

TDD in 5G LEO Satellite Networks:

A Comparative Study of Guard-Period Strategies and Frame Durations

Madyan Alsenwi, Jorge Querol, Eva Lagunas

*Interdisciplinary Centre for Security, Reliability and Trust (SnT)
University of Luxembourg, Luxembourg*

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Outline

01 Introduction — Background & Motivations • The Guard-Period Limitation • Contributions

02 Solution Comparison — Three GP Design Methods • Extraordinary Downlink (xDL) • Chronogram Sequence

03 System Model & Setup — System Scenario • Communication Model • Simulation Parameters

04 Performance Evaluation — Frame Efficiency • DL/UL Overlap Fraction • Average User Data Rate

05 Conclusion — Summary, Main Findings & Future Work

Section 1: Introduction

Background, Motivations & Paper Contributions

Background and Motivations

1. LEO Broadband Growth

Starlink, OneWeb, Project Kuiper
LEO Altitude: 500–2,000 km

2. Current LEO Standard

Frequency-Division Duplex (FDD)
Paired bands • Fixed DL/UL split

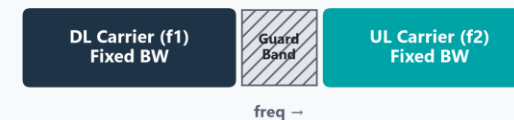
3. Target 5G NR Standard

Time-Division Duplex (TDD)
Single shared band • 3GPP TR 38.821

Feature	FDD (Current LEO)	TDD (Target 5G NR)
Spectrum	Paired UL & DL bands + guard band	Single shared band (time split)
CSI Estimation	Explicit feedback (extra delay)	Direct channel reciprocity
Traffic Split	Fixed DL/UL allocation	Dynamic on-demand slots
RF Hardware	Duplexer / dual antennas	Single antenna + RF switch

Legacy FDD Architecture — Paired Spectrum ($f_1 \neq f_2$)

Frequency Domain (Rigid Split):



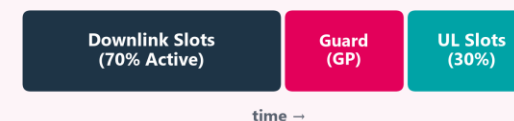
■ Heavy Diplexer Filter | ■ Wasted Capacity under Asymmetric Traffic

Non-Reciprocal CSI Loop



5G NR NTN TDD Architecture — Unified Carrier (f_0)

Time Domain on Single Band f_0 (Dynamic 70:30 Split):



■ Fast RF Switch (No Diplexer) | ■ Bottleneck: GP Must Absorb LEO RTT

Direct Channel Reciprocity (f_0)



Background and Motivations: The Guard-Period Limitation

1. TDD Guard Rule (DL $\rightarrow$ UL Switch)

- **Condition:** $GP \geq RTT$ at every DL $\rightarrow$ UL switch.
- **Purpose:** Finish DL RX before UL TX (zero self-interference).



2. LEO Consequence (600 km Altitude)

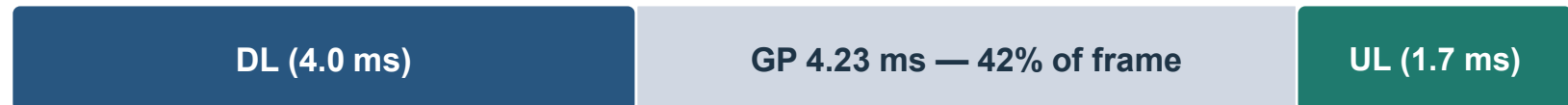
- **Long RTT:** Spans 4 ms (nadir) to 8 ms (30° edge).
- **10 ms NR Frame:** 40% to 80% of the frame is idle guard!

Example: $h = 600$ km Altitude • 10 ms NR Frame • 70:30 DL:UL Split

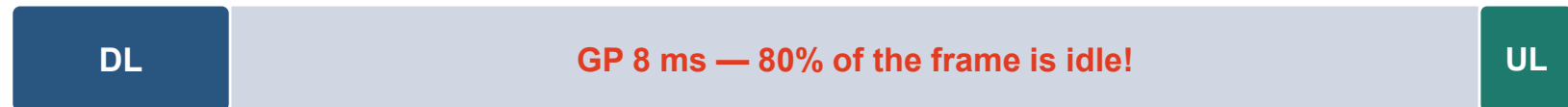
Nadir, 90°: $RTT \approx 4$ ms



Elevation 60°: $RTT \approx 4.23$ ms



Elevation 30°: $RTT \approx 8$ ms



Key Bottleneck: At 30° cell edge, 80% of a 10 ms TDD frame is idle guard time (only 20% carries payload).

Contributions

Fix: Longer Frame Duration



Cost: Proportionally Higher Latency

Two Open Research Questions:

Q1 (GP Sizing): How should the GP be set across realistic TDD frame durations?

Q2 (GP Reuse): Can part of the reserved GP be reused for payload without self-interference?

1. Three GP Design Rules

- **Worst RTT:** Sized for cell-edge user (max RTT).
- **Adaptive per-UE:** Tailored to each user's RTT (TA).
- **Minimum RTT:** Sized for nadir user (min RTT).

2. Extraordinary DL (xDL)

- **Guard Reuse:** Reclaims trailing DL → UL guard.
- **Physical Principle:** Uses UL wave flight time to sat.
- **Key Benefit:** Extra DL with zero self-interference.

3. Joint Evaluation

- **Frame Durations:** 10, 20, 30, 40, and 182 ms.
- **Three Metrics:** 1) Frame Efficiency
- **Trade-Offs:** 2) DL/UL Overlap • 3) User Rate.

Section 2: Solution Comparison

Three Guard-Period Design Methods & Extraordinary Downlink Reuse

Frame Duration and GP Configuration

- **3 Frame Segments:** Downlink (DL) + Guard Period (Idle) + Uplink (UL).
- **GP Decomposition:** $GP_worst = RTT_min (altitude) + \Delta RTT (beam \text{ footprint size})$.
- **Slide 8 Focus:** Eliminate differential delay $\Delta RTT = RTT_max - RTT_min$ across beam.

$$T_{\text{frame}} = T_{\text{DL}} + T_{\text{GP}} + T_{\text{UL}}$$

1) Worst RTT:

- **Sizing:** Max RTT across cell (edge UE):

$$T_{\text{GP}}^{\text{worst}} = \max_i RTT_i$$

DL

Max GP (Idle)

UL

✓ **Zero Overlap:** No DL/UL self-interference.

