

Funded by the European Union

Laboratory Presentation

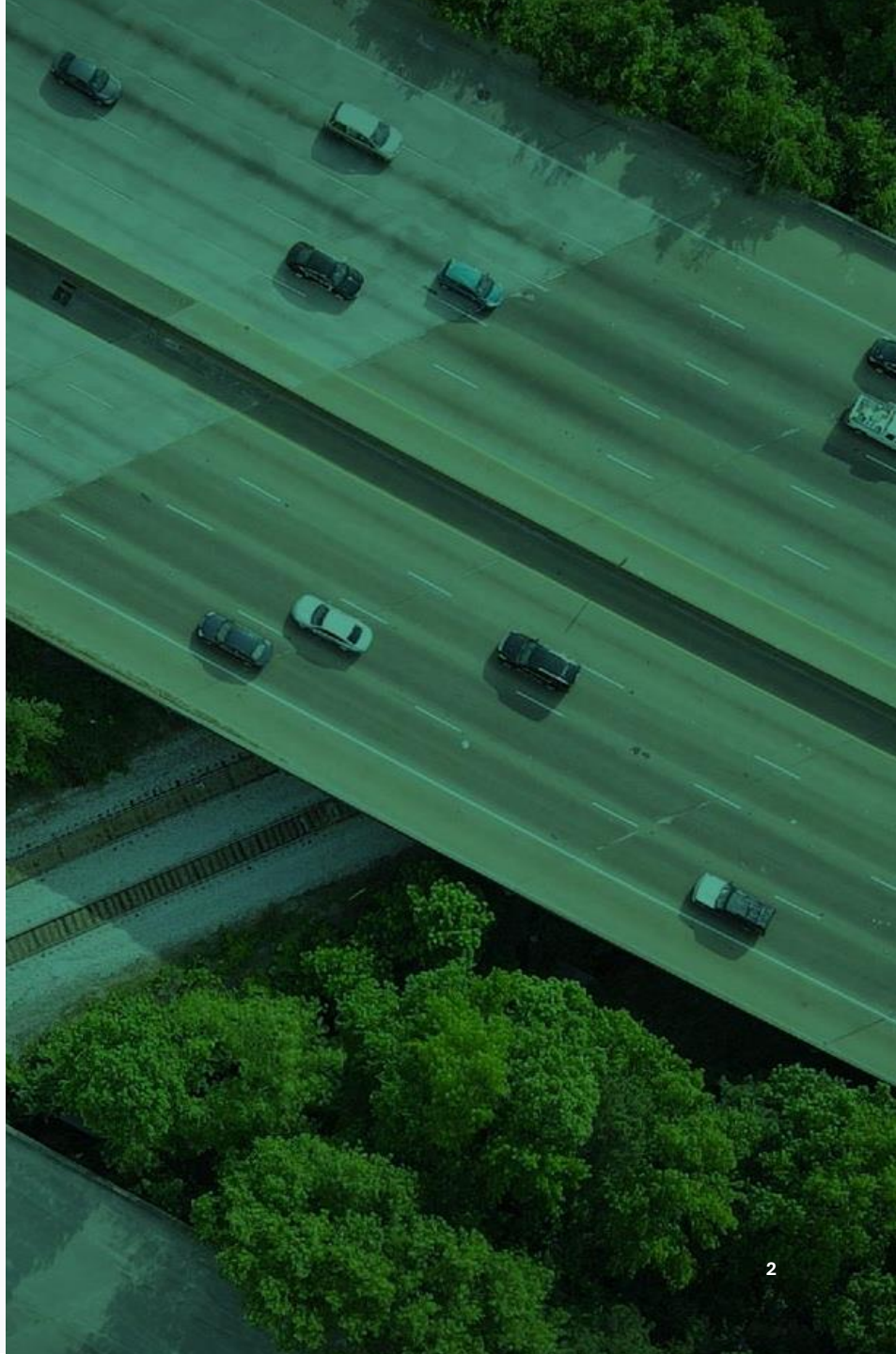
Table of Contents

1. **Lab Architecture**
   - S5LECT Architectures
   - Goals of the S5LECT Laboratory
   - Lab architecture
   - Lab architecture for orchestration

2. **Block by block**
   - ACS - Onboard
   - ACS - Trackside
   - 5G Emulator
   - MCx Voice & Video CCTV
   - S5LECT Lab Orchestrator
   - SatCom emulator
   - Lct Agent
   - Lct Server
   - Cybersecurity Demonstrator
   - Edge Computing Platform

