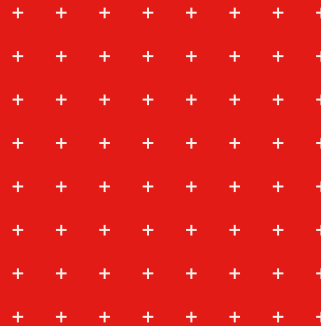


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From ground to Space: efficient downlink scheduling for direct-to- satellite LoRaWAN

NTN Days, Paris, 13 October 2026

Speaker:

- **Carlos Fernandez Hernandez**

01 | Technology Context and Motivation

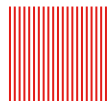
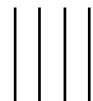
02 | DORSAL Downlink Scheduler

03 | Improving Downlink in DtS LoRaWAN

04 | Conclusion and Perspectives

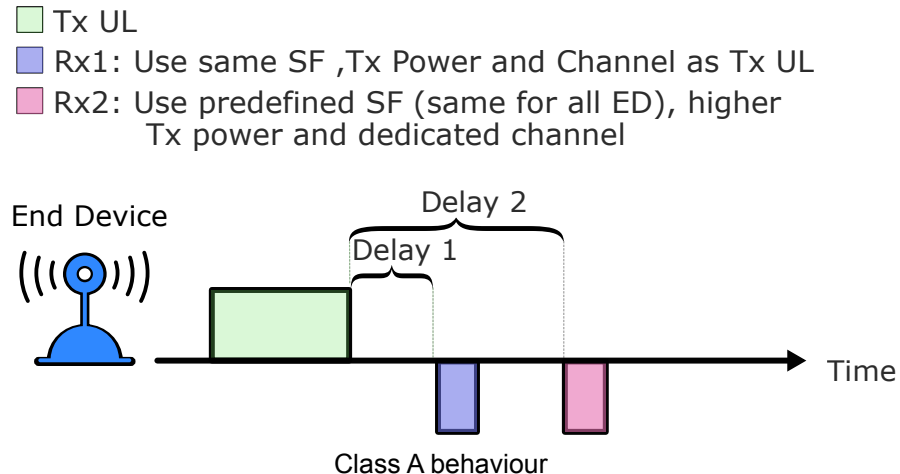
01

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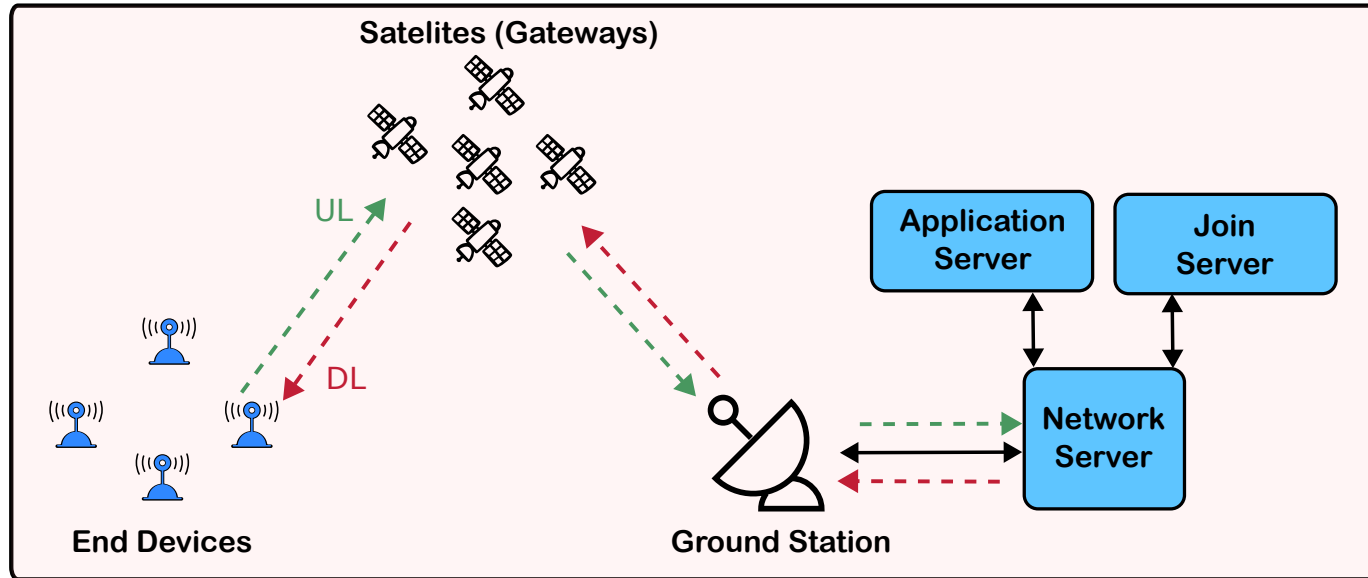


1.1 LoRaWAN in DtS Downlink Challenges

- Use of direct-to-satellite LoRaWAN [1,2]:
 - Remote Areas or lack of infrastructure [3-5]
- Downlink in LoRaWAN has always been challenging:
 - Class A timing limitations
 - Gateways are Half-Duplex
 - Fair access policy for spectrum usage (duty cycle in Europe)

