S5LECT

SatCom & 5G Link,
Edge & CybersecuriTy

Funded by the European Union

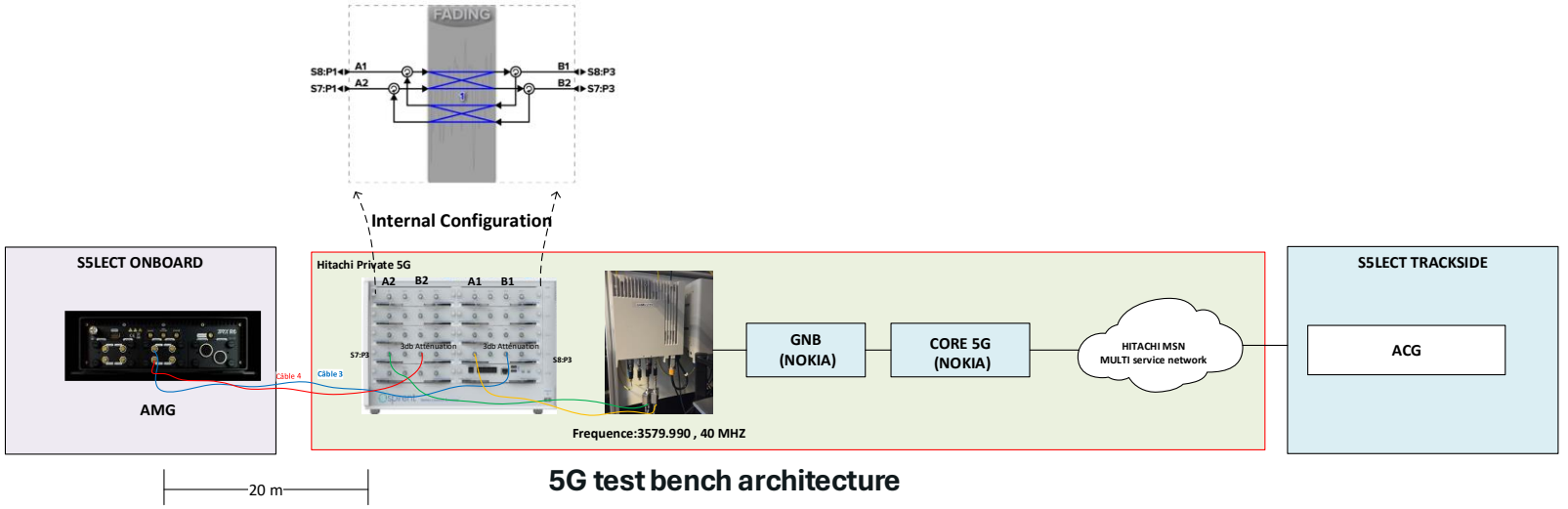
Laboratory Test Results

Christophe

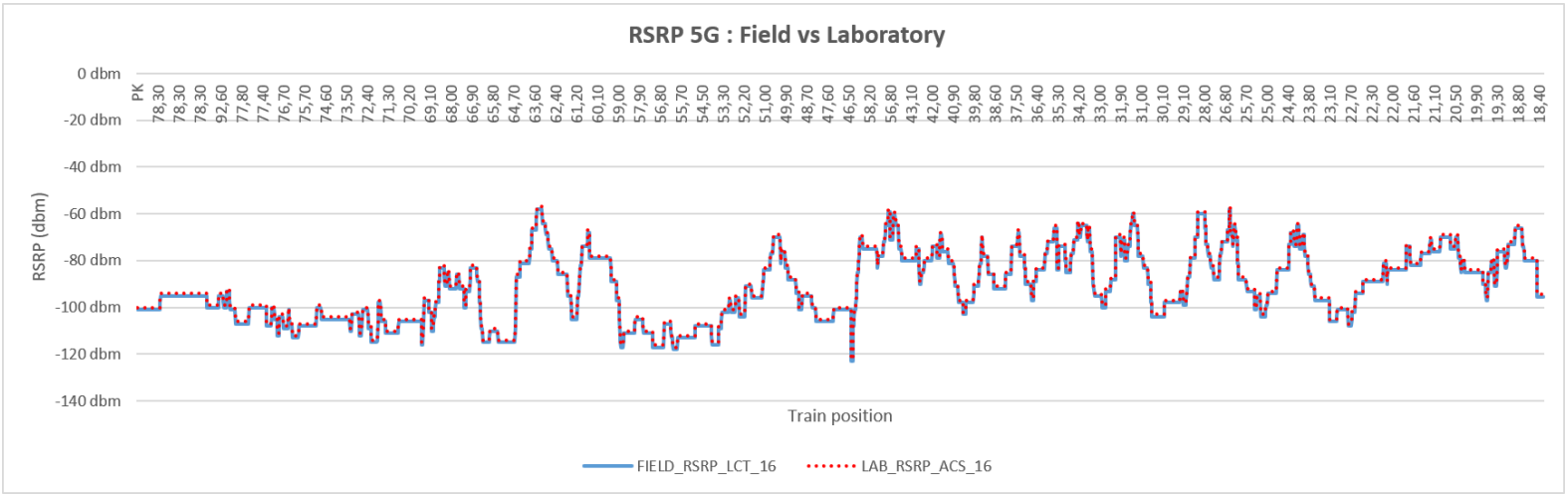
Agenda

1. **5G**
   Test bench and field vs laboratory results
2. **SATCOM**
   Test bench, scenarios V1 / V2 and results
3. **Automatic hybridisation**
   Handover behaviour vs LQI tuning
4. **Geographic hybridisation**
   Zone-based, anticipatory switching
5. **Summary of Tests Performed**
   Conclusion