3. **Overall lab**

4. **Demonstrations**



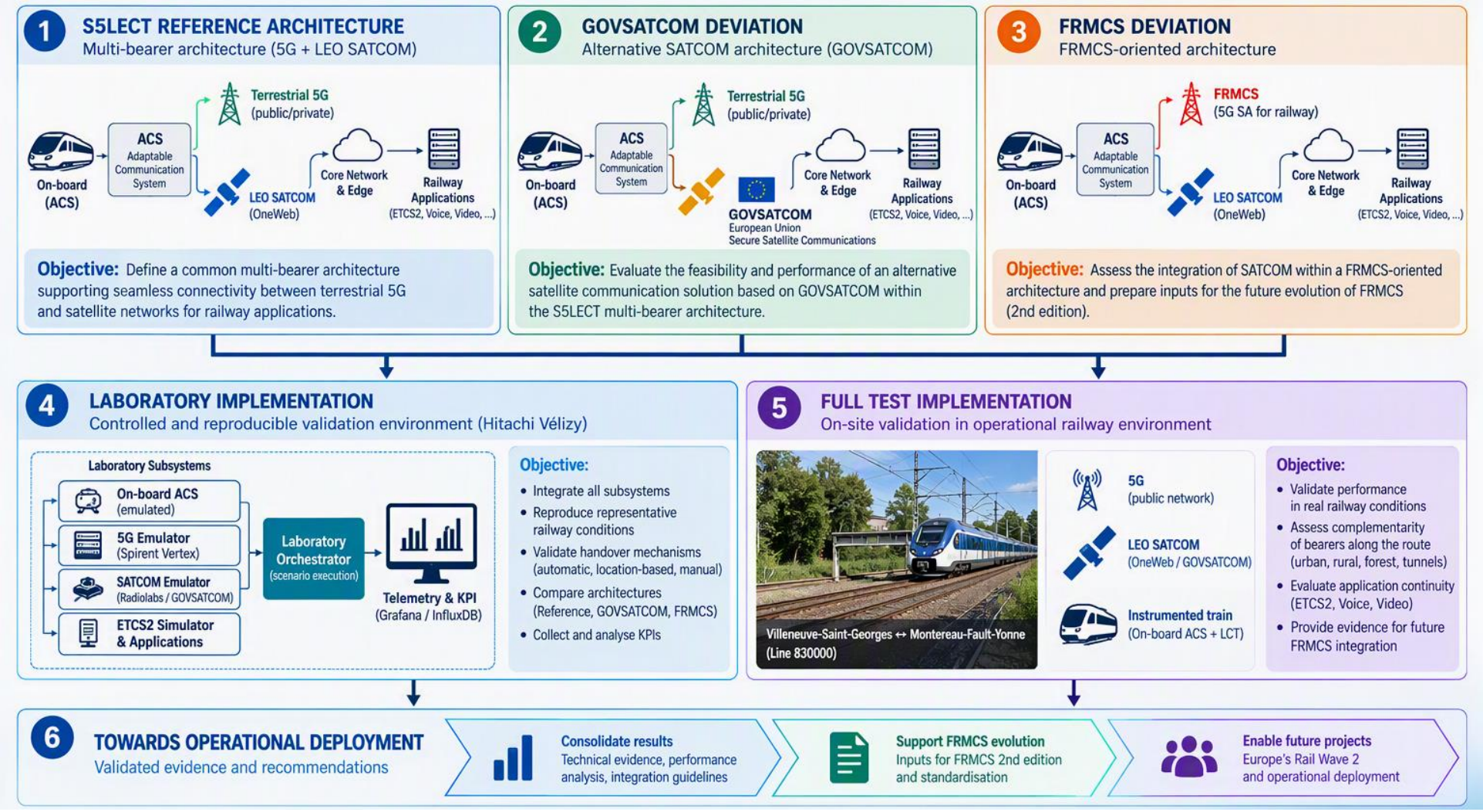
S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Lab Architecture



