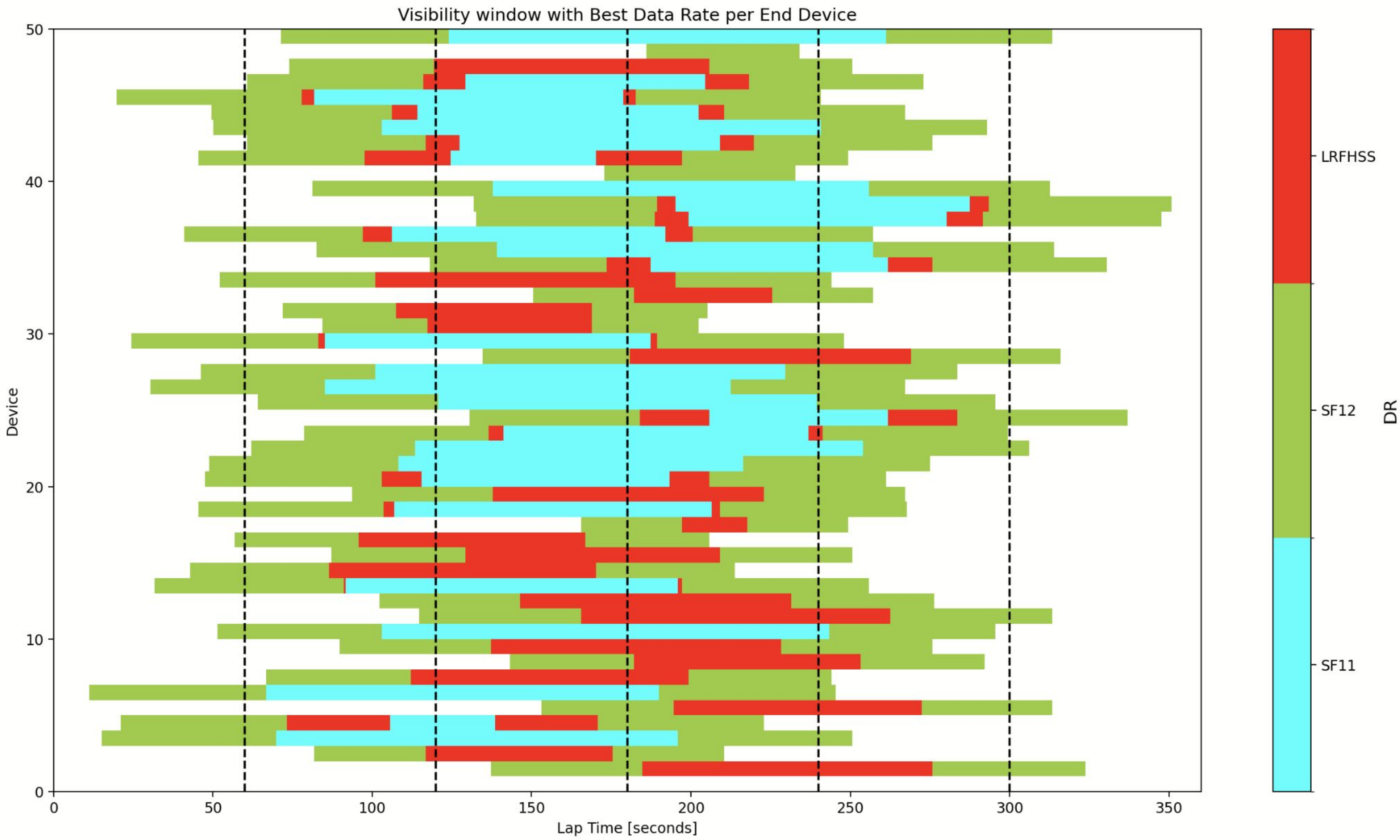
October 3rd 2025

Problem

New Semtech devices, such as LR1120, come with both LoRa CSS and LR-FHSS modulation available for uplink.

So which one to use? and which configuration?




Visibility window with Best Data Rate per End Device
Device
Lap Time [seconds]
0
10
20
30
40
50
0
50
100
150
200
250
300
350
LRFHSS
SF12
SF11
DR

Packet Collision Probability for LoRa CSS

In [1] the authors present a closed-form expression for the probability of no uplink collision **P(S)** for unconfirmed ALOHA over a single channel (LoRaWAN class A with LoRa-CSS modulation):

Then, the probability that no portion of the packet transmitted by the generic node is interfered, $P(\mathsf{S})$, is given by

$$P(\mathsf{S}) = e^{-4LT\nu\lambda}. \quad (4)$$

The results consider SF=7 and BW=125kHz.