5G Test Bench - Reproducing Field Radio Conditions in the Lab



5G test bench architecture



How the bench works

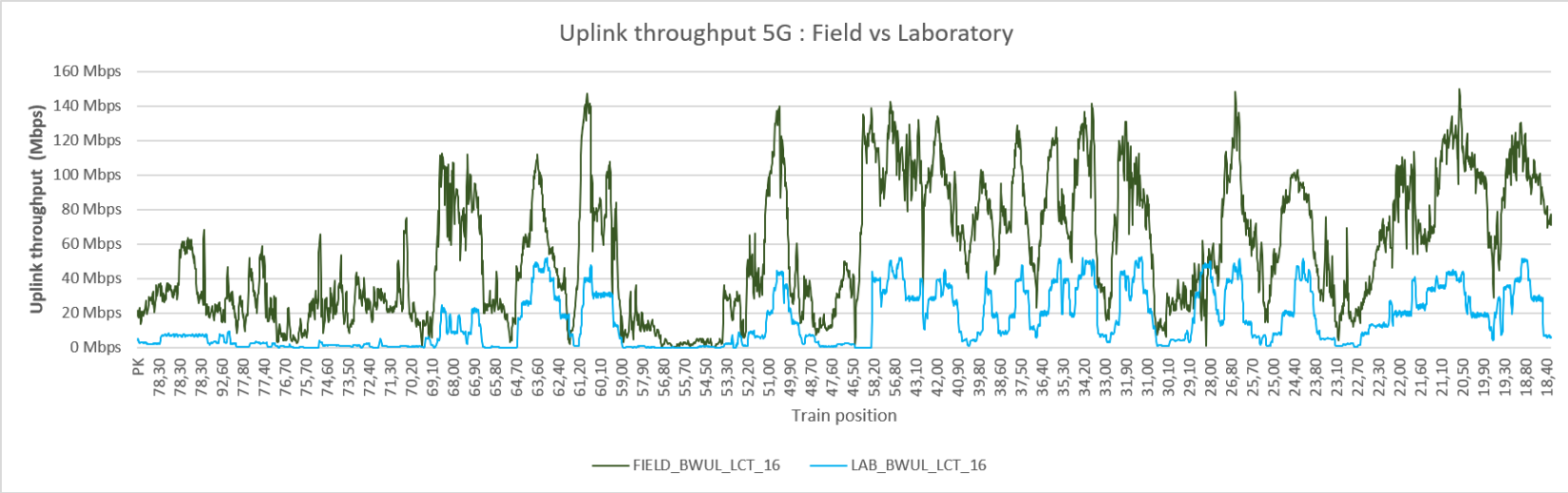
- Viavi Vertex 5G channel emulator is inserted on the radio link to manipulate radio conditions
- Radio conditions as measured in the field (RSRP, Train Velocity) are applied in the lab



Conclusion: lab RSRP follows the field RSRP profile along the route

5G - Field Dynamics Reproduced in the Lab

5G uplink throughput – field vs laboratory (test run of 16 September 2025)



Conclusion: the lab faithfully reproduces field dynamics, at a lower performance level and with radio-modelling limits

Faithful dynamics

Throughput rises, drops and plateaus occur in the same track sections as in real conditions