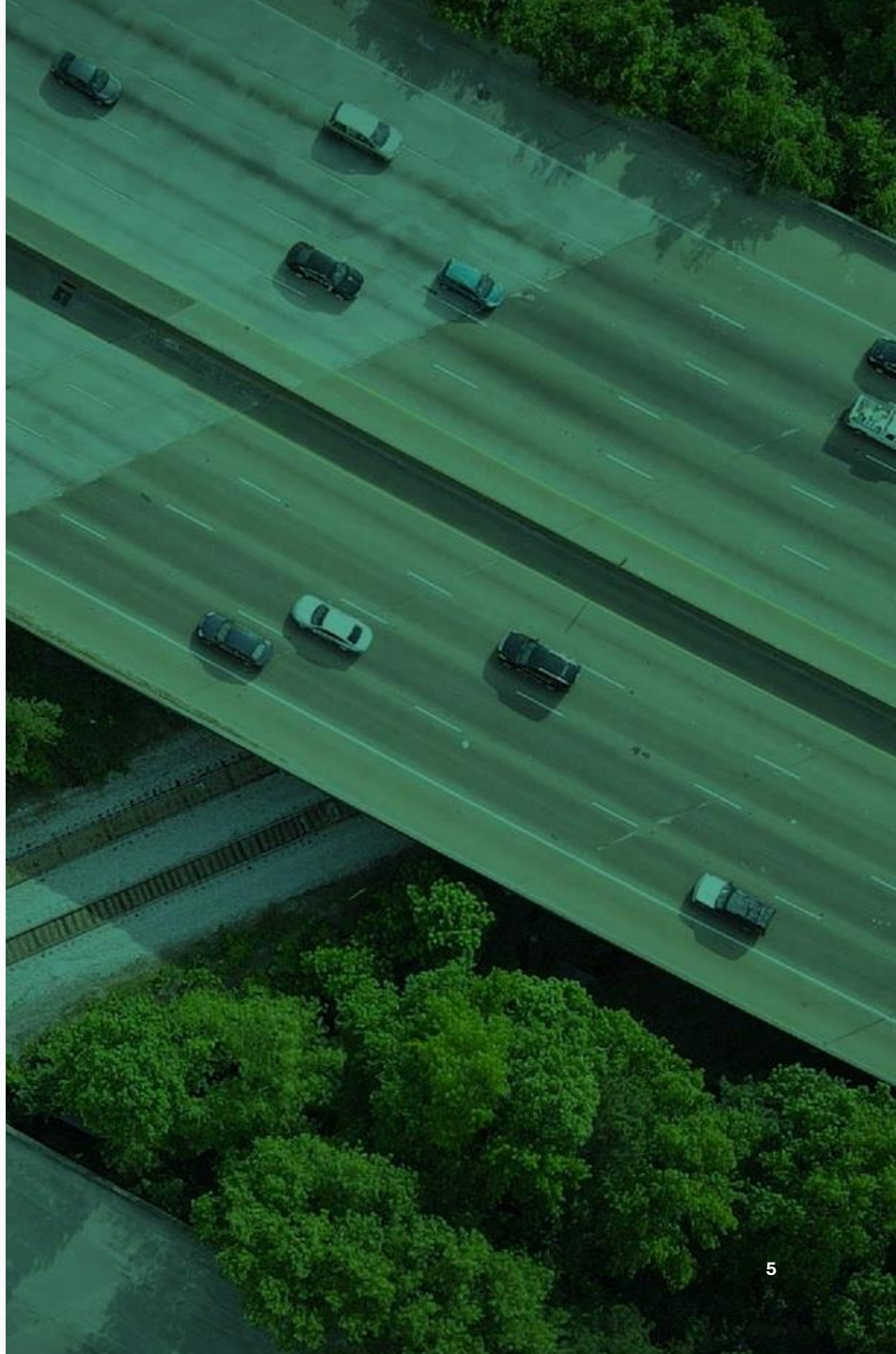
S5LECT
SatCom & 5G Link,
Edge & CybersecuriTy

S5LECT Architectures



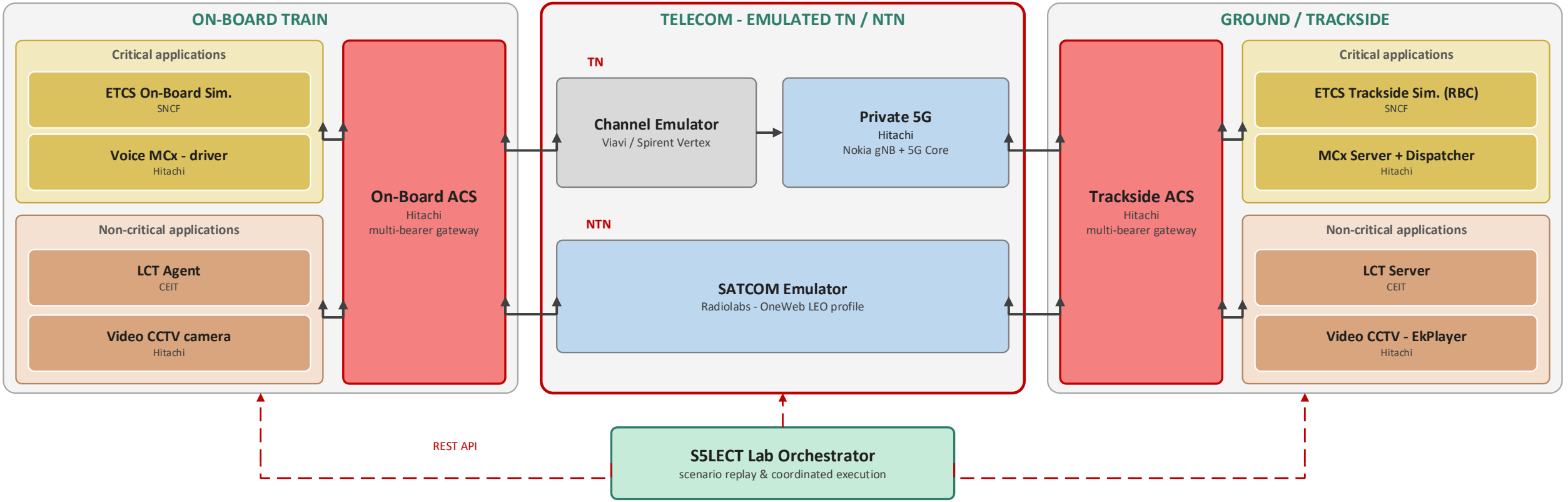
Goals of the S5LECT Laboratory

- **Reproduce** field 5G and SATCOM conditions in a controlled, repeatable environment
- **Fully orchestrable:** one orchestrator drives every equipment for automated, reproducible test campaigns
- **Validate** the ACS multi-bearer hybridisation (manual, automatic, geographic)
- **Test** critical (ETCS, MCx) and non-critical (video CCTV, LCT) railway applications over TN / NTN
- **Prepare** the S5LECT demonstrations