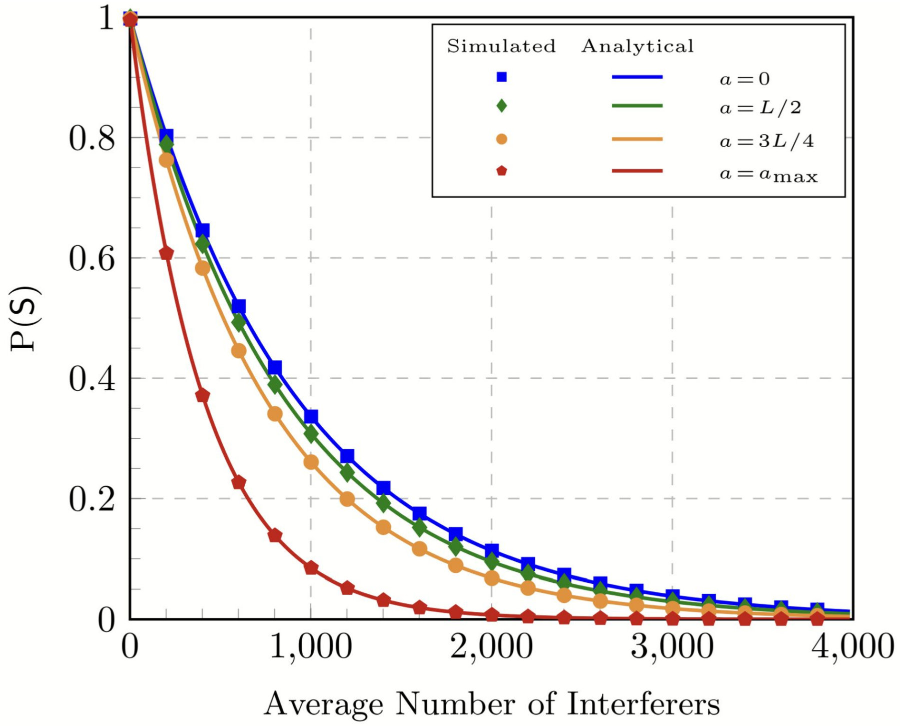


Fig. 4. Simulated and analytical probability of no interference over the single-frequency asynchronous channel (e.g., LoRa-CSS-based LoRaWAN) varying the average number of interferers.

[1] Testi, E., & Paolini, E. (2024). Packet Collision Probability of Direct-to-Satellite IoT Systems. *IEEE Internet of Things Journal*.

Single Channel System Optimization Model (Opt1D)

Optimal allocation of LoRa CSS transmissions.

1. an ED can transmit only once
2. up to M concurrent transmissions at any point
3. same SF cannot coexist at any point
4. Link Budget and Doppler constraint

$$\begin{aligned}
\text{maximize} \quad & \textstyle\sum_{i\in\mathcal{I}}\sum_{p\in\mathcal{P}} x_{i,p} d_i P_i^{\text{cap}} & \\
\text{subject to} \quad (1) \quad & \textstyle\sum_{m\in\mathcal{M}}\sum_{p\in\mathcal{P}} x_{i_{n,m,p}} \leq 1, & \forall n \\
(2) \quad & \textstyle\sum_{(i,a)\in\xi_p} x_{i,a} \leq M, & \forall p \\
(3) \quad & \textstyle\sum_{(i,a)\in\xi_{p,m}} x_{i,a} \leq 1, & \forall p, \forall m \\
(4) \quad & x_{i,p} \leq \delta_{i,p}, & \forall p, \forall i
\end{aligned}$$

Proposed Joint Allocation MAC

- Satellite Orbit Aware: This category of MAC protocols assume EDs are capable of tracking the satellite's position. Each ED is assumed to be capable of calculate its visibility window and channel condition, thus, having its own prediction of the δ variable.
- Interference Aware: For each uplink window, the satellite broadcasts the number of competing EDs C_m for each SF from the variable δ, assuming an ED will always attempt to use the lowest SF available.