✗ **Low Efficiency:** Includes full ΔRTT overhead.

- **Standard:** Baseline terrestrial TDD.

2) Adaptive per UE:

- **Sizing:** User-specific GP per RTT:

$$T_{\text{GP}}^i = RTT_i$$

DL

Per-UE GP

UL

• **Reclaims ΔRTT :** Removes beam differential delay.

• **Per-UE TA:** Aligns UL bursts (sat scheduling).

✓ **Zero Overlap:** Cuts GP to RTT_min safely.

3) Minimum RTT:

- **Sizing:** Min RTT (nadir best UE):

$$T_{\text{GP}}^{\text{min}} = \min_i RTT_i$$

DL

Min GP

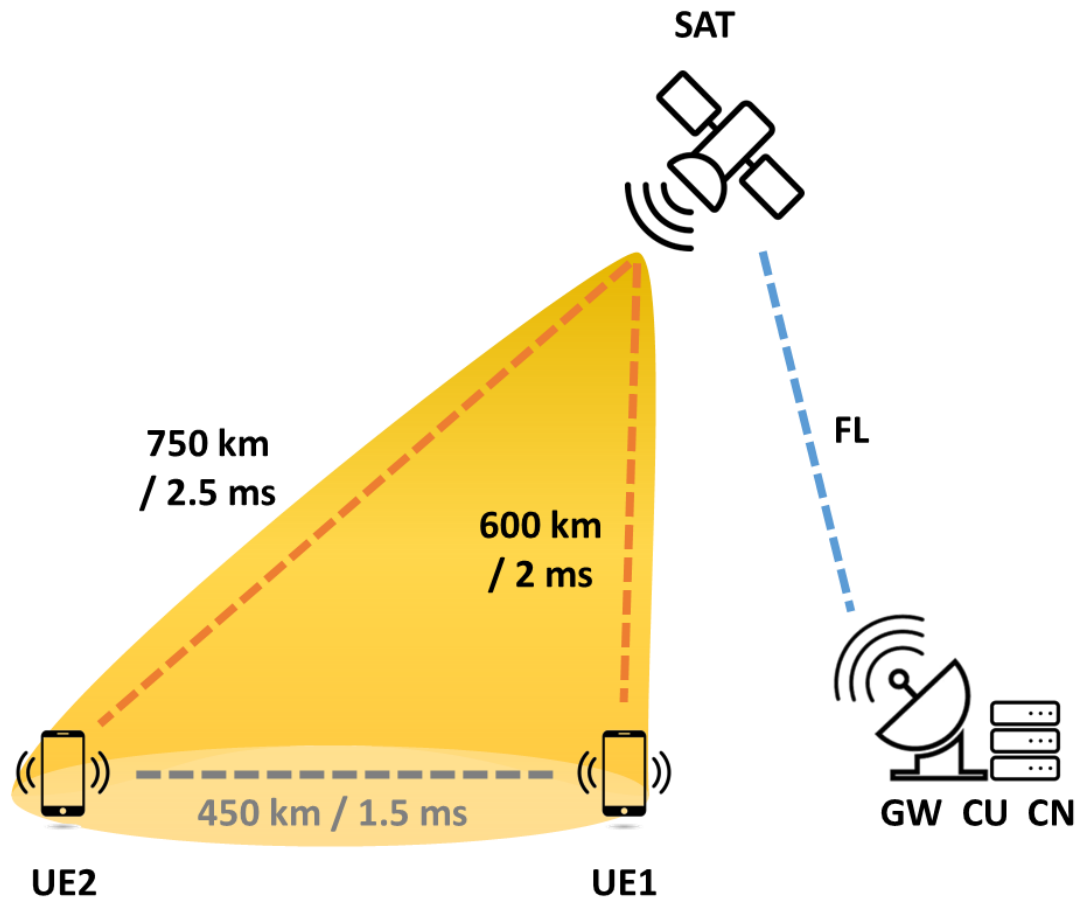
UL (Overlap!)

✓ **Best Efficiency:** Shortest GP (RTT_min).

✗ **Self-Interference:** ΔRTT overlap for edge UEs!

- **Trade-Off:** Efficiency vs. interference.

Example Scenario: Two-UE Differential RTT



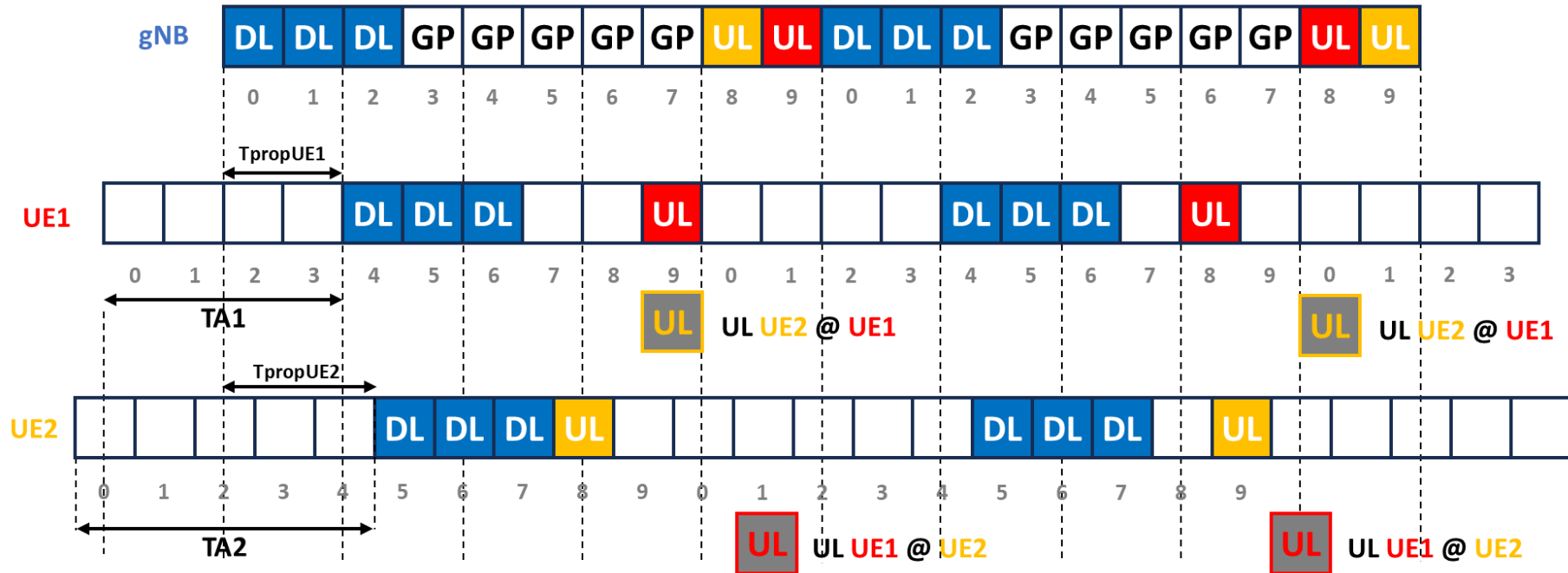
Qualitative Example Parameters (10 ms Frame):