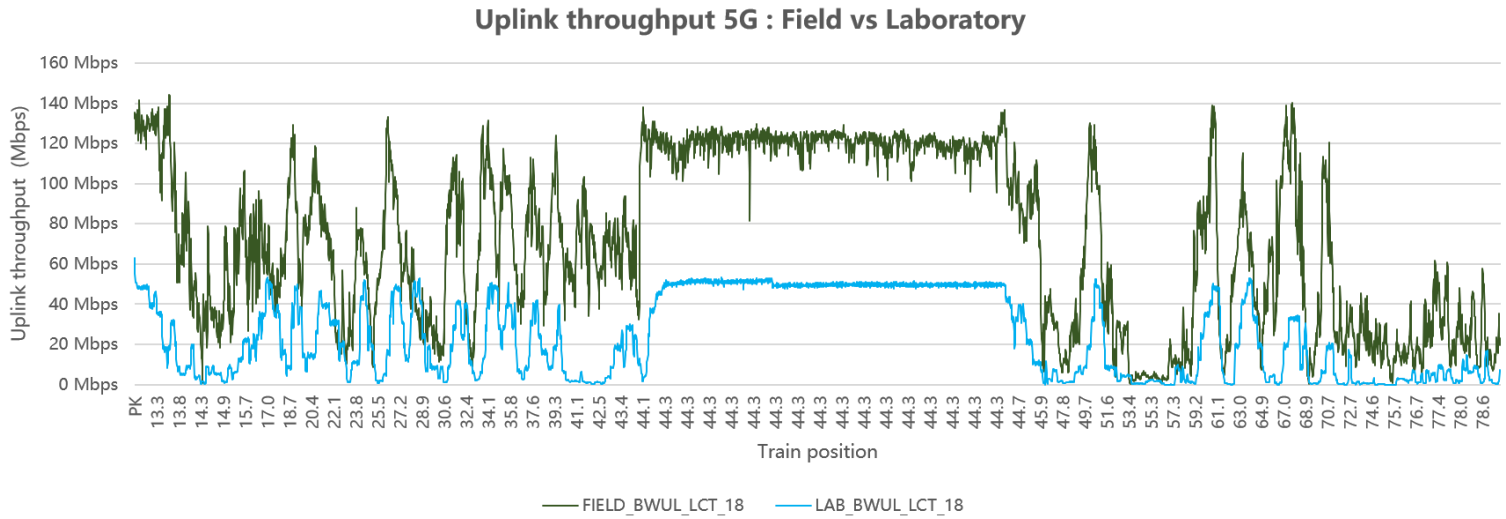
Level gap explained

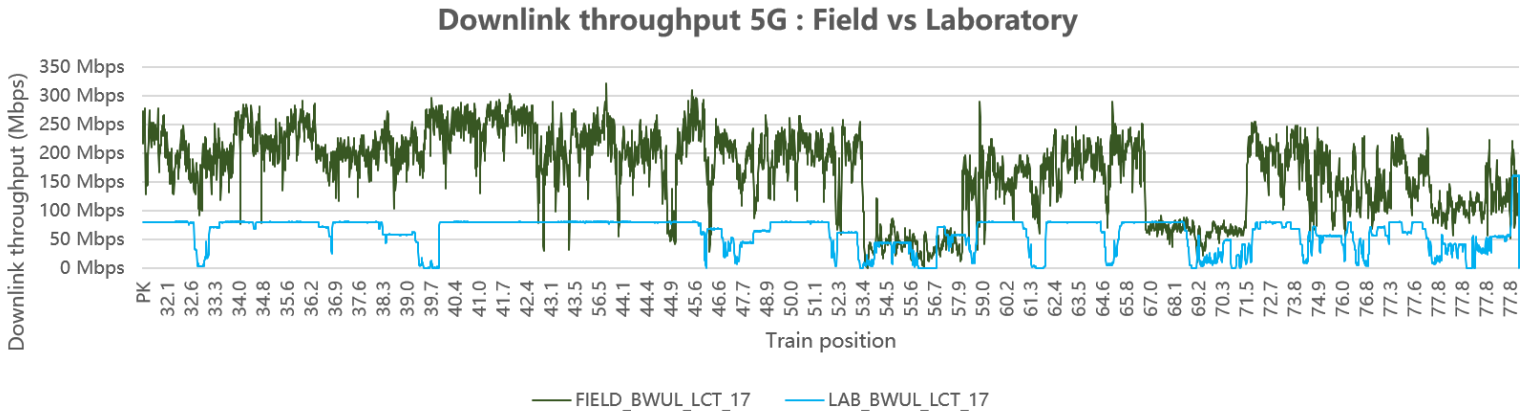
Peak throughput ≈ 120 Mbit/s in the field vs ≈ 55 Mbit/s in the lab

1. **Wider bandwidth in the field**
   ≈ 90 MHz (public network) vs 40 MHz (lab), 2.25× wider
2. **Different TDD configuration**
   Uplink/downlink split differs between the live network and the test bench

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5G - Same Behaviour on Different Runs (UL & DL)





What we observe

Uplink - run of 18 Sept. 2025

Lab curve follows the field rises and drops, peaks lower in the lab

Downlink - run of 17 Sept. 2025

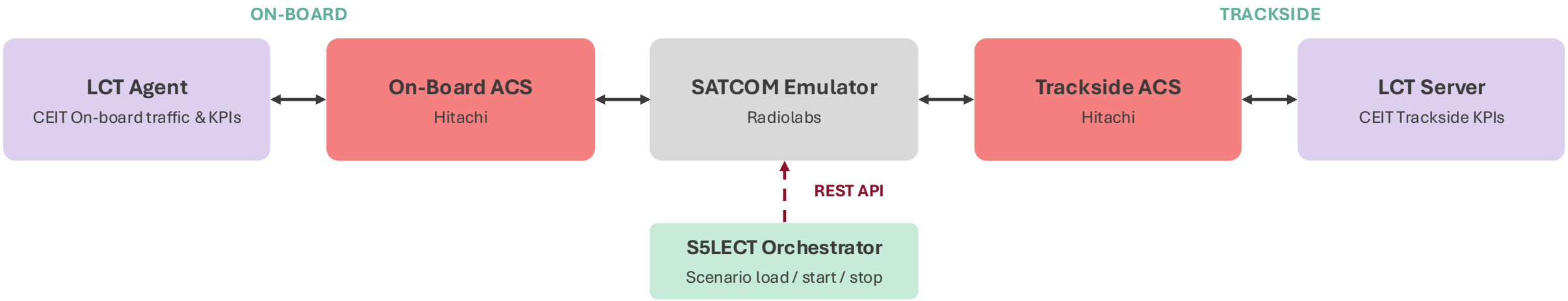
Same behaviour: dynamics reproduced, absolute level lower in the lab

Reason

Narrower lab bandwidth (40 vs ≈ 90 MHz) and different TDD split

Conclusion: every 5G run shows the same behaviour

SATCOM Test Bench: IP-Level Link Emulation



What is emulated

Throughput, latency and losses of the satellite link, replayed from the field data acquisition (train route)

Scenario V1

First version prepared for the initial lab tests: correct nominal level, link too smooth

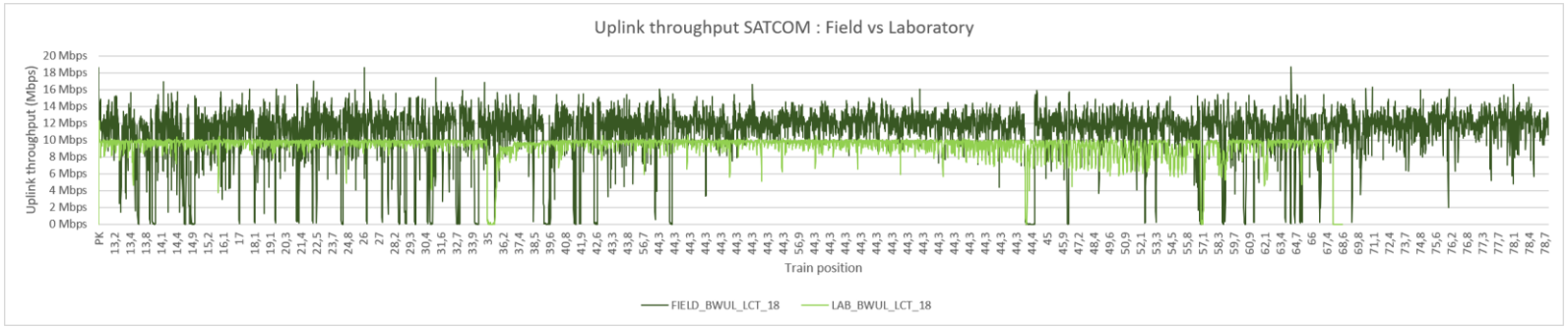
Scenario V2

Second version delivered with modifications: field drops and outages reproduced

Conclusion: IP-level emulation replays field SATCOM conditions in a reproducible way, the V1 and V2 scenarios are the reference for the following tests

SATCOM V1: Nominal Level OK, Link Too Smooth

SATCOM Uplink – field vs lab, V1 scenario (run of 18 Sept. 2025)



Nominal level reproduced

Lab throughput mostly 35–45 Mbit/s, close to field levels (45–55 Mbit/s)

More stable behaviour

In the field, throughput sometimes drops close to 0 (real outages). In the lab these deep fades are less marked: the emulator smooths the link

Why this difference?