For each ED n we define :

- $\mathcal{M}_{\text{avail}} = \{m \mid \exists\, t \text{ such that } \delta_{n,m,t} > 0\}$, the set of available SFs.
- $\mathcal{T}_m = \{t \mid \delta_{n,m,t} = 1\}$, the set of available timeslots using modulation m.
- $\bar{m} = \min\{m \mid \exists\, t \text{ such that } \delta_{n,m,t} > 0\}$, the best SF achieved.

$$C_m = \sum_{n=1}^{N} \left[\max_{t \in T} \delta_{n,m,t} \right]$$

Proposed Joint Allocation MAC

2) *Success-based Sequential SF:* An alternative to the previous method is to sequentially assign the SF, as in Algorithm 5. It is also convenient to define the cumulative number of expected competitors $C_m^{\text{cum}} = \sum_{i=0}^{m} C_i$, where C_i is the number of competitors using SF i. Then, the Success-based Sequential SF protocol is almost the same as the one described in Algorithm 5, but the difference is in the transmission probability in line 9. The new P_{TX} is defined as follows.

$$P_{\text{TX}}(\bar{m}) = N_{\max}(P_{\min}, \bar{m})/C_{\bar{m}}^{\text{cum}} \tag{8}$$

3) *ALOHA max interference:* A possible improvement for the ALOHA max Sequential SF is to make use of the number of competitors informed in the beacon of the uplink period. The transmission probability can be calculated using the cumulative number of competitors instead of the total network size. The new P_{TX} defined as follows.

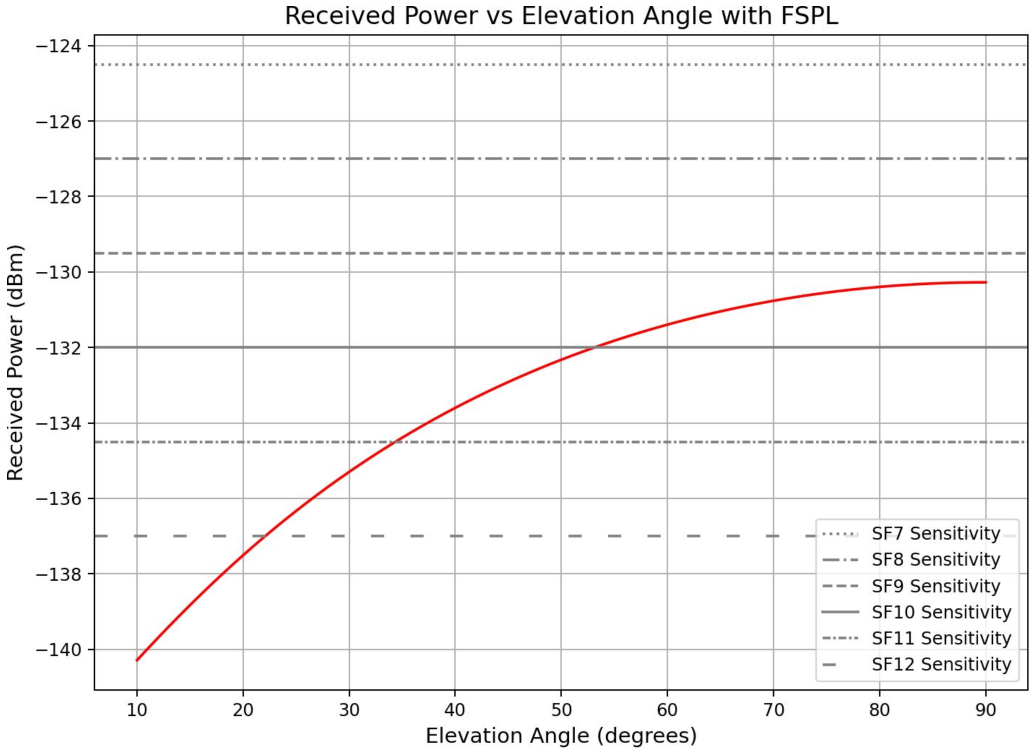
$$P_{\text{TX}}(\bar{m}) = \min\left(1, \bar{N}_{\bar{m}}/C_{\bar{m}}^{\text{cum}}\right) \tag{9}$$