Link / User	Distance / 1-Way	RTT / Timing
Frame / Slot	10 Slots / Frame	$T_{\text{frame}} = 10 \text{ ms}$ (1 ms/slot)
UE1 (Close)	600 km (2.0 ms)	$\text{RTT1} = 4 \text{ ms}$ ($\text{TA1} = 4 \text{ slots}$)
UE2 (Far)	750 km (2.5 ms)	$\text{RTT2} = 5 \text{ ms}$ ($\text{TA2} = 5 \text{ slots}$)
UE1 ↔ UE2	450 km (1.5 ms)	Cross-link delay = 1.5 slots

- **Differential RTT:** $\text{RTT2} - \text{RTT1} = 1 \text{ ms} = 1 \text{ slot}$.
- **xDL Window:** $T_{\text{xDL}} \leq \text{RTT}_{\text{min}} / 2 = 2 \text{ slots}$.
- **4-Step Build:** Worst RTT → Priority UL → xDL → Combined.

Example Chronogram (1/4): Baseline Worst-RTT GP

10 ms Frame (1 ms Slots) • No RTT-based priority scheduling $\Rightarrow$ GP = 5 ms (5 Idle Slots)



■ gNB Schedule (GP = 5 Slots)

0–2: DL • 3–7: Idle GP • 8–9: UL

■ Timing Advance (TA)

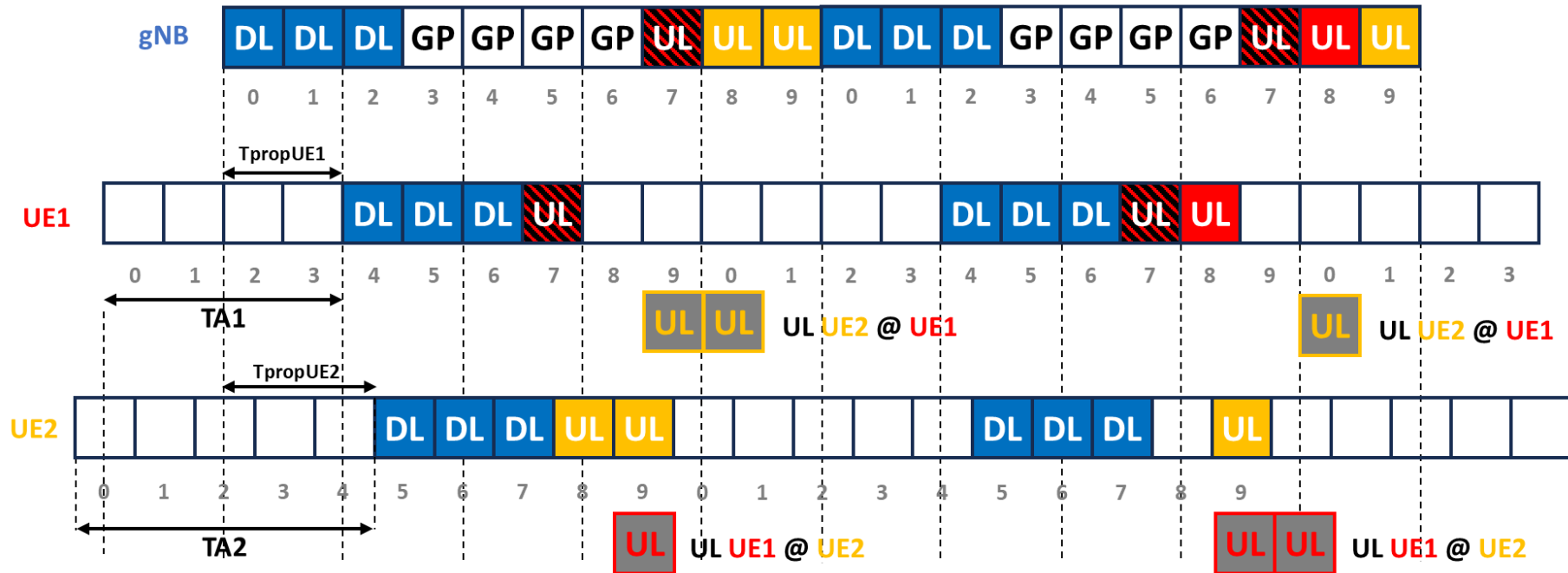
UE1: TA1 = 4 slots • UE2: TA2 = 5 slots

■ Zero Overlap

50% of frame is idle guard overhead

Example Chronogram (2/4): User-Specific GP (Priority UL)

10 ms Frame (1 ms Slots) • RTT-based priority scheduling $\Rightarrow$ GP = 4 ms (Slot #7 Reclaimed)