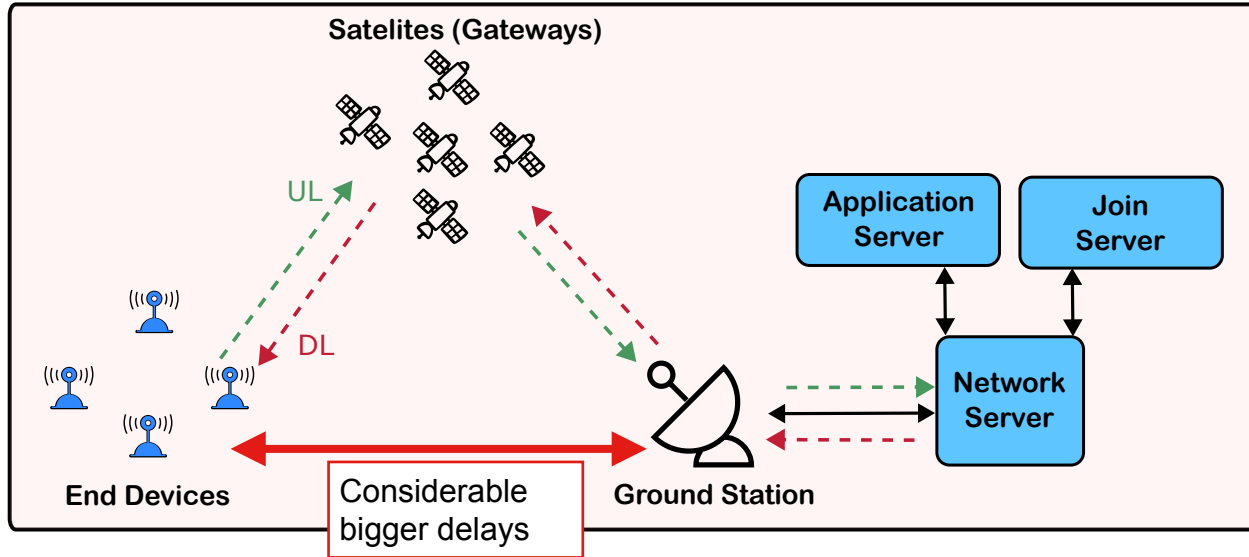


1.2 LoRaWAN in DtS Downlink Challenges



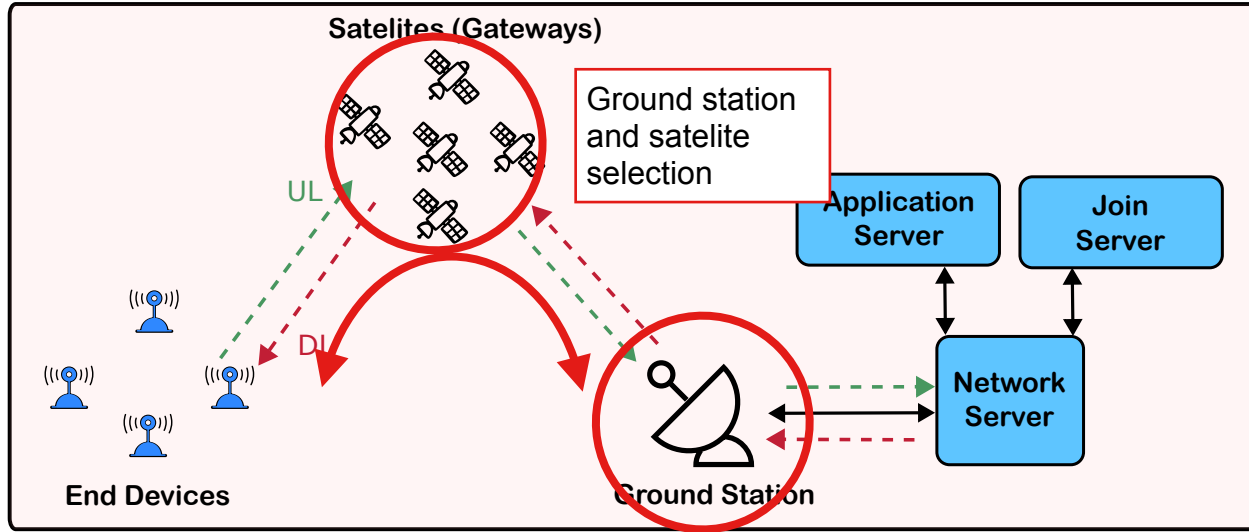
1.2 LoRaWAN in DtS Downlink Challenges

- In the DtS IoT is extra challenging!
 - + Timing feasibility scheduling
 - + Path selection