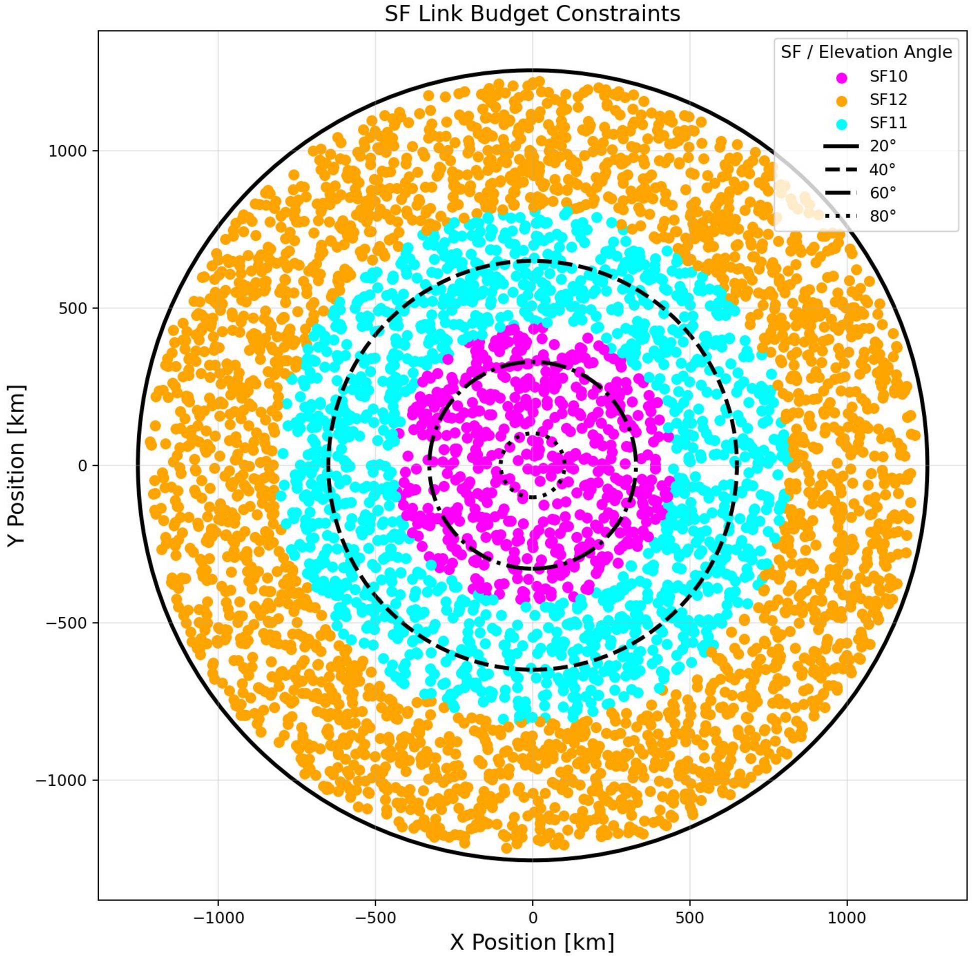
Allocation Method	Satellite orbit aware	Interference aware	Modulation selection technique	Spreading Factor selection technique	Coding Rate selection technique	Time allocation technique
1) Class A	NO	NO	RUS between LoRa and LR-FHSS	RUS of SF such that SF $\geq$ minSF	RUS between CR1/3 and CR2/3	RUS over the UL window
2) Class A Valid SF	YES	NO	RUS between LoRa and LR-FHSS	RUS of available SF during UL window	RUS between CR1/3 and CR2/3	RUS over the time when selected SF is available
3) ALOHA max total	YES	NO	ALOHA max throughput based load traffic control and total network size	Sequential selection of SF starting with the lowest SF	RUS between CR1/3 and CR2/3	RUS over the time when selected SF is available
4) ALOHA max interference	YES	YES	ALOHA max throughput based load traffic control and number of interferers	Sequential selection of SF starting with the lowest SF	RUS between CR1/3 and CR2/3	RUS over the time when selected SF is available
5) Success Best SF	YES	YES	Success probability based on number of interferers	Select best SF achieved during UL window	RUS between CR1/3 and CR2/3	RUS over the time when selected SF is available
7) Success Sequential SF	YES	YES	Success probability based on number of interferers	Sequential selection of SF starting with the lowest SF	RUS between CR1/3 and CR2/3	RUS over the time when selected SF is available
7) Optimal 1D Allocation	YES	YES	Optimal allocation of LoRa signals. Unallocated transmissions use LR-FHSS.	Optimal selection	RUS between CR1/3 and CR2/3	Optimal selection

Link Budget: Free Space Path Loss

RX Gain (satellite)	3 dB
TX Gain	0 dB
TX power	14 dB

REMARK: even though SF10 is possible given the link budget, it is blocked due to Doppler Rate limitations.