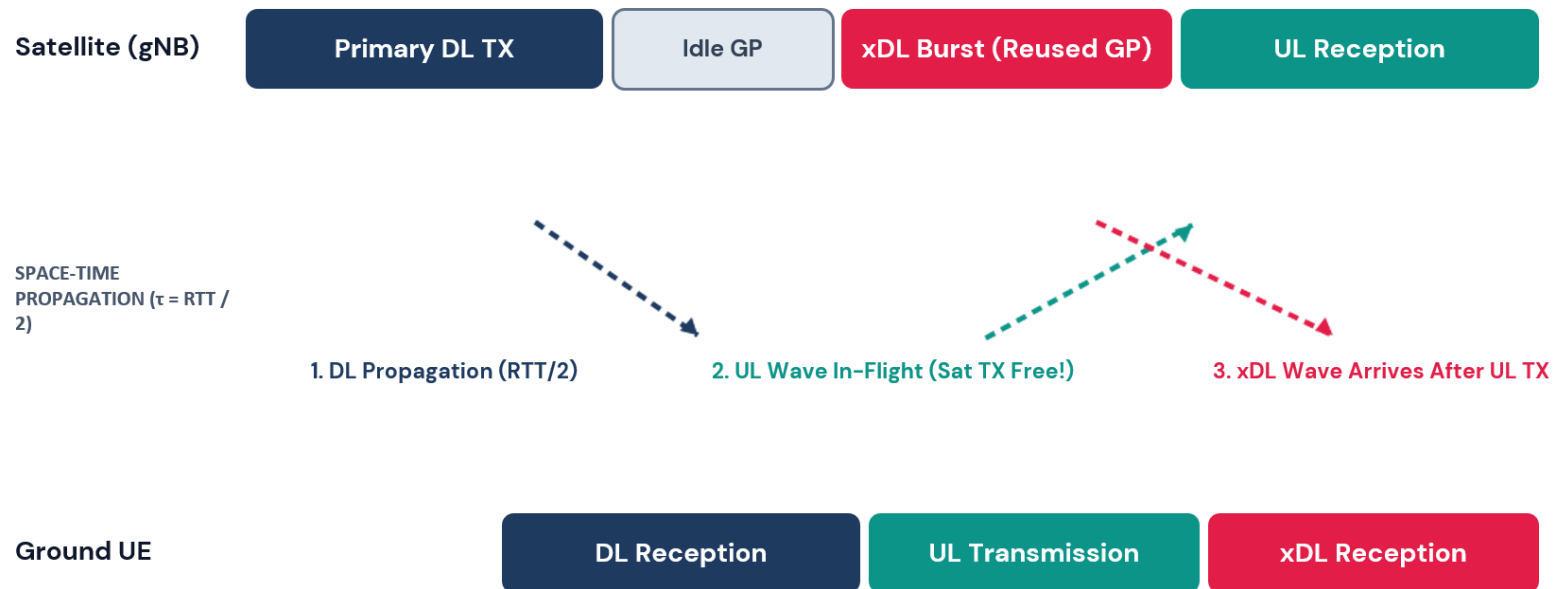


■ **gNB Schedule (GP: 5 $\rightarrow$ 4)**
Slot #7 reclaimed for UL reception

■ **Slot #7 Priority UL**
Allocated only to closer UE1 (RTT1 = 4 ms)

■ **Physical Condition**
Requires $2 \cdot (\tau_{\max} - \tau_{\min}) > T_{\text{slot}}$

Extraordinary Downlink (xDL)



Extraordinary downlink: reusing part of the guard period

- **UE TX In-Flight Window:** Satellite transmits xDL during UL wave propagation.
- **Satellite Self-Interference Avoided:** xDL burst finishes before closest UL arrives.
- **UE Isolation:** xDL arrives after ground UE completes UL TX.
- **Agnostic Pairing:** Operates with Worst-RTT or Adaptive Per-UE GP.

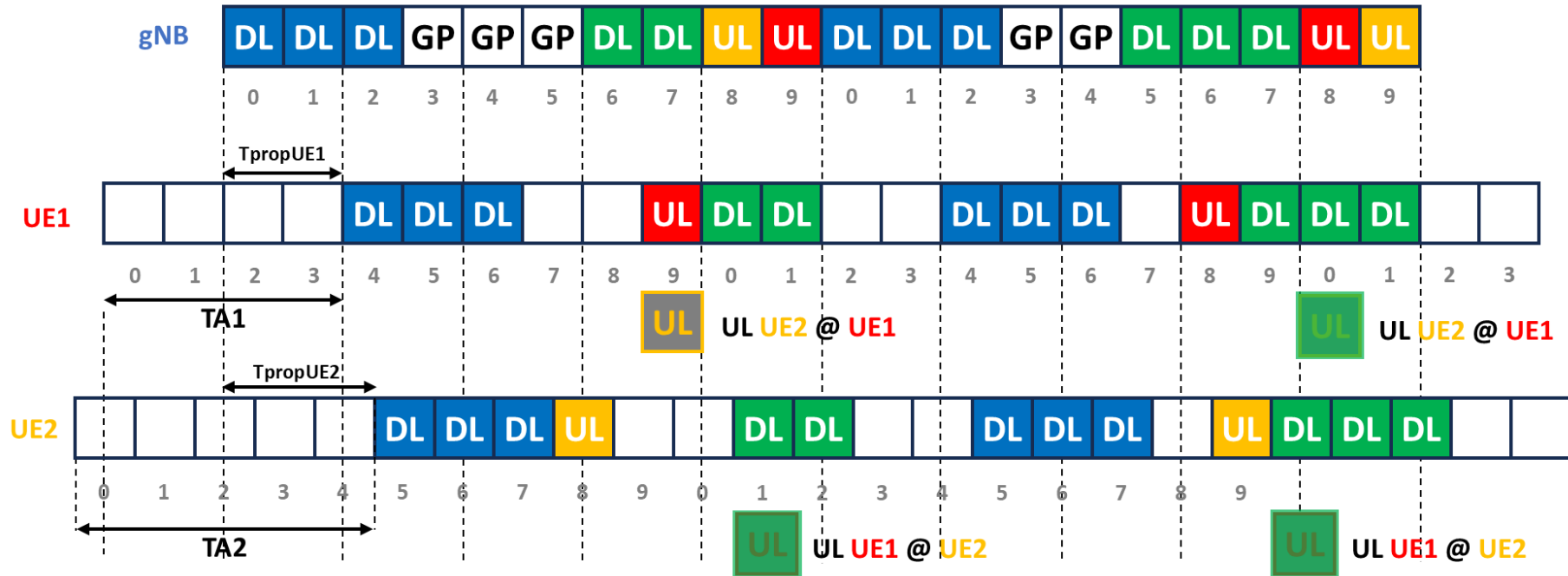
MAXIMUM REUSE WINDOW

$$T_{\text{xDL}} \leq \frac{RTT_{\min}}{2}$$

Bounded by one-way propagation delay of the nadir user.