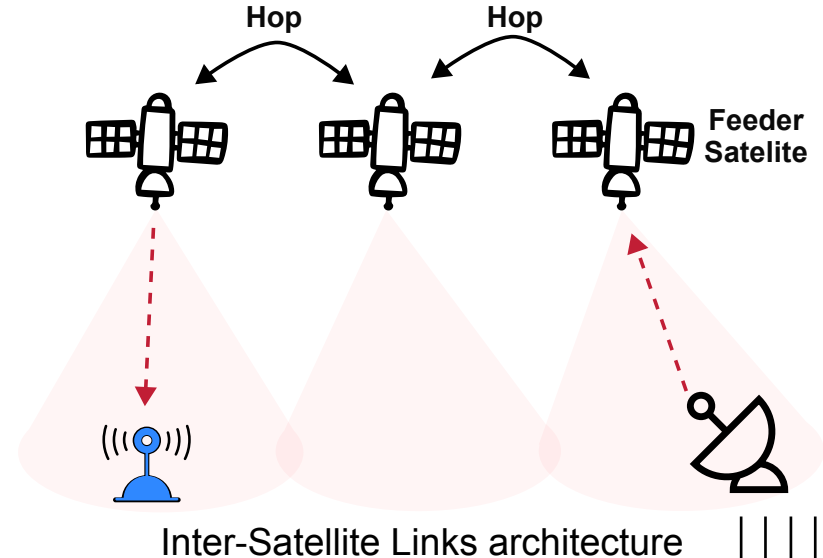
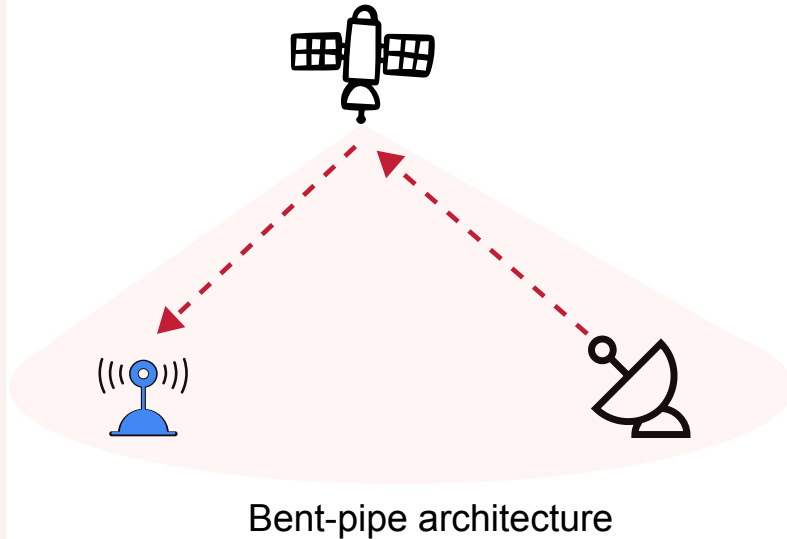
1.3 LoRaWAN in DtS Downlink Challenges

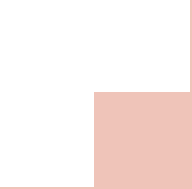
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1.4 DtS Networks Architectures

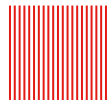
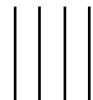
- Network Components: Satellites $\mathcal{S}$, End devices $\mathcal{N}$, Ground Stations, $\mathcal{G}$ and network server
- Network architectures:
 - Bent-Pipe (BP)
 - Inter-Satellite Links (ISL)





02

02 | DORSAL Downlink Scheduler



2.1 DORSAL Scheduler Formulation [7]

- Total end-to-end delay for a path $k=(g, s_1, \dots, s_{dl})$ is given by:

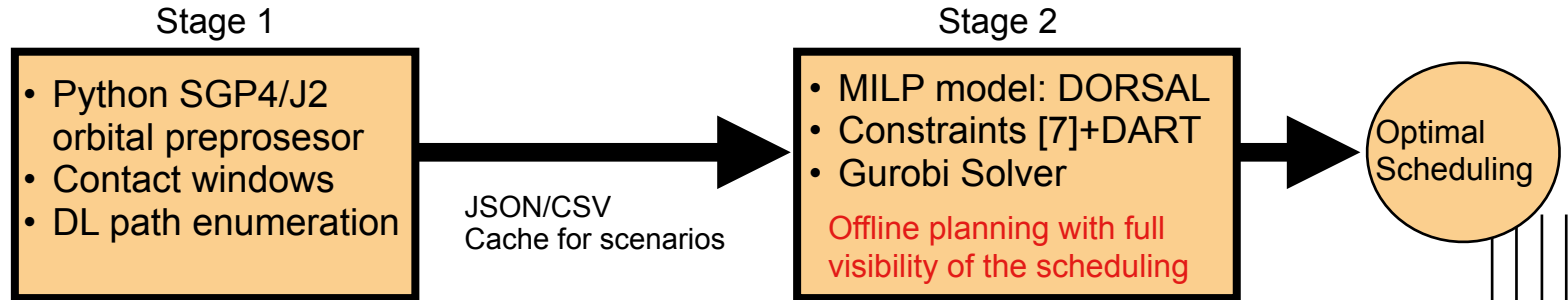
$$\delta(k, f) = \underbrace{\delta_{gs}(g, s_1) + \sum_{l \in ISL(k)} \delta_{isl,l}}_{\text{propagation}} + \underbrace{h_k \tau_{isl}}_{\text{store-and-forward}} + \underbrace{\delta_{rad}(s_{dl}, n_i)}_{\text{radio leg}}$$

- Downlink Arrival Receive Window Timing (DART) metric where NS targets $DART_w = 0$:

$$DART_w = (t_{inj} + \delta(k, f)) - \tau_{RXw} = 0 \rightarrow t_{inj} \approx \tau_{RXw} - \delta(k, f).$$

- We build on top of the terrestrial optimal downlink scheduler Caillouet et al [8]

$$\max \sum_{n_i \in \mathcal{N}} \sum_{t_j^i \in \text{eul}(n_i)} \sum_{s \in \mathcal{S}} [(1 + \alpha) y_1(s, t_j^i) + y_2(s, t_j^i)]$$