1 IP-level emulator

Reproduces the main link characteristics, not every physical phenomenon of a real satellite network

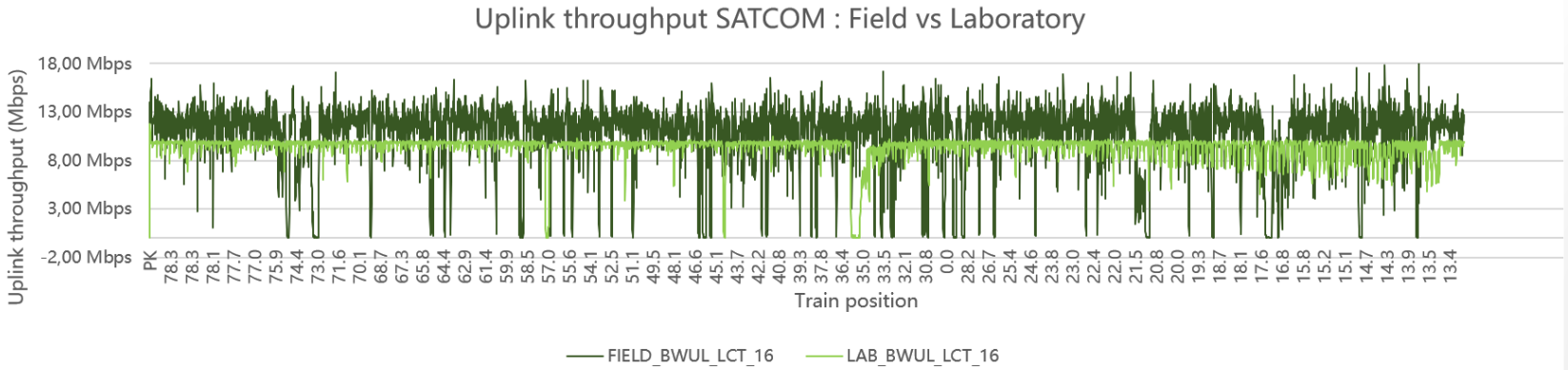
2 Field events hard to replicate

Obstacles, satellite changes and propagation variations are not reproduced exactly

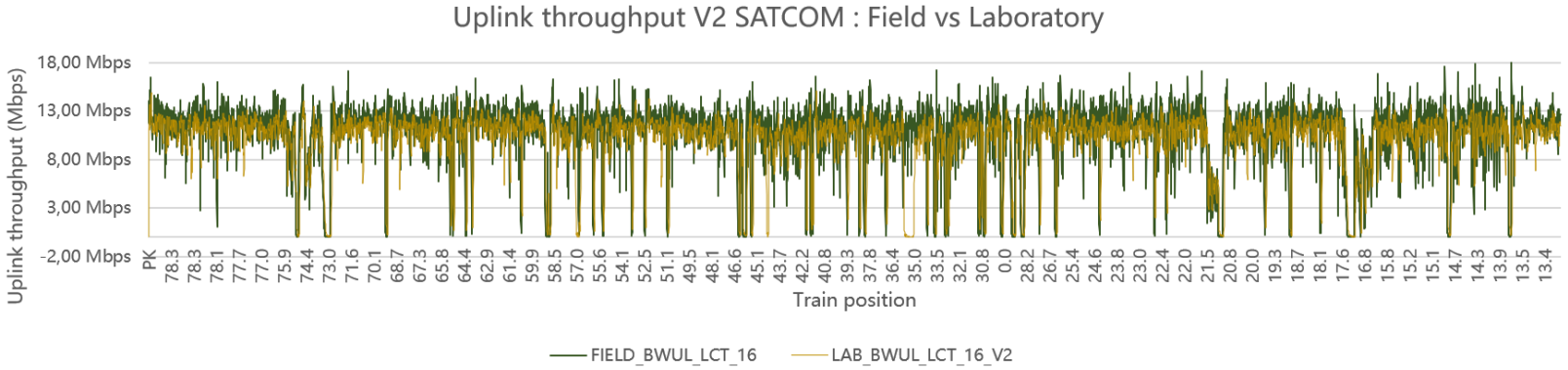
Conclusion: the V1 scenario reproduces the nominal level but is more stable than the field-corrected by the V2 scenario (next slides)

SATCOM V2 Scenario Matches Field Uplink

V1 scenario



V2 scenario



Two emulator scenarios

V1 - first version

Initial scenario prepared for the first lab tests. Nominal level correct, but the link is too smooth: field drops are not reproduced

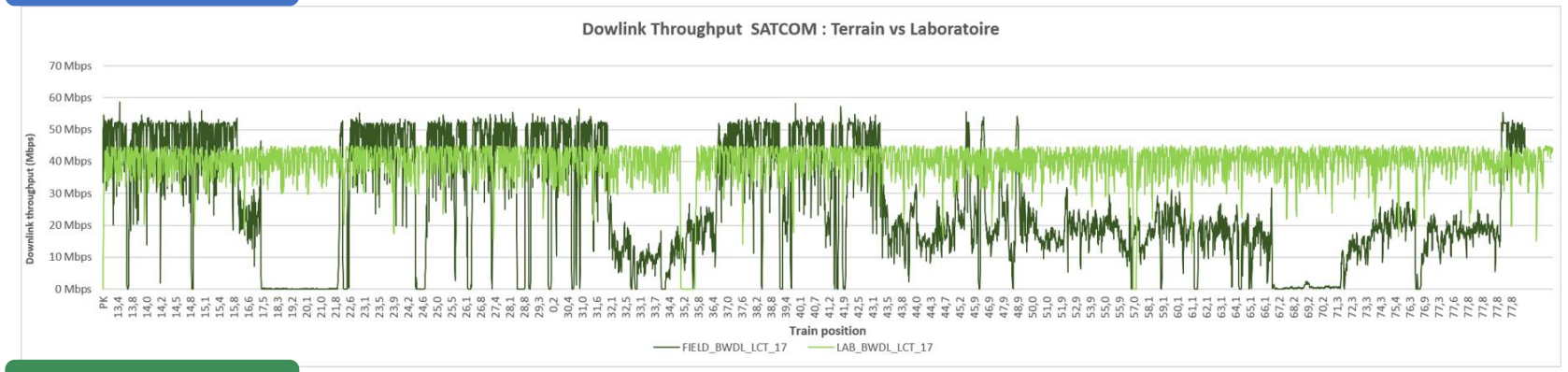
V2 - second version

Delivered with modifications to the scenario. The lab now reproduces the field drops and variations