Example Chronogram (3/4): Worst-RTT GP + xDL

10 ms Frame (1 ms Slots) • No RTT-based priority + Extraordinary DL (xDL)



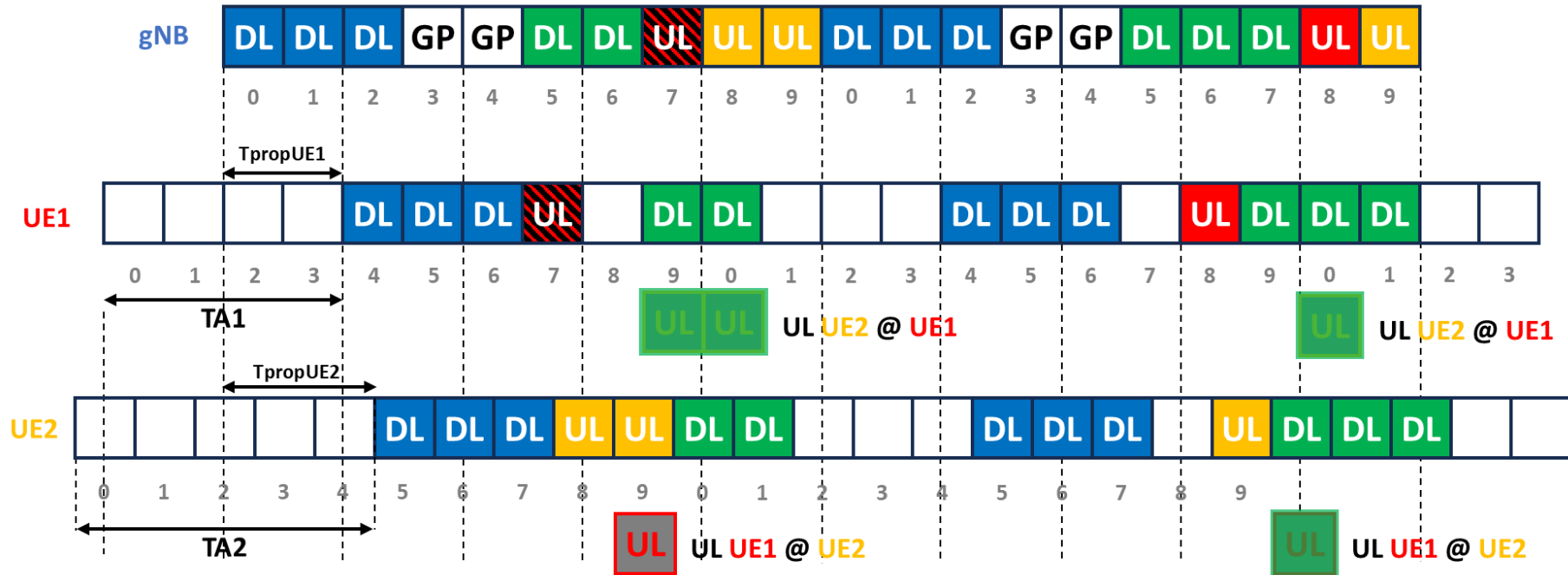
■ **Reclaimed xDL (Green DL)**
Trailing GP slots (5–7) carry extra DL

■ **Zero Self-Interference**
UEs receive xDL after finishing UL TX

■ **Cross-Link Condition**
Requires limited UE-to-UE interference

Example Chronogram (4/4): User-Specific Guard + xDL

Figure 2: **RTT-based priority scheduling + Extraordinary DL (xDL) ⇒ Only 2 Idle GP Slots!**



■ gNB Schedule (GP: 5 → 2)

0–2: DL • 3–4: GP • 5–6: xDL • 7–9: UL

■ Slot #7 Priority UL

Allocated only to UE1 (RTT-based priority)

■ Extraordinary DL (xDL)

Allocated if UE-to-UE interference is limited

Section 3: System Model & Simulation Setup

Network Geometry, Communication Model & Simulation Parameters

System Scenario

1. User Slant Range & Elevation Angle ($u \in U$)

- Terrestrial users distributed across satellite footprint at altitude h :

$$d_u^{\text{slant}} = \sqrt{x_u^2 + y_u^2 + h^2}, \quad \theta_u = \arcsin\left(\frac{h}{d_u^{\text{slant}}}\right)$$

2. Beam Coverage Footprint Radius (R_{cov})

- Earth-central angle α set by altitude h and minimum elevation θ_{min} :

$$R_{\text{cov}} = R_E \alpha, \quad \alpha = \arccos\left(\frac{R_E}{R_E + h} \cos \theta_{\text{min}}\right) - \theta_{\text{min}}$$

3. Two-Way Propagation Round-Trip Time (RTT)

$$\text{RTT}(d) = \frac{2d}{c}$$

- Nadir UE (90°): Shortest distance $\rightarrow$ RTT_min**
- Edge UE (θ_{min}): Longest distance $\rightarrow$ RTT_max**

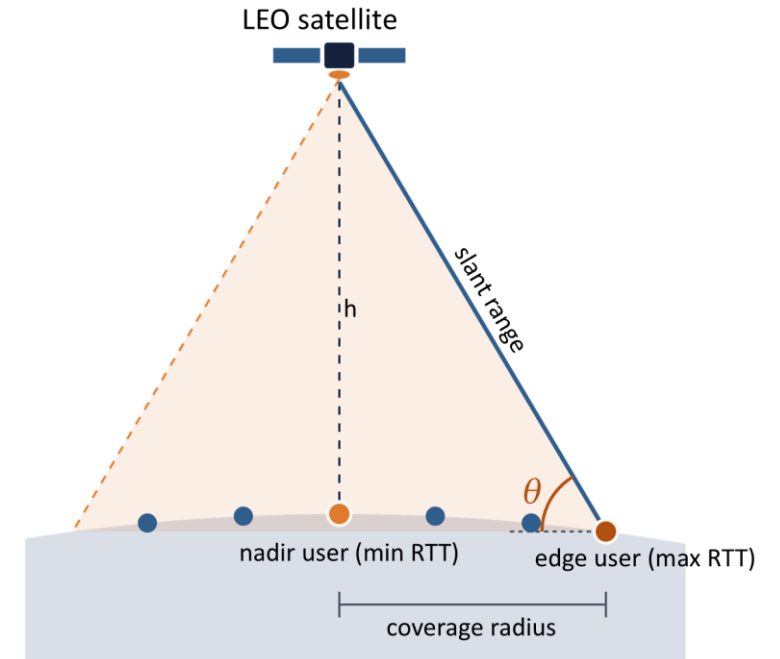


Figure 1: The considered network model.