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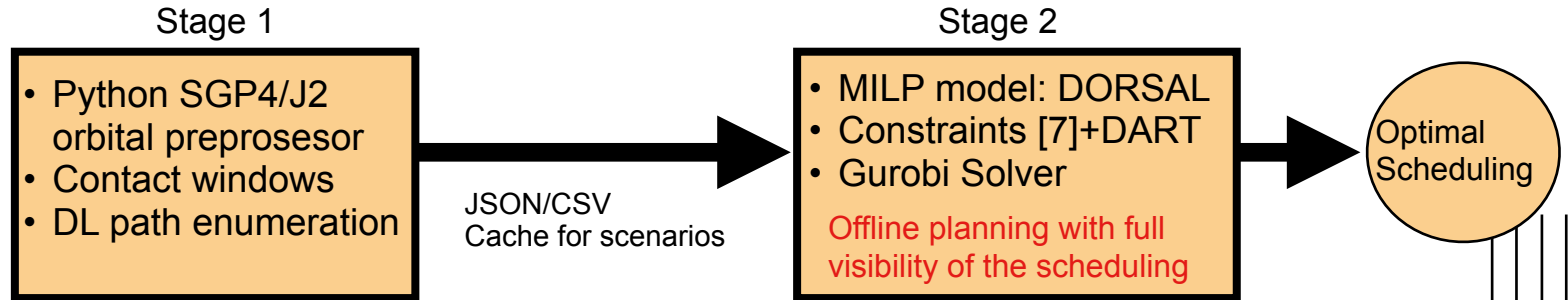
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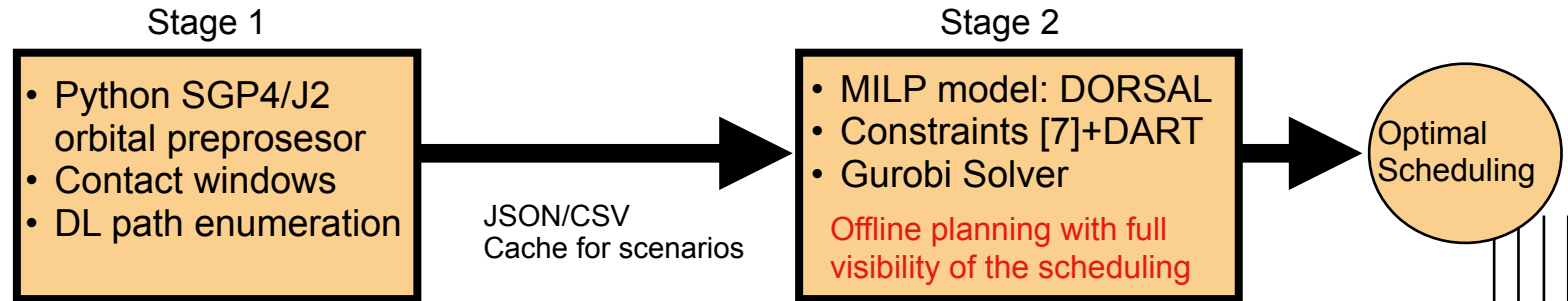
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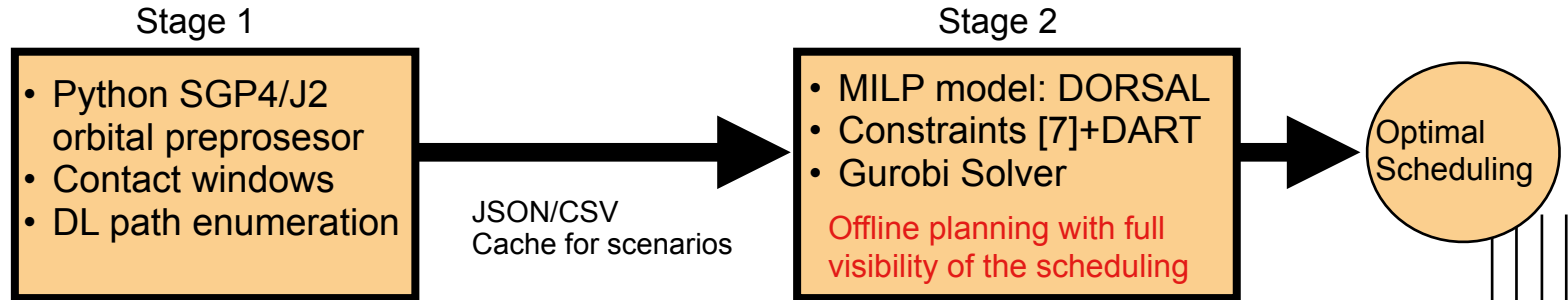
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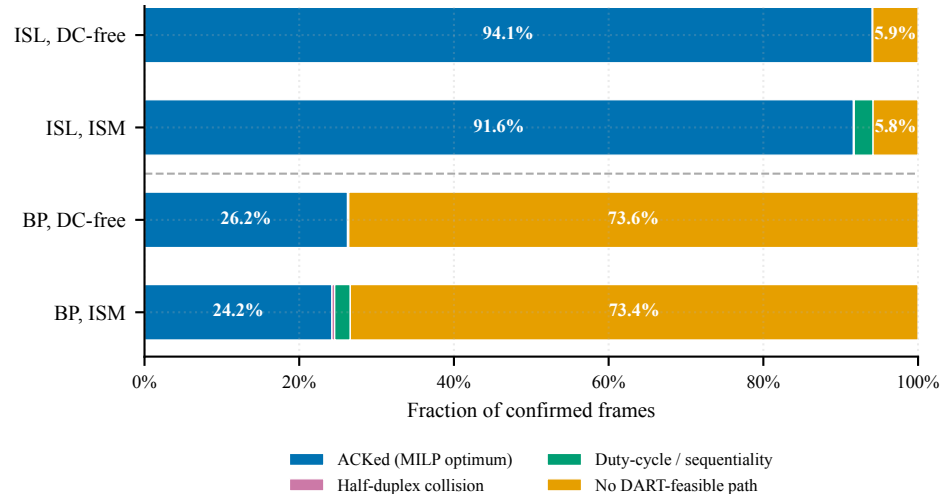
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2.2 Reasons Behind Unfeasibility and GS dependancy