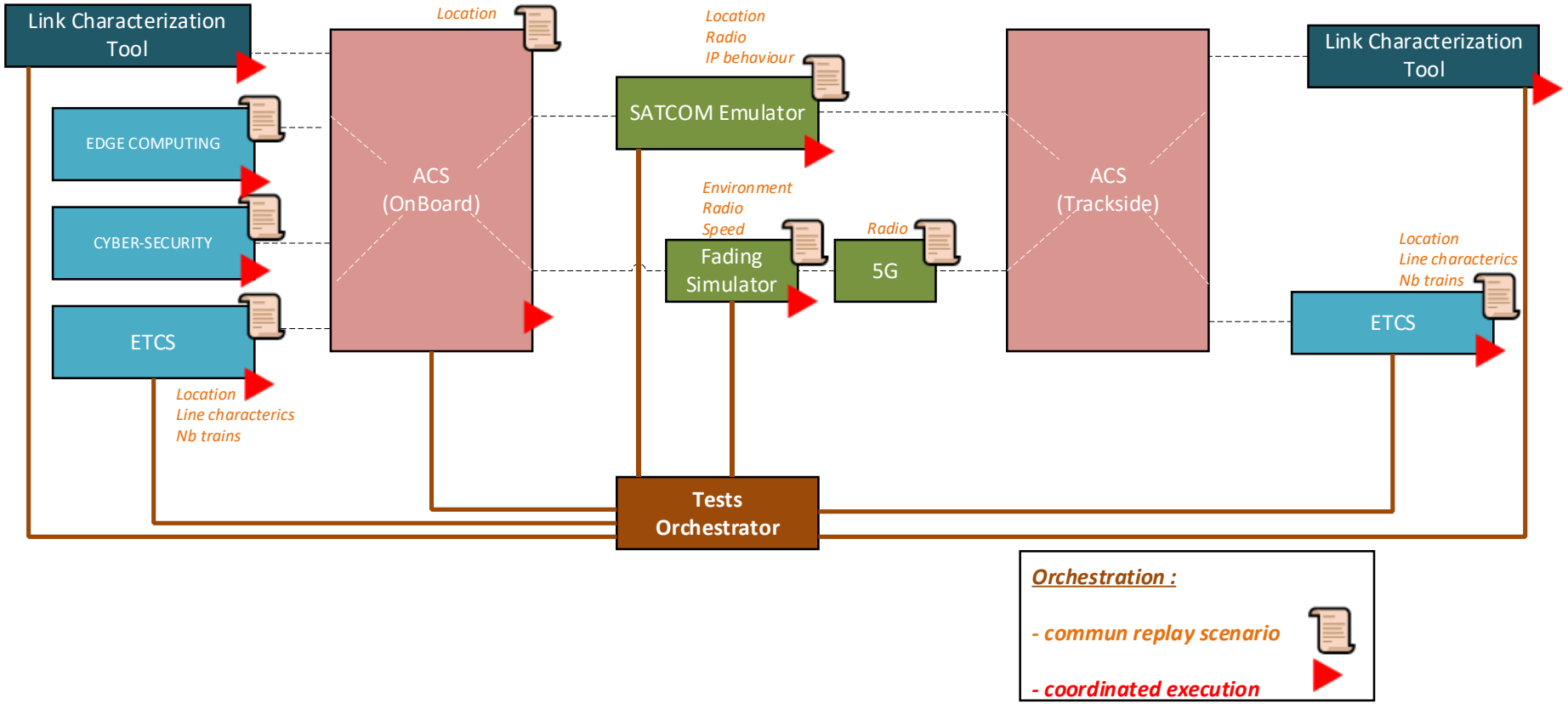


Lab architecture

S5LECT Laboratory - Lab Architecture



Lab architecture for orchestration



Main functions & why

Common replay scenario

The orchestrator sends scenarios ID then each element loads its own data from the same field run (location, radio, IP behaviour, line characteristics…).

Coordinated execution

Readiness check, then start / stop of all elements in one action.

Why: reproducible, automated test campaigns.

Elements

- ACS: system under test • SATCOM emulator, fading simulator 5G: emulated links • LCT, ETCS, edge, cyber: applications and measurement tools