Communication Model

■ Antenna Characteristics (ITU-R S.672)

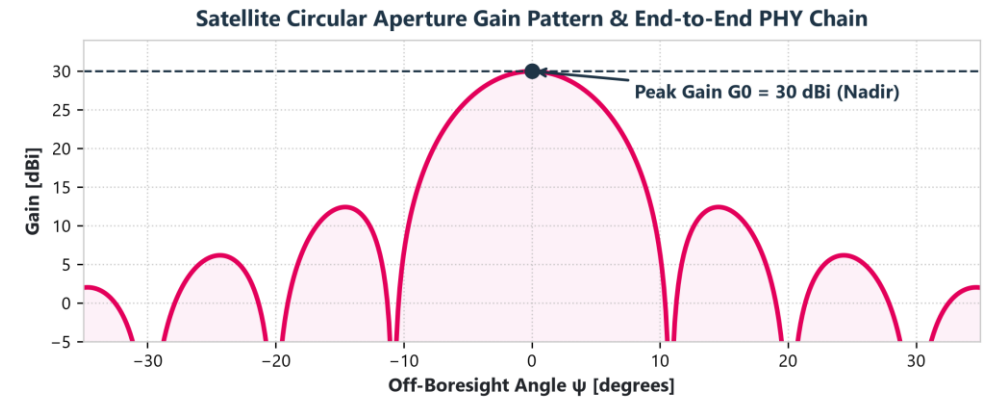
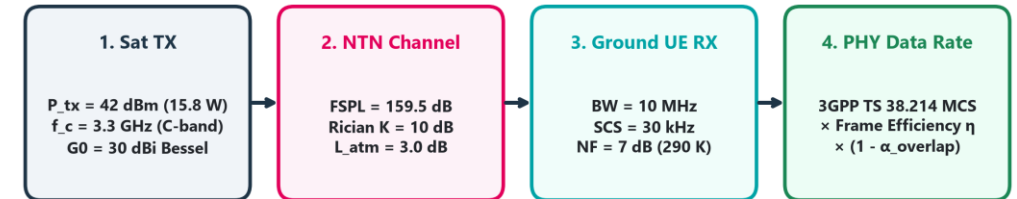
- **Circular Aperture:** 30 dBi peak gain, 42 dBm Sat TX power.
- **Radiation Pattern:** Bessel-function off-boresight roll-off.

■ Channel Model (C-band, 600 km)

- **Free-Space Path Loss:** 159.5 dB (at 600 km, 3.3–3.75 GHz).
- **Atmospheric Loss:** Up to 3.0 dB total aggregated losses.
- **Small-Scale Fading:** Rician distribution ($K = 10$ dB).

■ Link Budget & Net PHY Rate

- **Receiver Config:** UE NF = 7 dB, 10 MHz BW (SCS 30 kHz).
- **Per-User SNR:** Gain + FSPL + atmospheric loss + fading.
- **Net PHY Data Rate:** 3GPP MCS $\times \eta_{\text{frame}} \times (1 - \alpha_{\text{overlap}})$.



Network Configuration and Parameters

1. User Placement in Coverage Footprint (10 UEs):

Best User (Beam Center)

- **Nadir (90°):** Shortest distance.
- **Role:** Min RTT → Upper performance bound.

Worst User (Cell Edge)

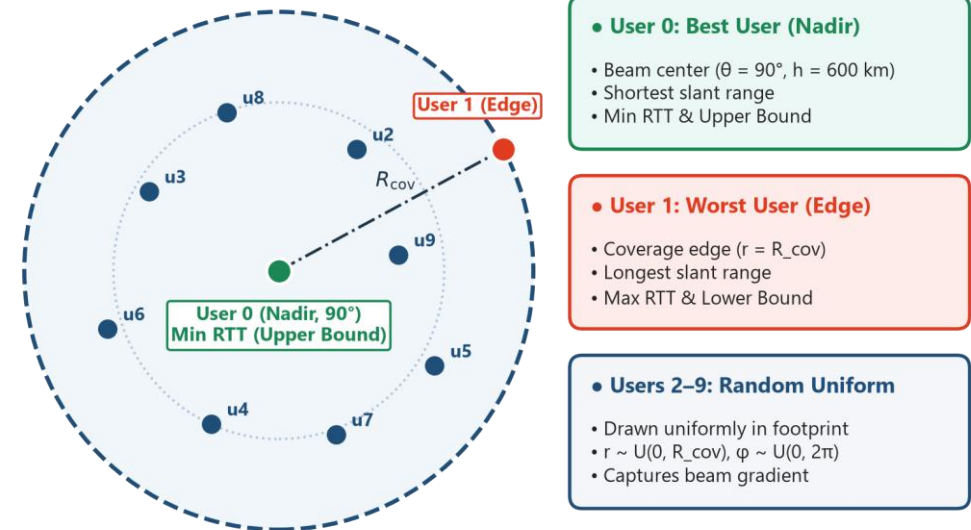
- **Coverage Edge:** Longest distance.
- **Role:** Max RTT → Lower performance bound.

- **Users 2–9 (Random Uniform):** 8 UEs drawn uniformly across footprint.

2. Five Evaluated Frame Durations:

- **Standard 10 ms:** Baseline 3GPP 5G NR terrestrial frame.
- **Extended 20, 30, 40 ms:** Frame aggregation to amortize NTN GP.
- **Ultra-Long 182 ms:** Reaches >97% terrestrial-like efficiency.