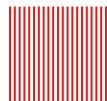
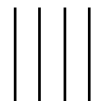
- **Scenario:** Walker 5×5 constellation (650 km altitude, 87° inclination) and 5,860 s observation window 100% confirmed uplink traffic 150 s transmission period
- **Main bottleneck:** DART feasibility, rather than duty-cycle restrictions, drives ACK losses
- **ISL benefits:** Low impact of DART and reduced dependence on ground-station coverage



100 End devices 3 ground stations

03

03 | Improving Downlink in DtS LoRaWAN

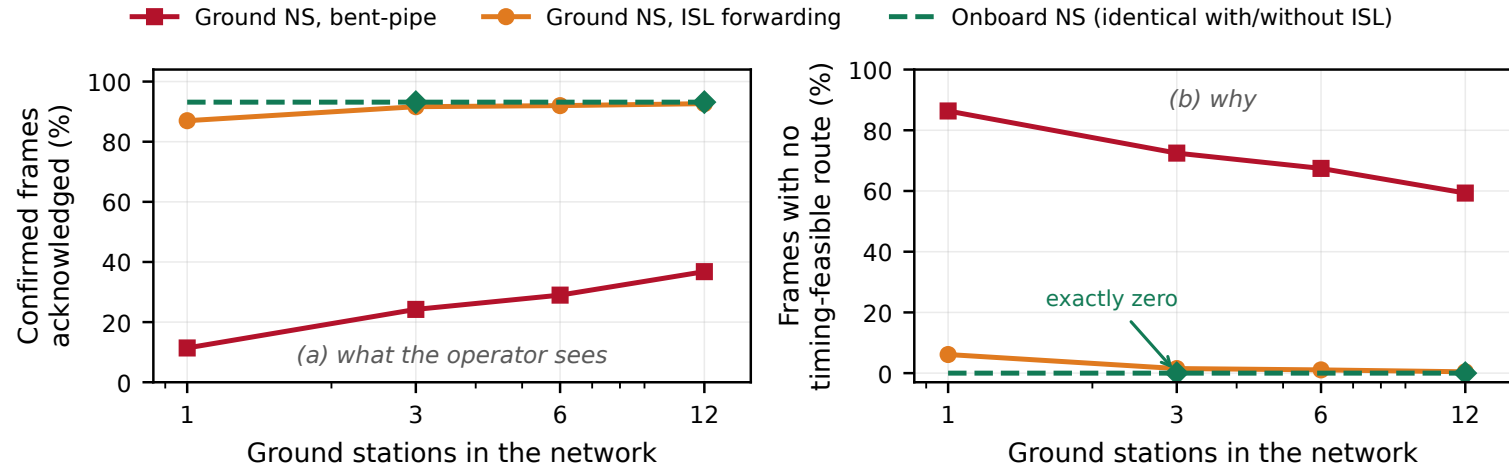


3.1 What Happens if the Network Server Runs in the Satellite?

- **Idea:** Each satellite decides on the downlink scheduling

$$\delta(k, f) = \underbrace{\delta_{gs}(s, s_1)}_{\text{propagation}} + \underbrace{\sum_{l \in ISL(k)} \delta_{isl,l}}_{\text{store-and-forward}} + \underbrace{h_k \tau_{isl}}_{\text{radio leg}} + \underbrace{\delta_{rad}(s_{dl}, n_i)}_{\text{radio leg}}$$

- Onboard BP placement achieves 93.2% ACK delivery approaching ISL
- Onboard placement nearly matches a 12-ground-station network, without requiring ISL hardware