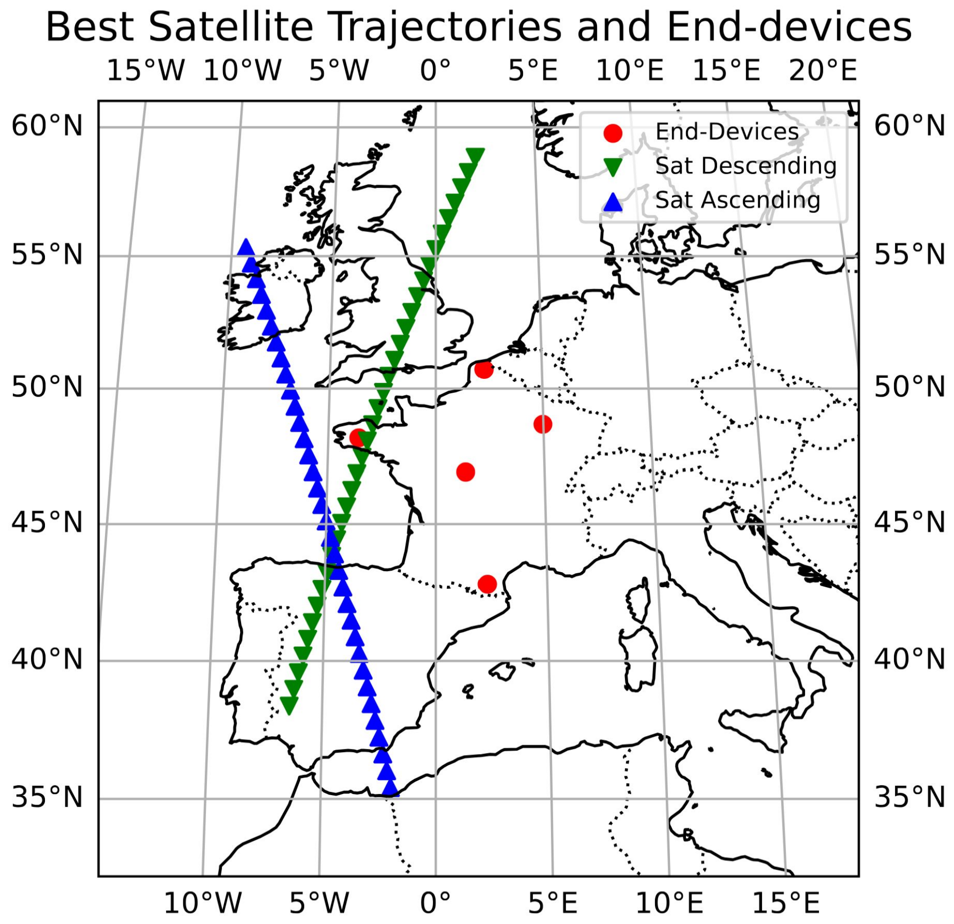




Test Scenario

Assumptions:

- End-devices (EDs) are stationary and their position is known to the network server. They uniformly distributed over France.
- EDs cannot communicate with each other and rely on themselves and the satellite beacon.
- EDs have full knowledge of the satellite's orbit [1].
- We assume full channel conditions knowledge.
- We consider a real satellite in orbit (KINEIS-1A).
- LoRa and LR-FHSS signals will use separate disjoint channels.