10-User Beam Footprint & Evaluated Frames



5 Evaluated TDD Frame Durations (DL : UL Ratio = 70 : 30)



Section 4: Performance Evaluation

Numerical Results and Comparison

Performance Evaluation: Frame Efficiency

Frame efficiency:

$$\eta_{\text{frame}} = \frac{T_{\text{DL}} + T_{\text{UL}}}{T_{\text{frame}}} = 1 - \frac{T_{\text{GP}}}{T_{\text{frame}}} \rightarrow \text{Useful DL + UL payload fraction}$$

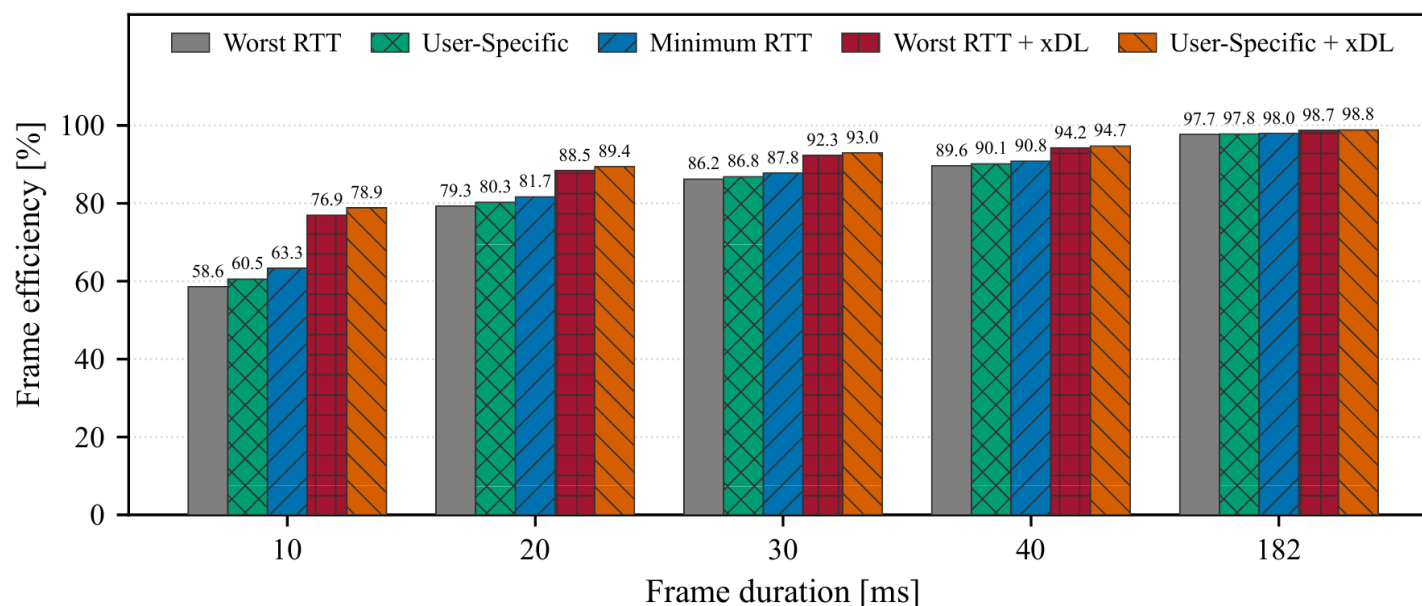


Figure 3: Frame efficiency across GP sizing methods and frame durations.

■ Frame Aggregation

Longer frames amortize fixed GP overhead.

■ Baseline Ranking (10 ms)

Worst (58.6%) < User-Spec. (60.5%) < Min (63.3%).

■ Major xDL Gain (10 ms)

Boosts Worst → 76.9% & User-Spec. → 78.9%.

■ 182 ms Convergence

All methods reach 97.7–98.8% (high latency).

Performance Evaluation: Overlap Time and Fraction (only for min RTT)

Overlap Time and Fraction:

$$T_{\text{overlap}}^u = \min\{\max(\text{RTT}_u - T_{\text{GP}}, 0), T_{\text{DL}}\}$$

$$\alpha_{\text{overlap}}^{\text{DL}}(u) = \frac{T_{\text{overlap}}^u}{T_{\text{DL}}}, \quad \alpha_{\text{overlap}}^{\text{UL}}(u) = \frac{T_{\text{overlap}}^u}{T_{\text{UL}}}$$

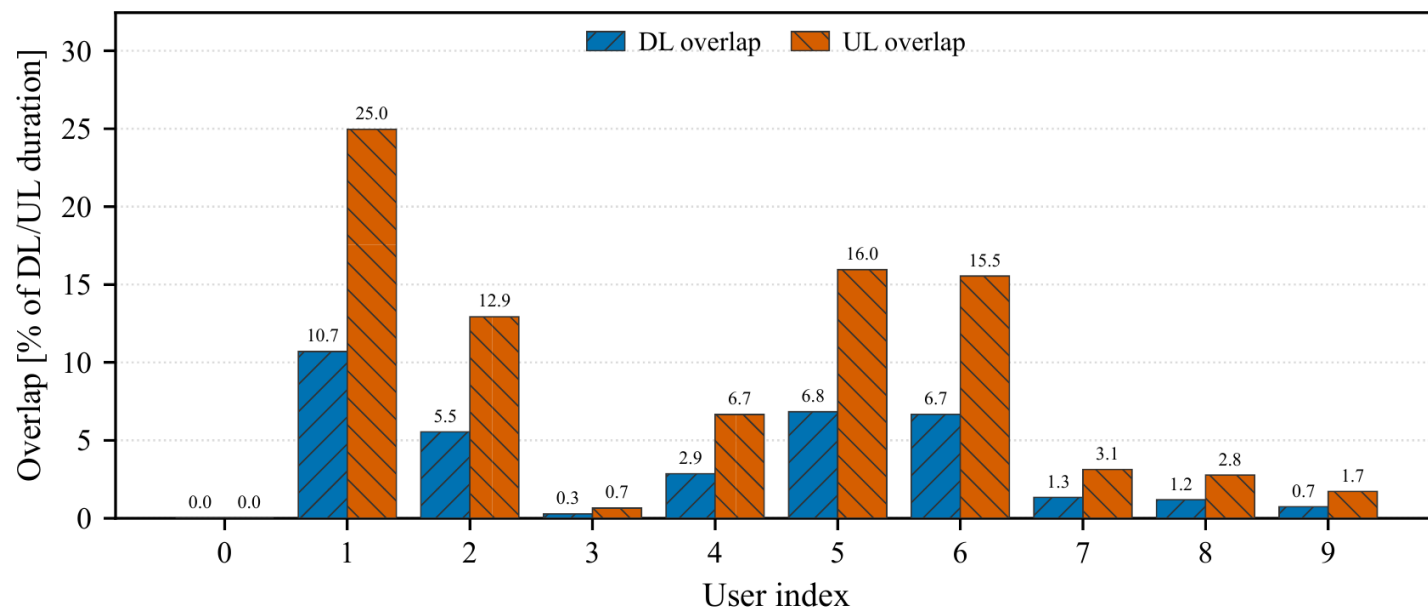


Figure 4: Per-user DL/UL overlap duration and percentage at 10 ms (Minimum RTT).