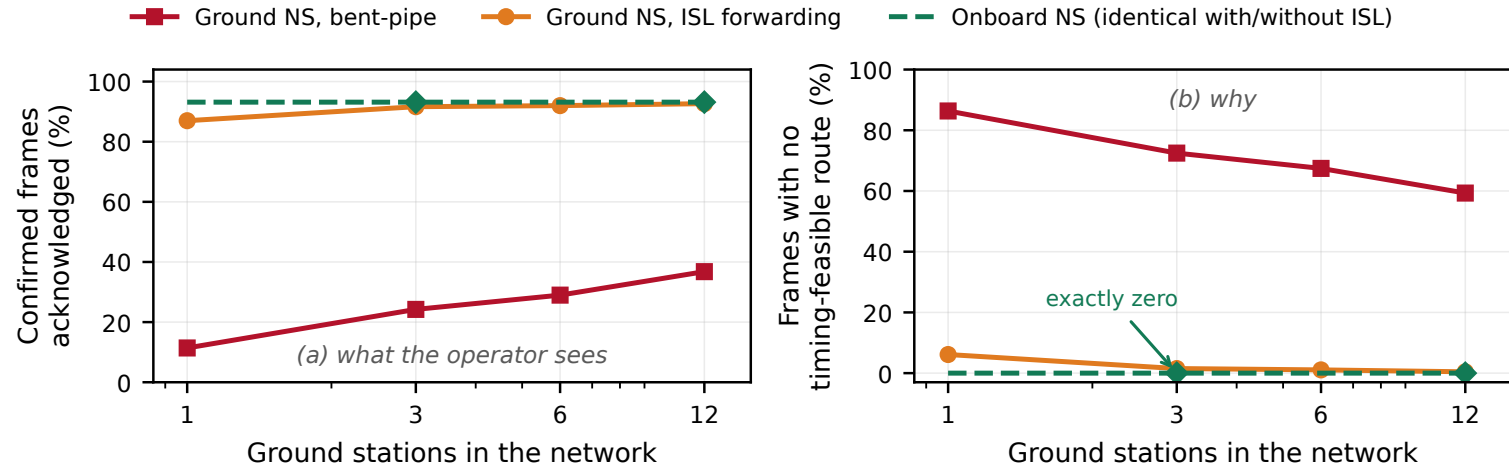


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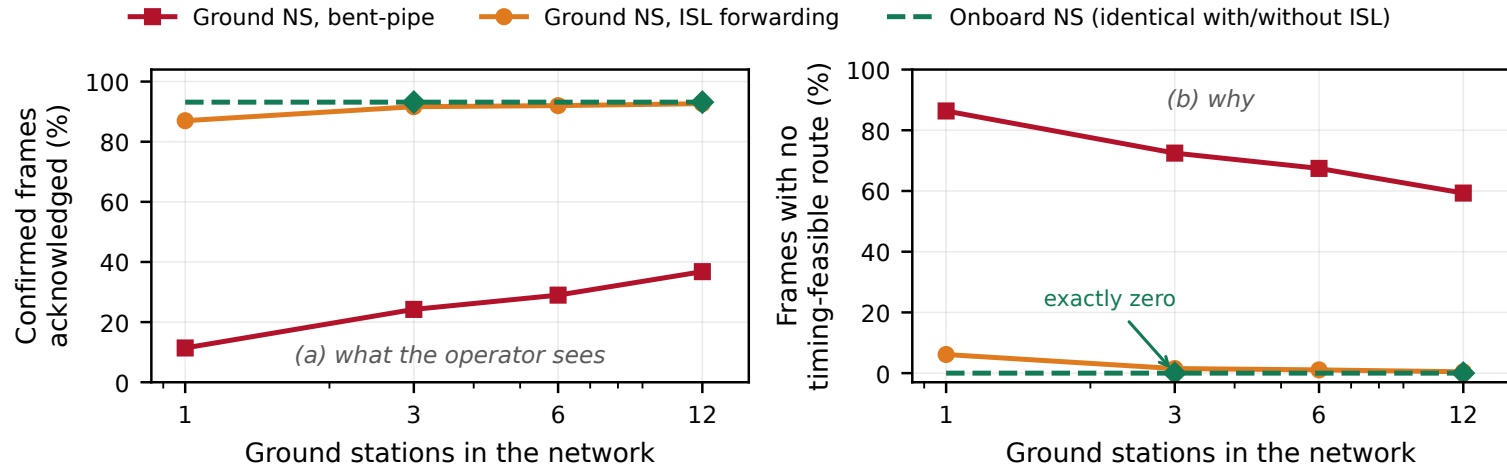


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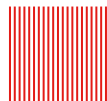
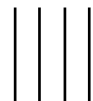
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04

04 | Conclusions and perspectives





4.1 Conclusions and Perspectives

- Conclusions:
 - DART feasible path is the main constraint at this scale, associated with orbital geometry
 - ISL architecture makes a great difference in capacity
 - With onboard downlink scheduling, bent-pipe approaches ISL
- Perspectives:
 - How can we implement an onboard network server
 - **Implementation of functional decoupling in real hardware:**

1 • Regional access rules

Apply each device's regional rules on the move: duty cycle, dwell time, listen-before-talk. The 868 and 915 MHz bands may need separate radios.

2 • Duplicate uplinks

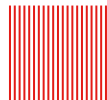
When 2–3 satellites hear one uplink, a rule each computes the same way picks who answers: no messages, no double answers, no repeated downlink counter.

3 • Security

Verify the uplink MIC, sign the downlink MIC and reject replays onboard. LoRaWAN 1.0.x needs one network key per device, 1.1 needs three.

4 • Memory and state

Per device: keys, frame counters, receive settings. Small in size. The hard part is keeping it fresh across satellites over intermittent links.