Block by block



S5LECT
SatCom & 5G Link,
Edge & CybersecuriTy

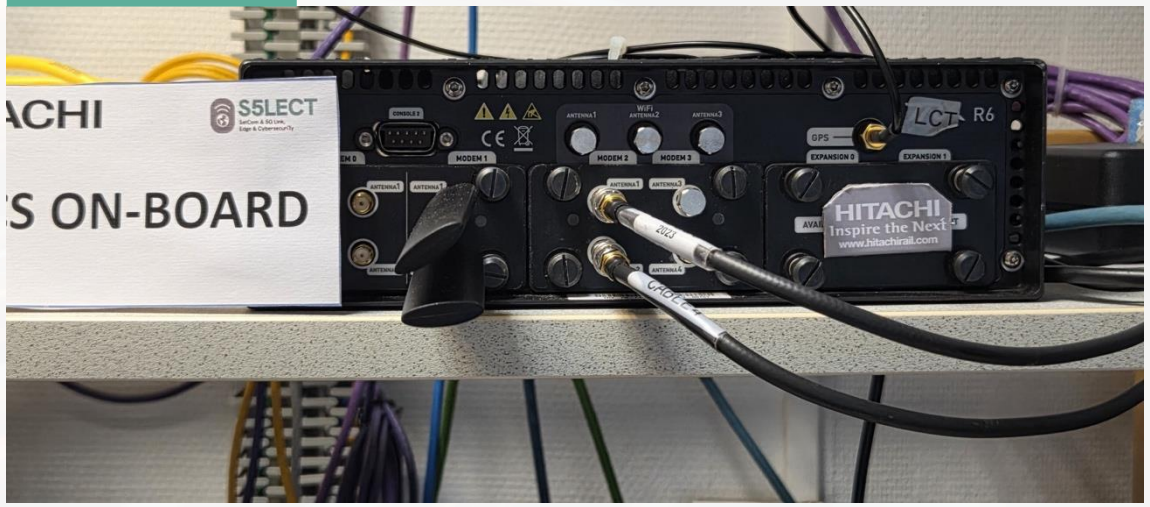
ACS - Onboard

Functions

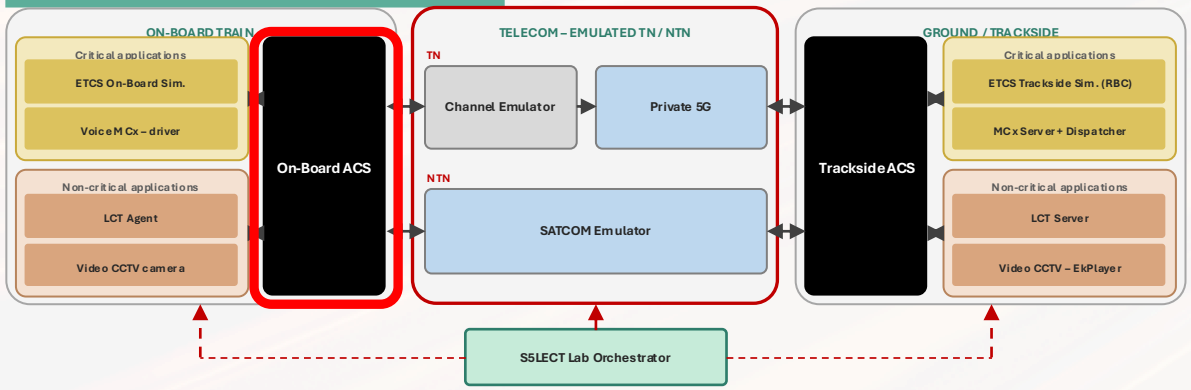
Smart on-board gateway for seamless train-to-ground connectivity

- On-board part of the Hitachi Adaptable Communication System (ACS): a modular rail-grade unit with modem slots and Wi-Fi / GNSS antennas.
- Links on-board applications (ETCS, Voice MCx, LCT agent, CCTV) to their trackside counterparts.
- Switches between private 5G and SATCOM (OneWeb LEO) for seamless TN/NTN handover.
- Secures the data path (VPN, firewall); gives the LCT agent time, location and RF data via REST API.
- Driven by the Lab Orchestrator through its API.

On lab



On Architecture



ACS - Trackside

Functions

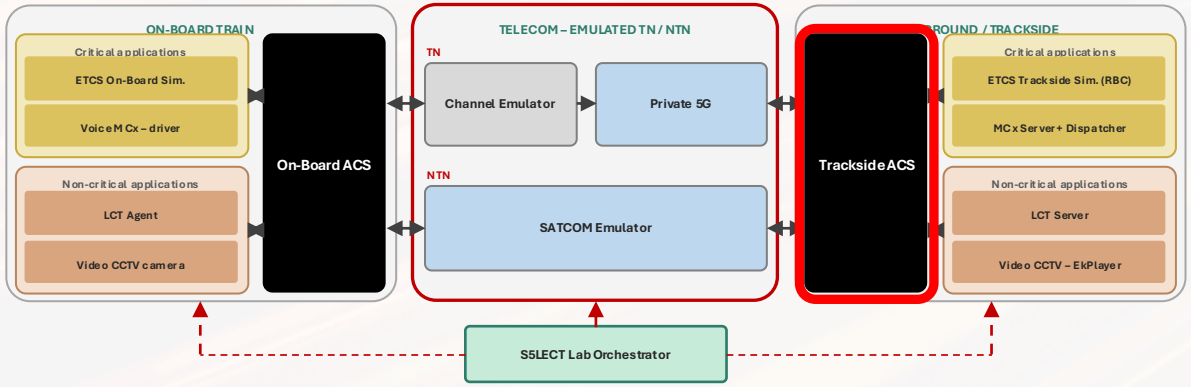
Ground-side gateway to trackside applications and networks

- Trackside part of the Hitachi Adaptable Communication System (ACS), mirroring the on-board unit, deployed on a Dell rack server in the lab.
- Terminates the secure VPN with the train over terrestrial (5G) and non-terrestrial (SATCOM) bearers.
- Links trackside applications (ETCS server, MCx server, LCT server, CCTV) to the telecom subsystem.
- Offers API / orchestration / O&M interfaces and a firewall security edge, NTP-synchronised with the LCT server.
- Driven by the Lab Orchestrator together with the on-board ACS.