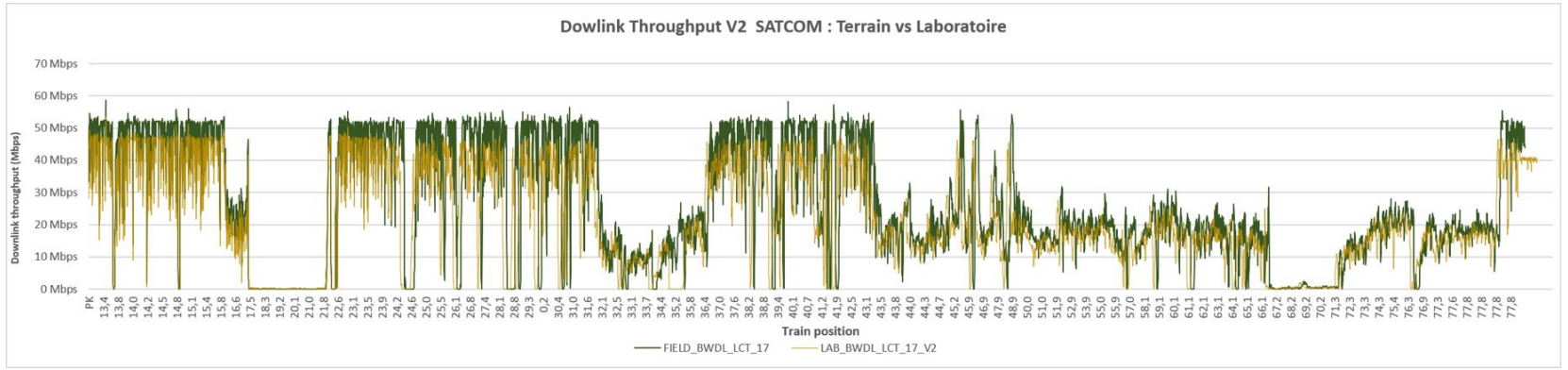
Conclusion: with V2, lab and field uplink curves match

SATCOM V2 Scenario Matches Field Downlink

V1 scenario



V2 scenario



Same observation on downlink

V1 - first version

Lab throughput stays flat around 40 Mbit/s, field outages and low-throughput sections are missing

V2 - second version

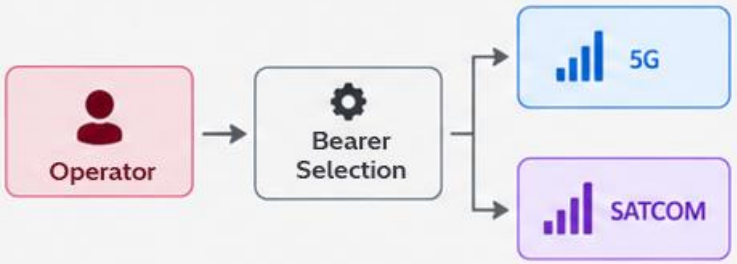
Lab follows the field profile, including outages to 0 and the 20 Mbit/s sections

Conclusion: with V2, lab and field downlink curves match

Multi-Bearer Hybridization: Three Modes

Manual

Direct selection of the bearer by the operator through the control interface. Used for testing and validation of the execution chain.



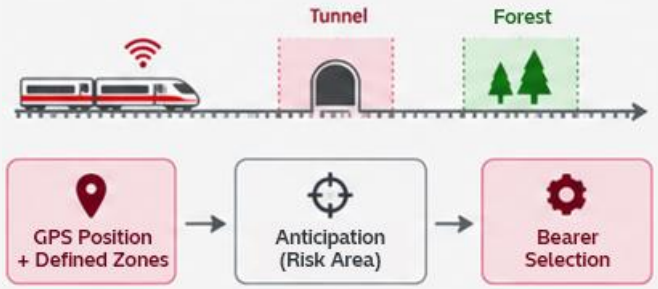
Automatic

Continuous analysis of bearer quality based on **LQI (Link Quality Indicator)**, followed by automatic switching to the most efficient link.



Geographical

Decision-making is based on GPS position and predefined geographical zones. Switching can be anticipated before entering a risk area.