Thank you for your attention

Contact Email: carlos.fernandez-hernandez@insa-lyon.fr



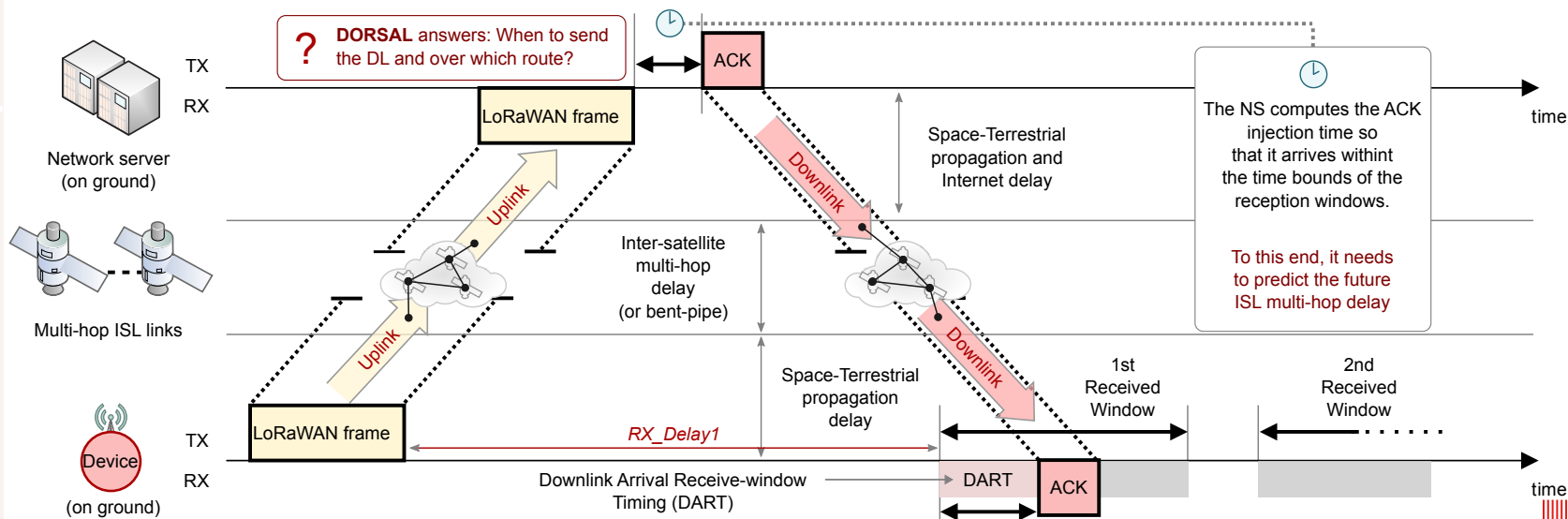
References

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- [2] LoRaWAN L2 1.0.4 Specification, TS001-1.0.4, LoRa Alliance, 2020.
- [3] A.-I. Pop, U. Raza, P. Kulkarni, and M. Sooriyabandara, “Does bidirectional traffic do more harm than good in lorawan based lpwa networks?” in IEEE GLOBECOM 2017, 2017, pp. 1–6. [Online]. Available: <https://ieeexplore.ieee.org/document/8254509>
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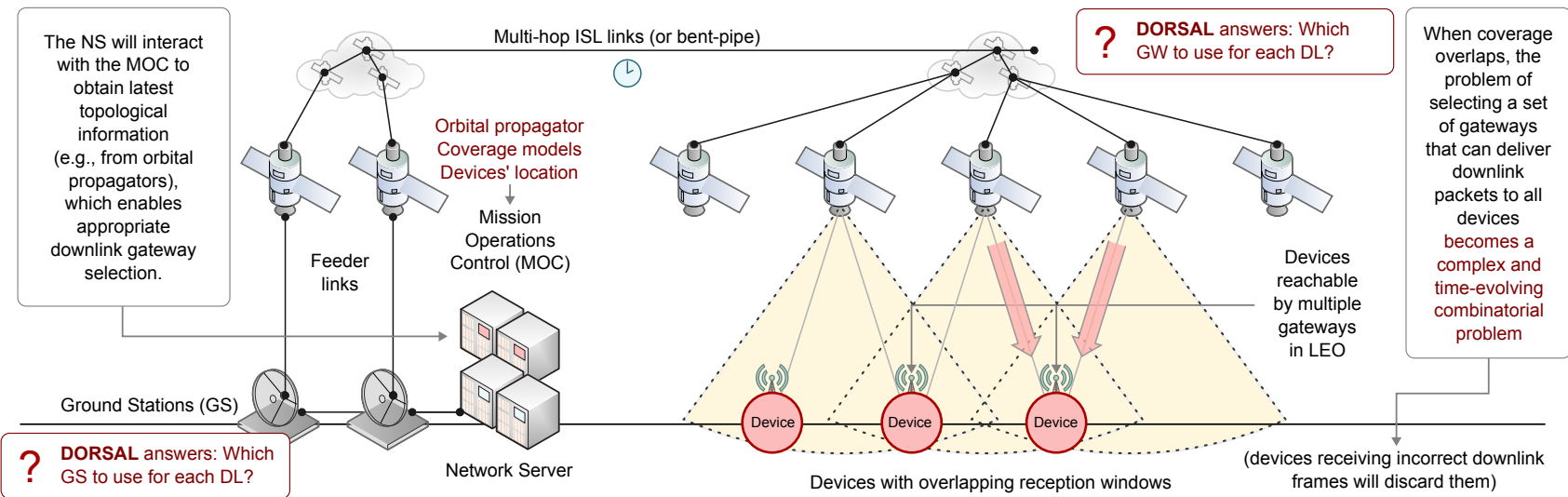