On lab



On Architecture



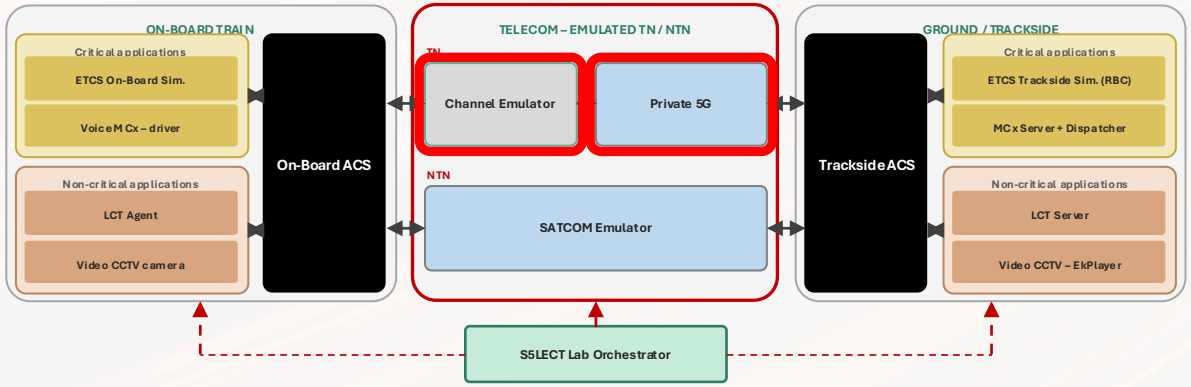
5G Emulator

Functions

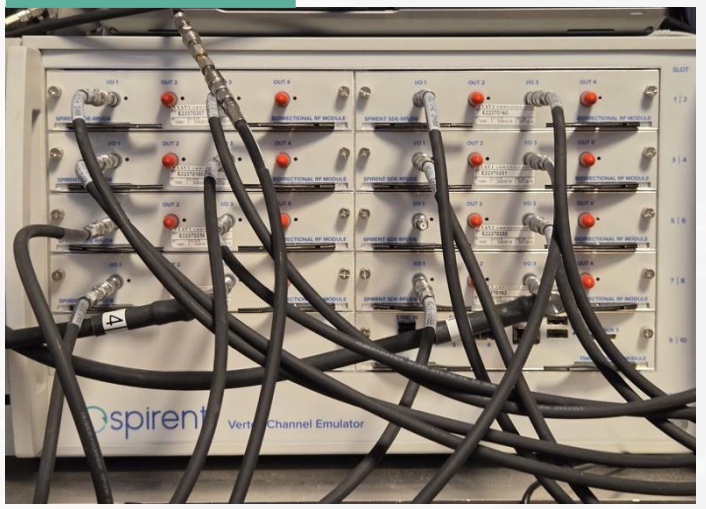
Private 5G network with a hardware fading emulator for realistic radio conditions

- Terrestrial 5G chain of the lab: Nokia private 5G (gNB at 3579.990 MHz + 5G Core) behind a Spirent Vertex channel emulator.
- Private 5G carries ETCS, MCx and LCT traffic to the trackside ACS through the multi-service network (MSN ACOR).
- Vertex: hardware RF fading emulator between the on-board ACS and the gNB (2x2 bidirectional, 6 dB attenuation per path).
- Replays tunnels, trees, bridges and urban effects, using profiles built from the Villeneuve-Montereau field data.
- Eight RF modules (SDE-RFUD6); channel models set from the Vertex GUI, scenarios triggered by the Lab Orchestrator.