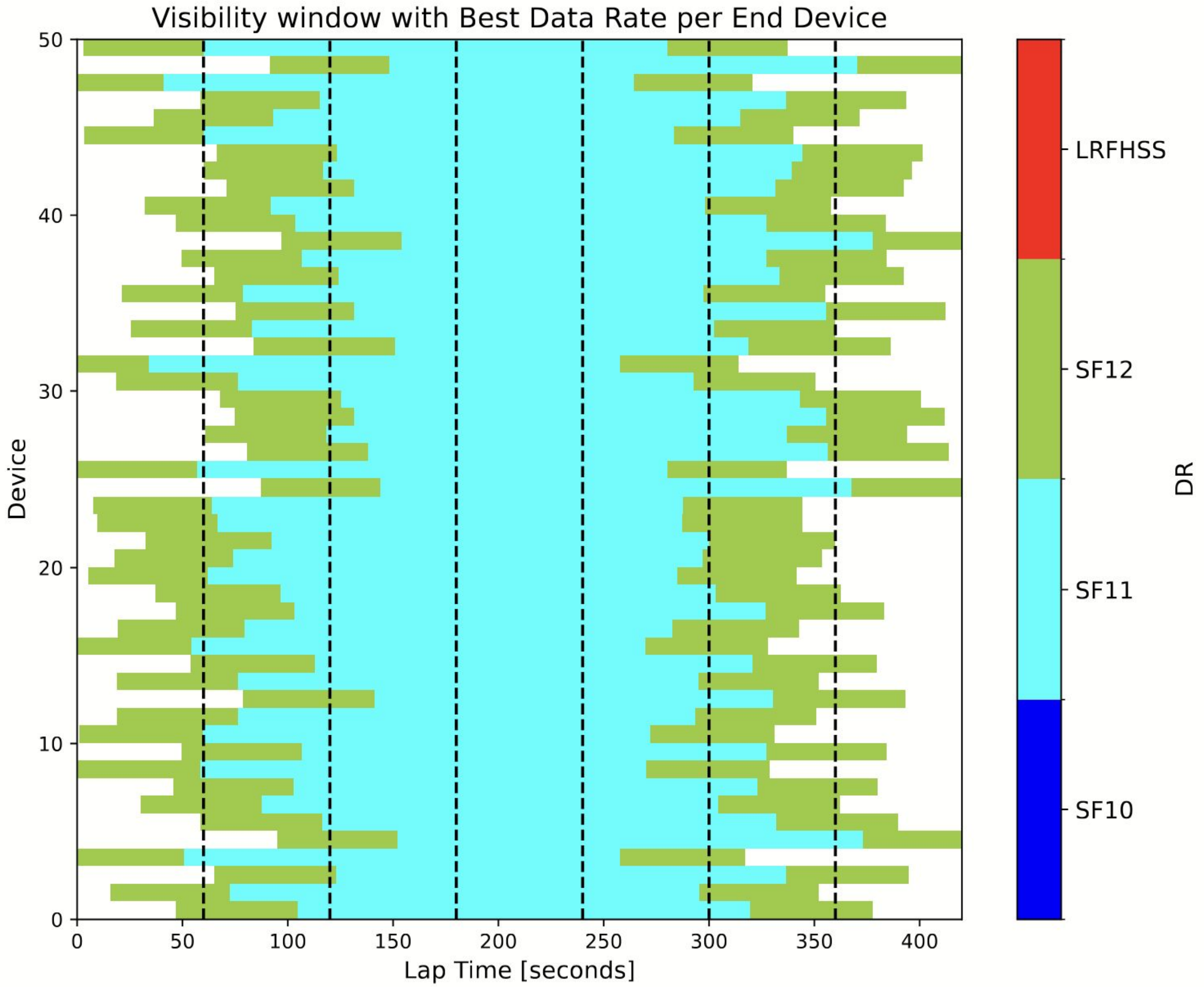


[1] Ortigueira, R., Montejo-Sánchez, S., Henn, S., Fraire, J. A., & Céspedes, S. (2024). Satellite visibility prediction for constrained devices in direct-to-satellite IoT systems. *IEEE Sensors Journal*.