A.1 Challenge 1: Timing-Feasible Downlink Scheduling

- Downlink Arrival Receive-window Timing:
 - Timing offset between packet arrival and receive window opening at the end device

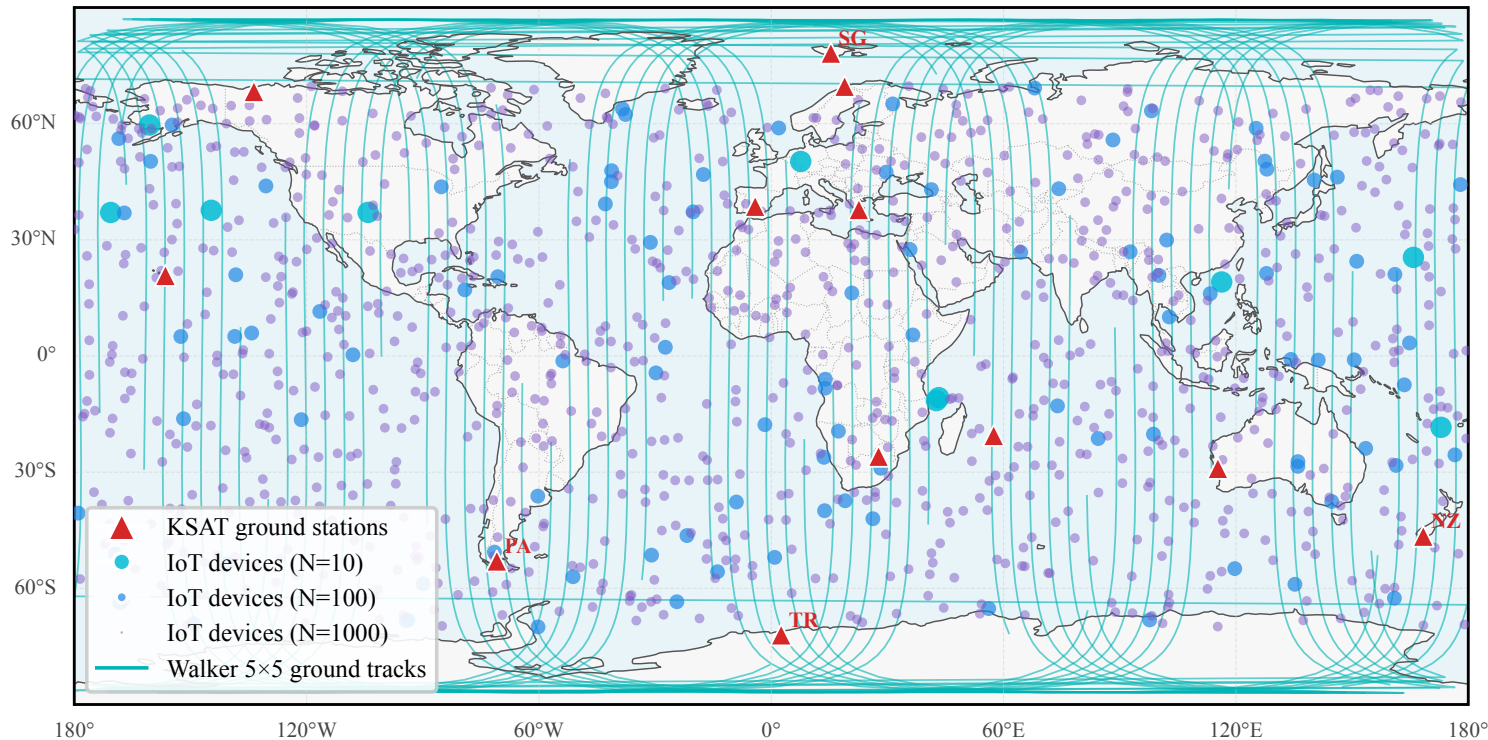


A.2 Challenge 2: Gateway and Delivery-Satellite Selection



B.1 System architecture overview

DORSAL Scenario Overview: Walker 5×5 (25 sats) @ 650.0 km, 87.0° inc. | KSAT network



C.1 MILP Model Objective Function

- Build on top of the terrestrial MILP model proposed by Caillouet et al [7]
- Objective function maximizes the amount of transmitted downlinks:

$$\max \sum_{n_i \in \mathcal{N}} \sum_{t_j^i \in \text{ul}(n_i)} \sum_{s \in \mathcal{S}} [(1 + \alpha) y_1(s, t_j^i) + y_2(s, t_j^i)]$$

- Constraints:
 1. (C1) Contact window feasibility
 2. (C2) DART feasibility and path selection
 3. (C3) Half-Duplex collision detection
 4. (C4-C5) Duty Cycle restrictions for Rx1 and Rx2
 5. (C6) Global Sequentiality
 6. (C7) One downlink per confirmed frame
 7. (C8) Gateway selection policy
 8. (C9) Link Capacity



C.2 Evalution Setup

- Walker 5x5 constellation 5 orbital planes 5 satellites 650 km altitude 87 degrees inclination.
- Real GS facilities (KSAT and SSC)
- EU868 band 1% and 10% duty cycle in Rx1 and Rx2, respectively

Parameter	Value
Constellation	25 satelites
Observation window	5860 s
Ground Stations	3,6,12
Number of End Devices	100,500,1000
Transmision period uplink	150 s
Confirmed Traffic (%)	100