On Architecture

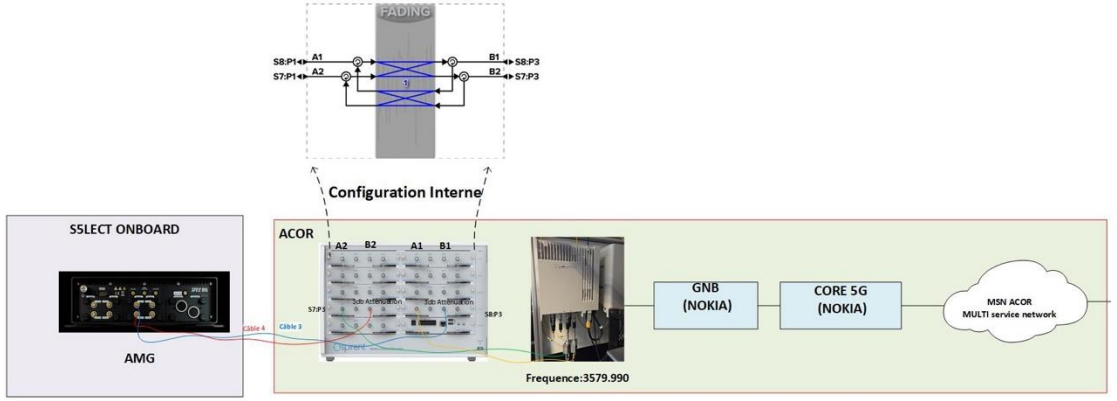


On lab





Test bench



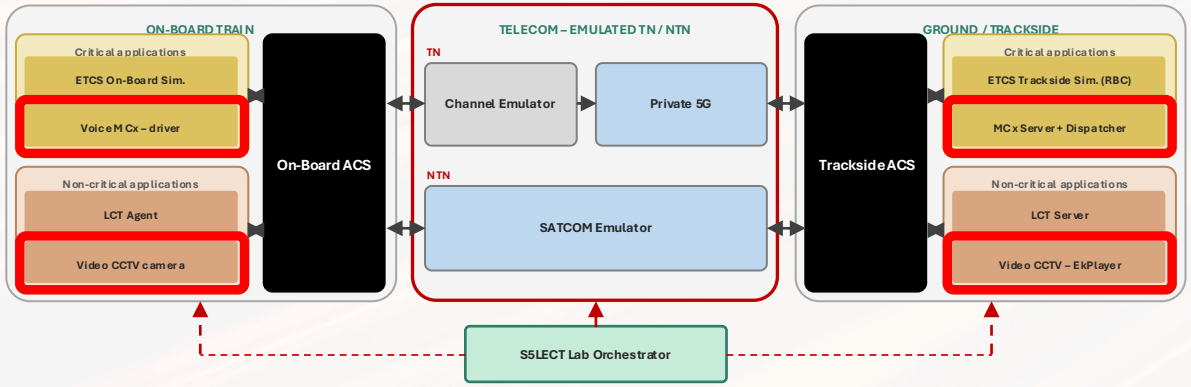
MCx Voice & Video CCTV

Functions

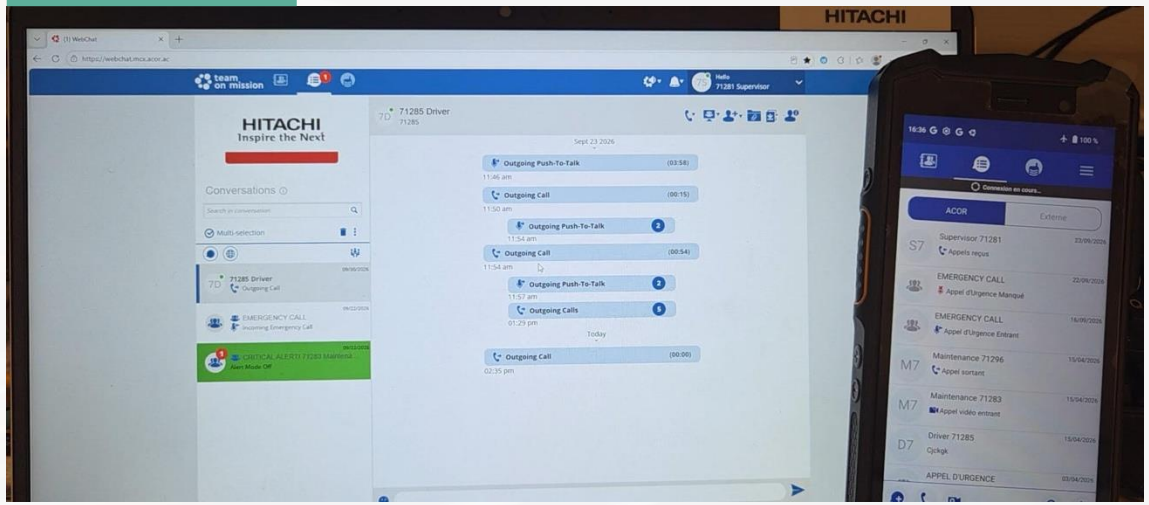
Mission-critical voice & real-time video over the ACS

- Voice MCx (“Team on Mission”): mission-critical push-to-talk, voice/video calls, emergency calls and alerts between the driver (on-board rugged handset) and the supervisor (trackside WebChat console, MCx server).
- Video CCTV (Ektacom): live HEVC stream (1 camera, 640x480) from the on-board camera to the trackside EkPlayer.
- Role in S5LECT: end-user applications used to assess ACS seamless handover (TN/NTN). Target KPIs -voice: RTT ≤ 150 ms, jitter ≤ 30 ms, ≥ 24 kbps, video: 1.3 / 5 Mbps (LQ/HQ), loss < 1 %.