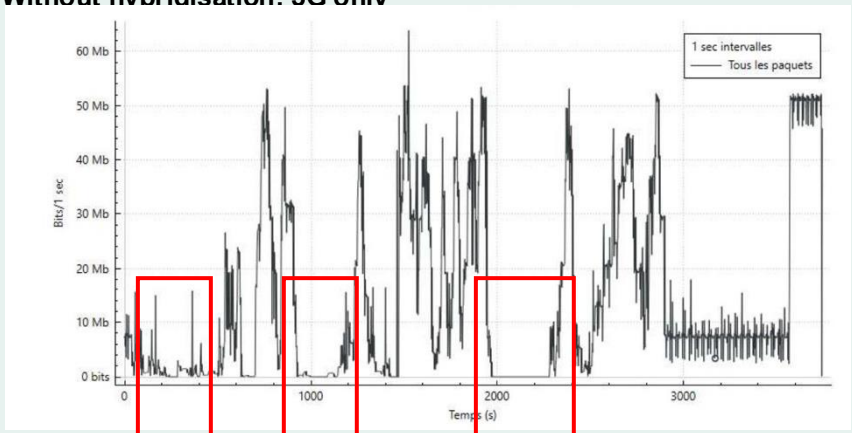


Automatic Hybridisation: LQI Tuning

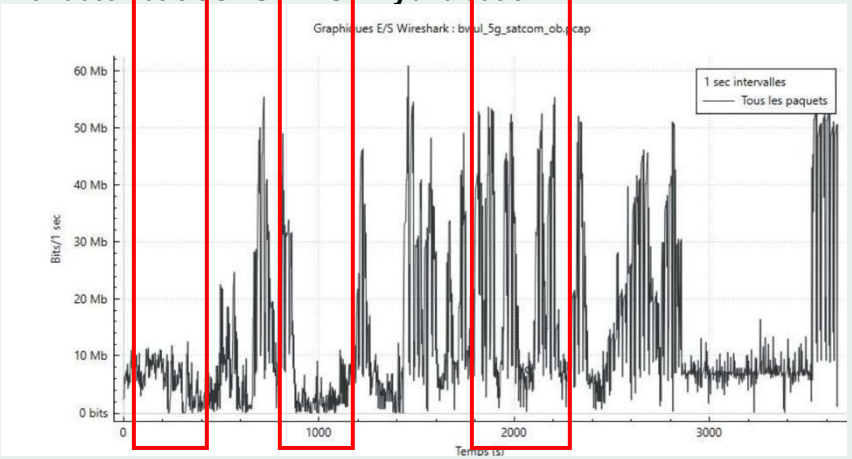


Application throughput with and without automatic hybridisation

Without hybridisation: 5G only



With automatic 5G / SATCOM hybridisation



Number of handovers vs LQI tuning reactivity

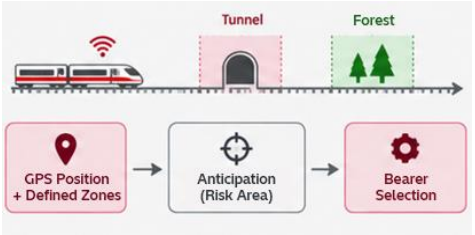
Conservative tuning	Intermediate tuning	Aggressive tuning
52 handovers	**100 handovers**	**250 handovers**
Few switches: stability first, slower reaction	Good balance between stability and reactivity	Aggressive scoring: maximum reactivity

Red frames: 5G coverage gaps along the route. Without hybridisation the throughput drops to zero,with automatic hybridisation traffic continues over SATCOM

Conclusion: LQI algorithm tuning must match each application's requirements to balance reactivity, stability and service continuity

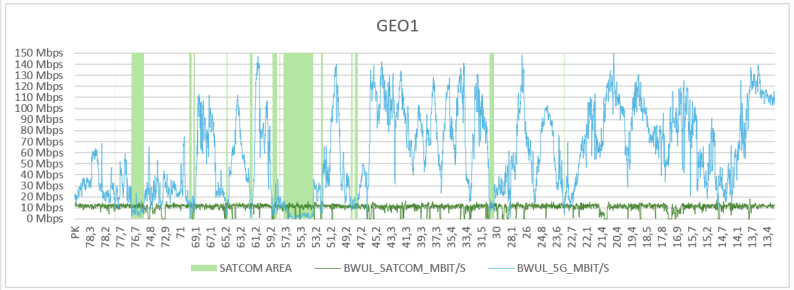
Geographic Hybridisation: Anticipation

blue: 5G throughput
green: SATCOM throughput
shaded bands: track sections assigned to SATCOM