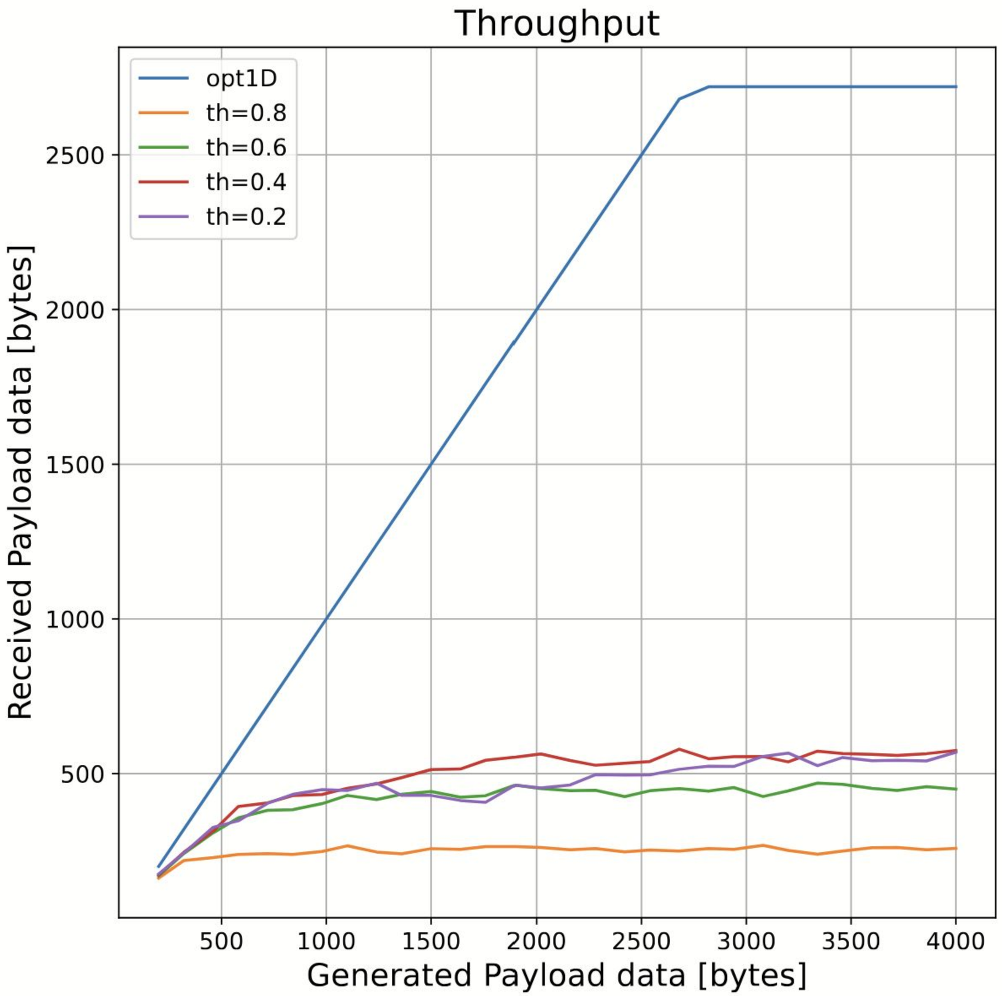
Test Scenario

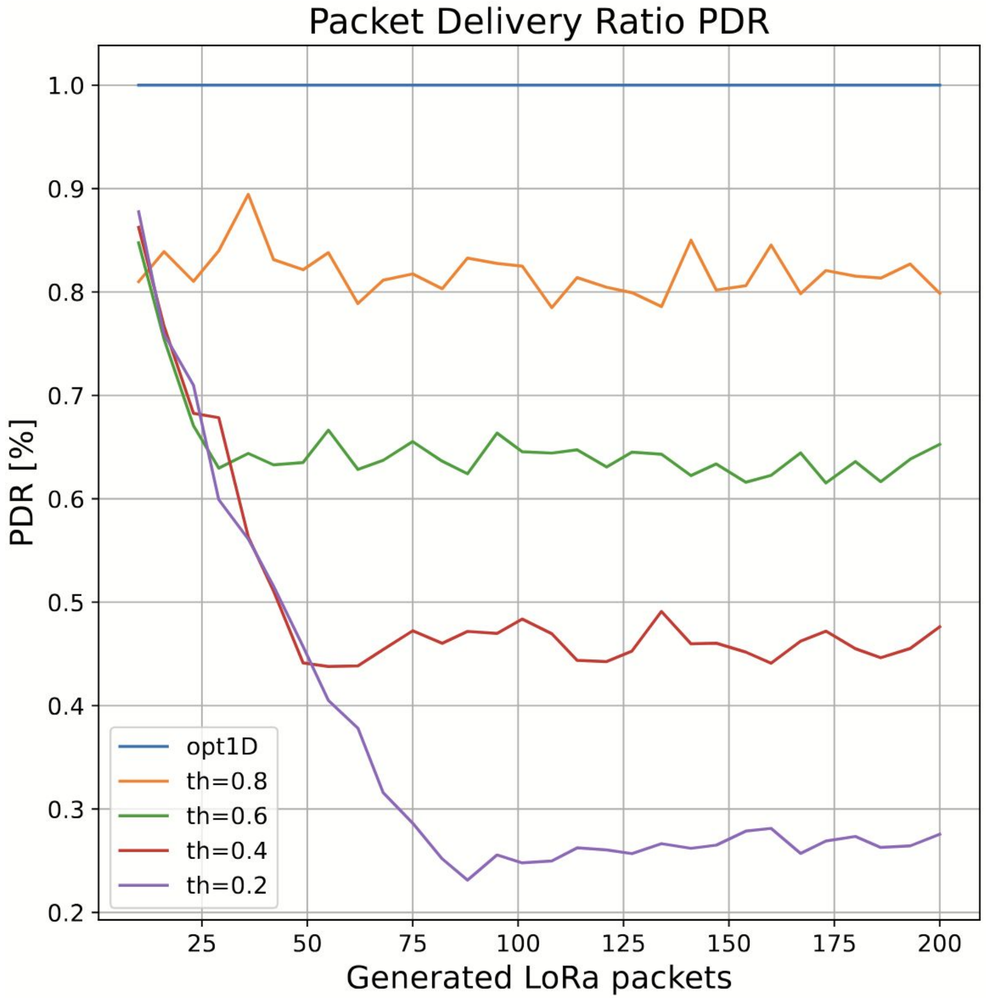
The following results consider the analysis of LoRa signals only. We consider 200 EDs deployed on ground.