■ User 0 (Nadir)

0% overlap — GP matches its exact RTT.

■ User 1 (Coverage Edge)

Severe collision: 10.7% DL & 25.0% UL lost!

■ Why UL % > DL %

Same overlap duration hits shorter 30% UL window.

■ Users 2–9 (Random)

Overlap scales monotonically with slant range.

Performance Evaluation: Average User Data Rate

Data Rate:

$$R_u = N_{RB}^u B_{RB} SE_{MCS}^u \eta_{frame} (1 - \alpha_{overlap}(u))$$

Combines Efficiency η_{frame} (Fig. 3)
× Non-Overlapped Fraction (Fig. 4)

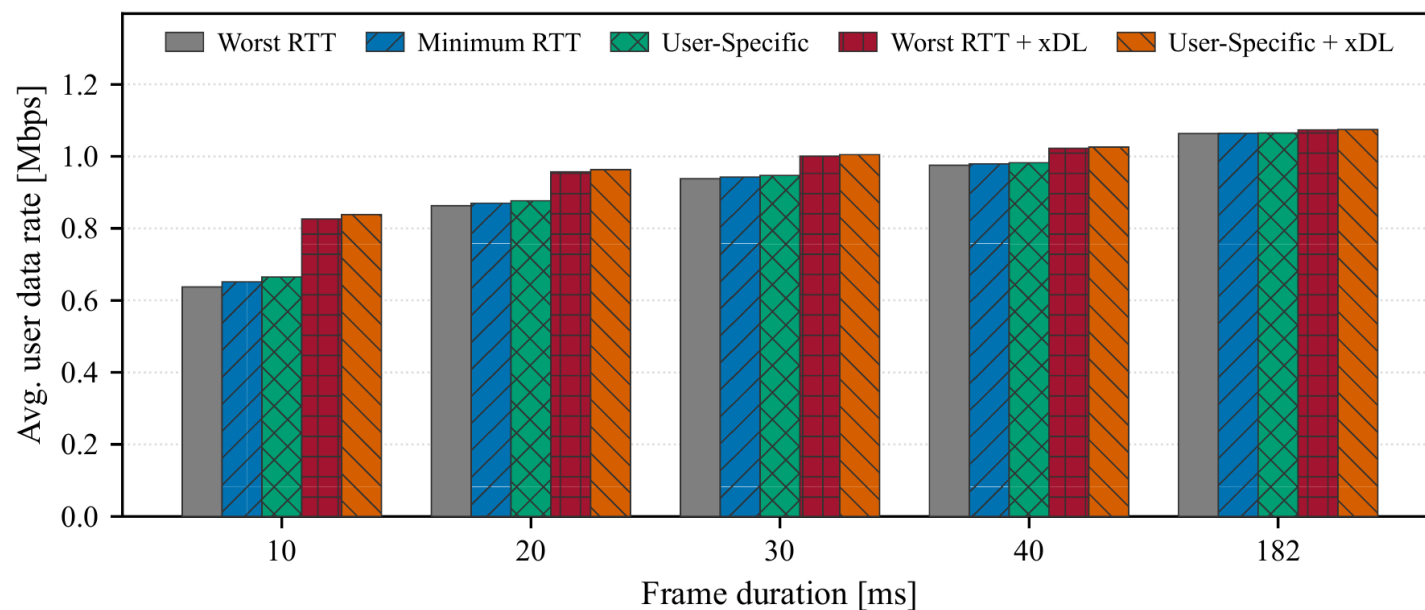


Figure 5: Average user data rate (combined DL and UL) across GP sizing methods.

Overall Winner

User-Specific GP + xDL achieves highest rate.

User-Spec. > Min RTT

Avoids $(1 - \alpha_{overlap})$ self-interference penalty.

Short-Frame Boost

xDL yields largest rate gain at 10–40 ms.

3GPP NR Link Mapping

$B_{RB} = 12 \times 30 \text{ kHz} = 360 \text{ kHz}$; 3GPP MCS.

Section 5: Conclusion

Summary, Main Findings, Future Work & Acknowledgments

Summary, Main Findings & Future Work

1. LEO TDD Challenge

Dynamic UL/DL split vs. long LEO RTT (4–8 ms) & Doppler.



2. Proposed Solutions

3 GP sizing rules + Extraordinary Downlink (xDL) reuse.



3. Multi-Frame Study

Evaluated across 10–182 ms frames (Efficiency, Overlap, Rate).

★ Best Overall Strategy

- **Winner:** Per-user GP + xDL.
- **Benefit:** Highest user data rate & zero DL/UL overlap.

▲ 10 ms xDL Efficiency Gain

- **Worst RTT:** 58.6% → 76.9% (+18.3%).
- **User-Specific:** 60.5% → 78.9% (+18.4%).

🕒 Frame Aggregation Trade-Off

- **182 ms Frame:** Reaches 97.7–98.8% efficiency.
- **Cost:** Proportionally higher switching latency.

Future Work:

- **Inter-UE Cross-Link Interference (CLI):** Account for mutual UE-to-UE interference during simultaneous xDL reception and UL transmission.
- **Extraordinary Uplink (xUL):** Reclaim the remaining RTT_{min} / 2 guard (Slots 3–4) by scheduling xUL with controlled CLI.
- **Towards >90% Efficiency in LEO TDD:** Address synchronization / Timing Advance (TA) errors in standard frames.

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OQ TECHNOLOGY

OQ Technology SARL

Industrial & Satellite Prime
5G NTN LEO Operator



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Interdisciplinary Centre
for Security, Reliability
and Trust

Contact



Dr. Jorge Querol

Research Scientist, SIGCOM Research Group

jorge.querol@uni.lu | jorge.querol.org | 6gspacelab.uni.lu

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