SATCOM zones defined with three methods : GEO-01, GEO-01,GEO-03

GEO-01

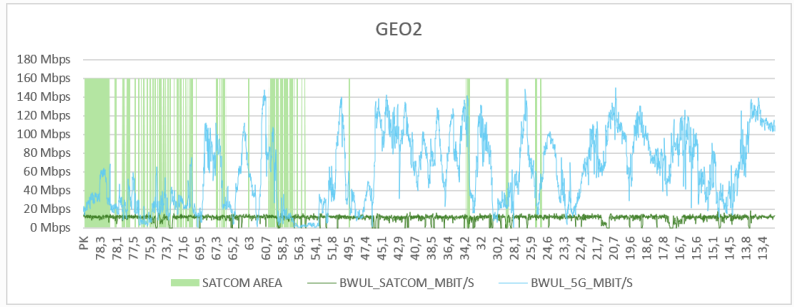


Throughput criterion

Direct 5G / SATCOM throughput comparison

Selection based on comparative observation of both links

GEO-02

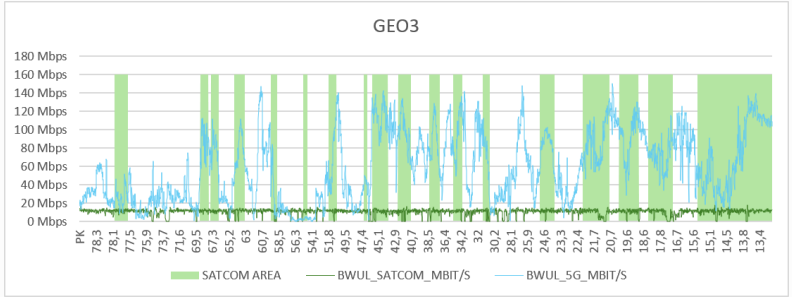


Latency criterion

Compliance with application KPIs

Zones defined from the requirements of the target services

GEO-03



Track route criterion

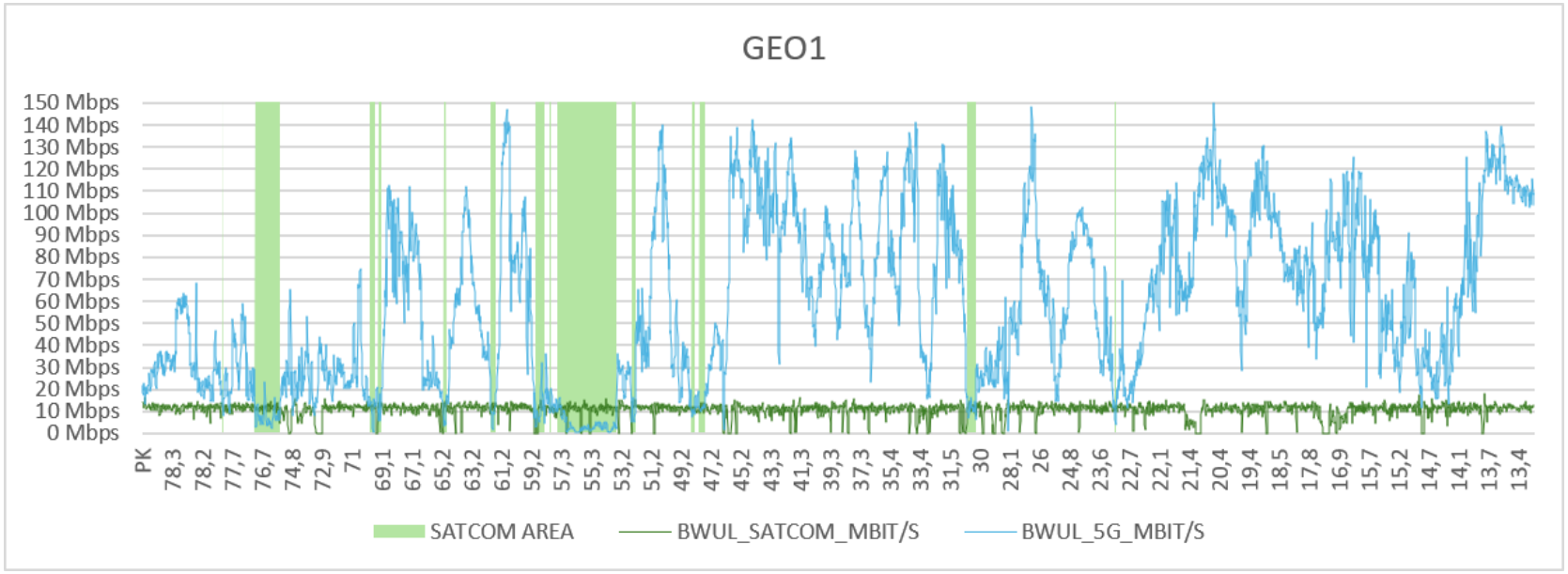
Geographic features (stations, viaducts)

Zones built from the specific characteristics of the route

Conclusion: The idea was to test different approaches to test their limits

GEO-01: Throughput Criterion

Geographic hybridisation - SATCOM zones from a direct comparison of measured 5G and SATCOM throughput



SATCOM zones

5G uplink throughput

SATCOM uplink throughput

How zones are defined

Each track section goes to SATCOM where the measured 5G throughput falls below the SATCOM throughput.

What we observe

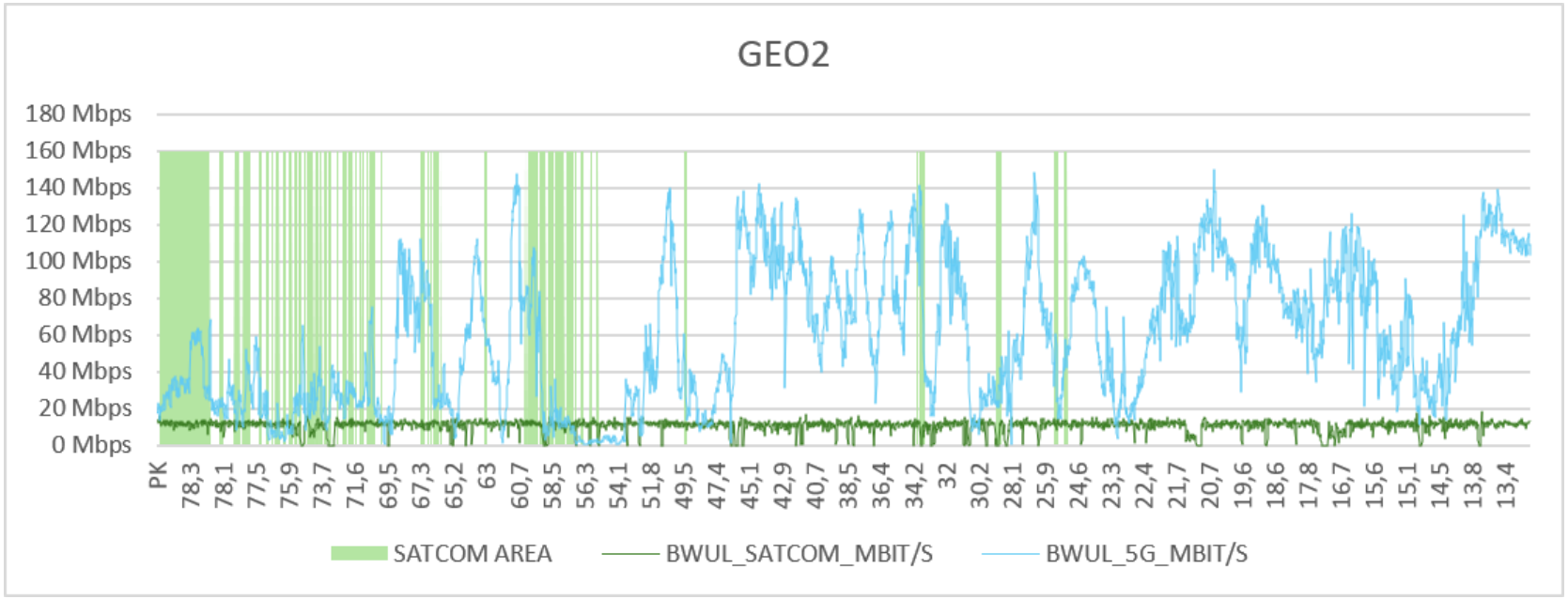
Few, targeted SATCOM zones placed on the 5G coverage holes (largest around PK 57–53).