All methods use a Monte Carlo approach with 40 repetitions, except for the optimal model which is run only once.

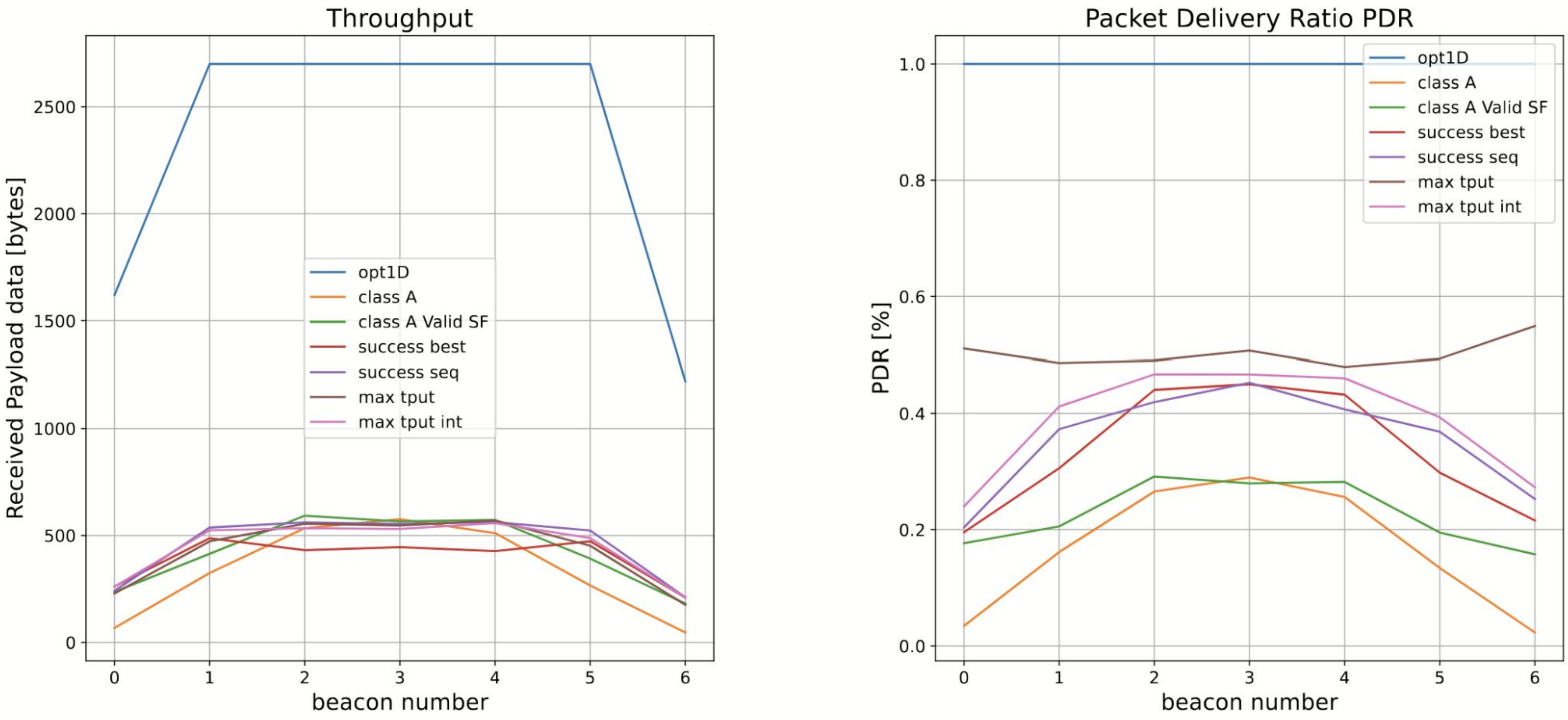


Throughput and PDR for Sequential SF with success prob





Throughput and PDR for different methods



Discussion

How to evaluate the performance of a joint allocation method?

Is it reasonable to prefer CSS over LR-FHSS whenever possible?

Is it reasonable to assume EDs can predict the satellite's position?

How are channels managed by LoRaWAN? How many for LoRa and for LR-FHSS?

Should the beacon broadcast data to the EDs?

Merci!