Best use of each link: SATCOM only where it really helps.

Conclusion: SATCOM is used only where 5G actually fails, with few switches.

GEO-02: Latency Criterion

Geographic hybridisation - SATCOM zones defined from the ETCS latency requirement (150 ms max)



SATCOM zones

5G uplink throughput

SATCOM uplink throughput

How zones are defined

ETCS accepts a maximum latency of 150 ms. Wherever the measured 5G latency exceeds 150 ms, the section is assigned to SATCOM.

What we observe

Many short zones, concentrated at the start of the route (PK 78-69) and around PK 60-56, where 5G is weak.

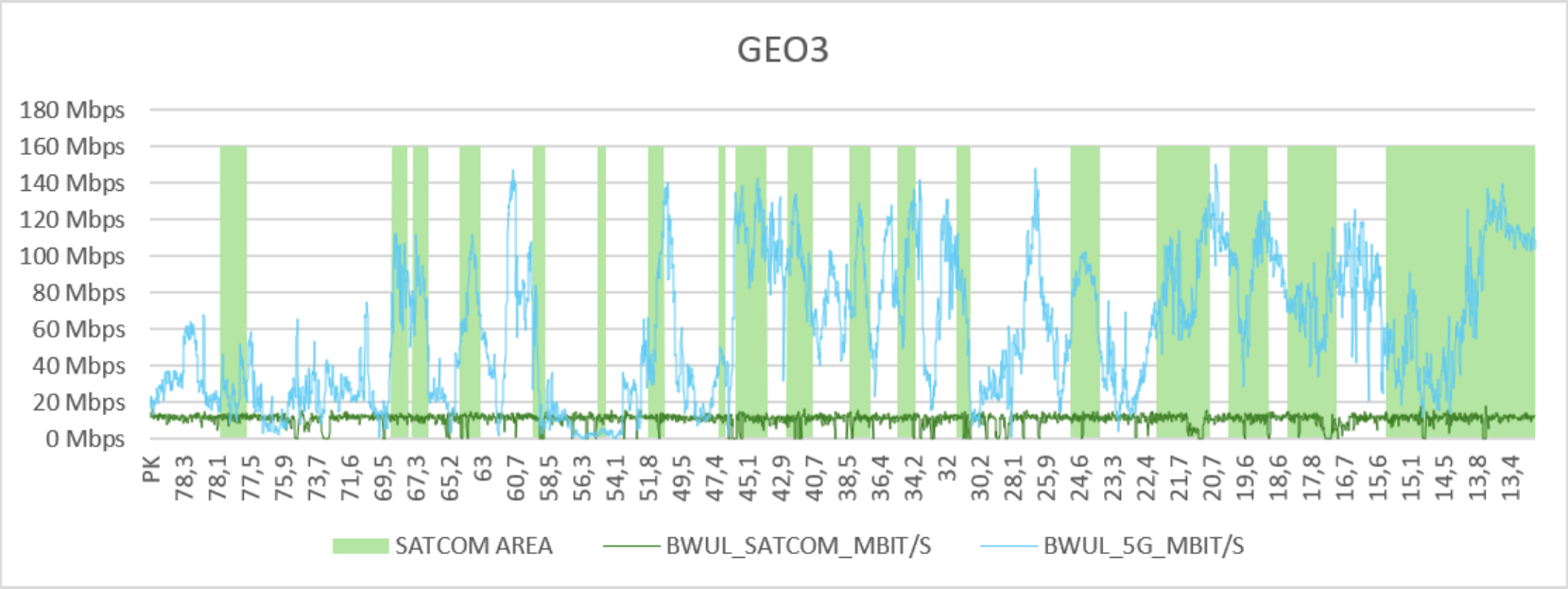
+ Service-oriented: guarantees the ETCS latency KPI along the route.

– Fragmented zones lead to more frequent switching.

Conclusion: best protection of the ETCS latency KPI (≤ 150 ms), at the cost of more frequent bearer switching.

GEO-03: Track Route Criterion

Geographic hybridisation - SATCOM zones built from the characteristics of the railway line



SATCOM zones

5G uplink throughput

SATCOM uplink throughput

How zones are defined

Zones are drawn from route features known in advance (stations, viaducts…), without radio measurements.

What we observe

Wide, regular blocks along the whole line, including sections where 5G throughput is high (PK 45-13).

+ Simple to configure, no measurement campaign needed.

– Not matched to radio conditions: SATCOM sometimes used where 5G is better.

Conclusion: simplest method to deploy but least matched to radio conditions. In all three methods, switching is anticipated before any de gradation is measured.

Summary of Tests Performed

Test area	What was tested	Set-up	Key result	Outcome
5G test bench	Field radio conditions replayed in the lab (RSRP)	Viavi Vertex channel emulator	Lab RSRP follows the field profile	✓ **Validated**
5G chain	UL / DL throughput, field vs lab (Sept. 2025 runs)	5G lab bench vs public 5G network	Dynamics reproduced; lower level (40 vs ≈ 90 MHz, TDD)	✓ **Validated, known limits**
SATCOM chain - V1	UL / DL throughput, field vs lab	Radiolabs IP-level emulator, scenario V1	Nominal level OK, link too smooth	⚠ **Improved by V2**
SATCOM chain - V2	UL / DL throughput, field vs lab	Radiolabs IP-level emulator, scenario V2	Lab and field curves match	✓ **Validated**
Automatic hybridisation	Handovers vs LQI tuning (3 settings)	ACS 5G / SATCOM, LQI scoring	52 / 100 / 250 handovers; traffic kept during 5G gaps	✓ **Tuning per application**
Geographic hybridisation	3 zoning methods (GEO-01 / 02 / 03)	ACS with GPS position and predefined zones	Throughput: targeted • Latency (ETCS ≤ 150 ms): fragmented • Route: simple	✓ **Anticipatory, reproducible**

Take-away: the S5LECT laboratory reproduces field 5G and SATCOM conditions and is ready to tune and compare hybridisation strategies before field deployment



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