On Architecture



On lab



On Action



Video CCTV: on-board camera view (left) received on the trackside EkPlayer (right)

S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

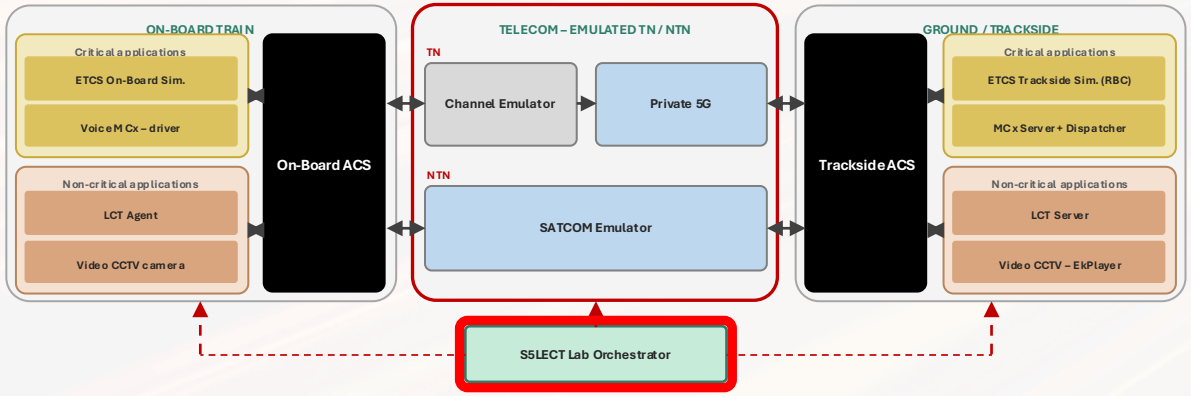
S5LECT Lab Orchestrator

Functions

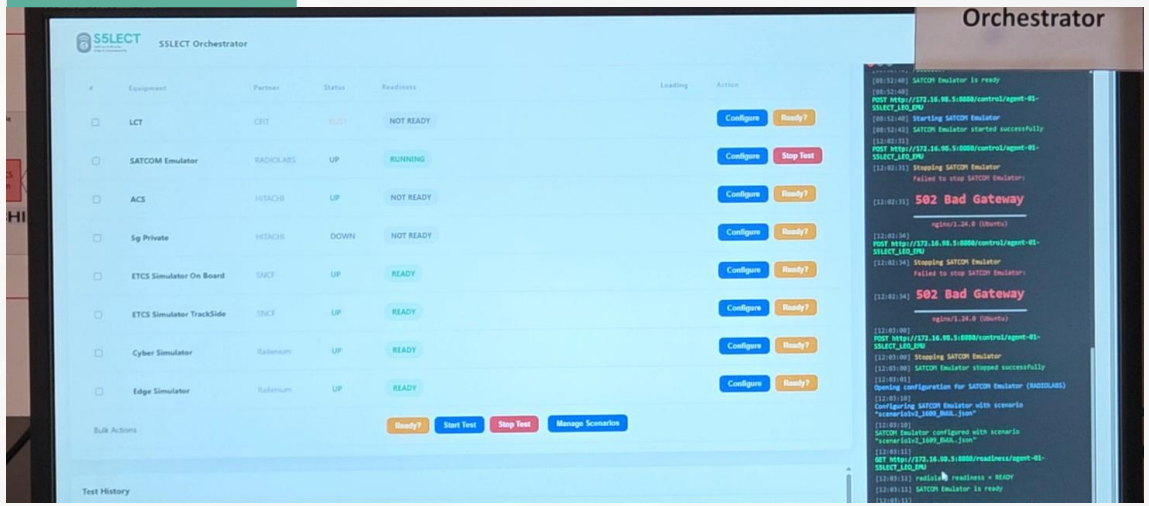
Centralised control and automation of lab tests

- Test execution: sends a scenario ID (CSV built from the data acquisition campaign) to each sub-system - SATCOM emulator, LCT, ACS, fading and ETCS simulators - checks their readiness, then starts/stops the test in sync.
- Interfaces: REST API over Ethernet to all on-board and trackside equipment, live status per equipment (Up/Down, Ready, Running).
- Supervision: web dashboard with bulk actions, scenario management, live log console and test history (JSON) for traceability;,user authorisation and logging of all interactions.

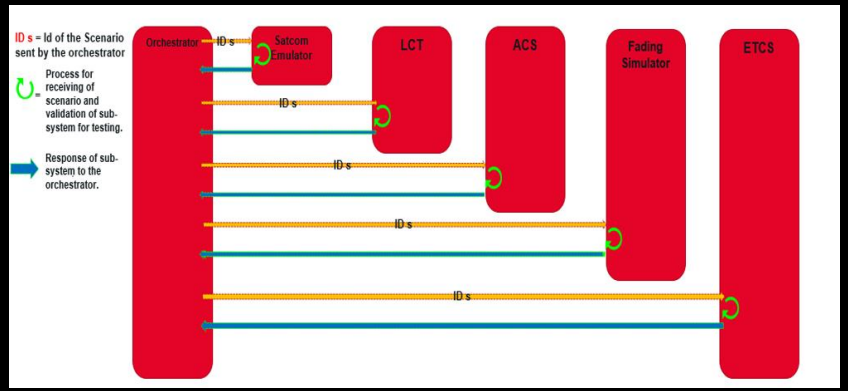
On Architecture



On lab



Test sequence



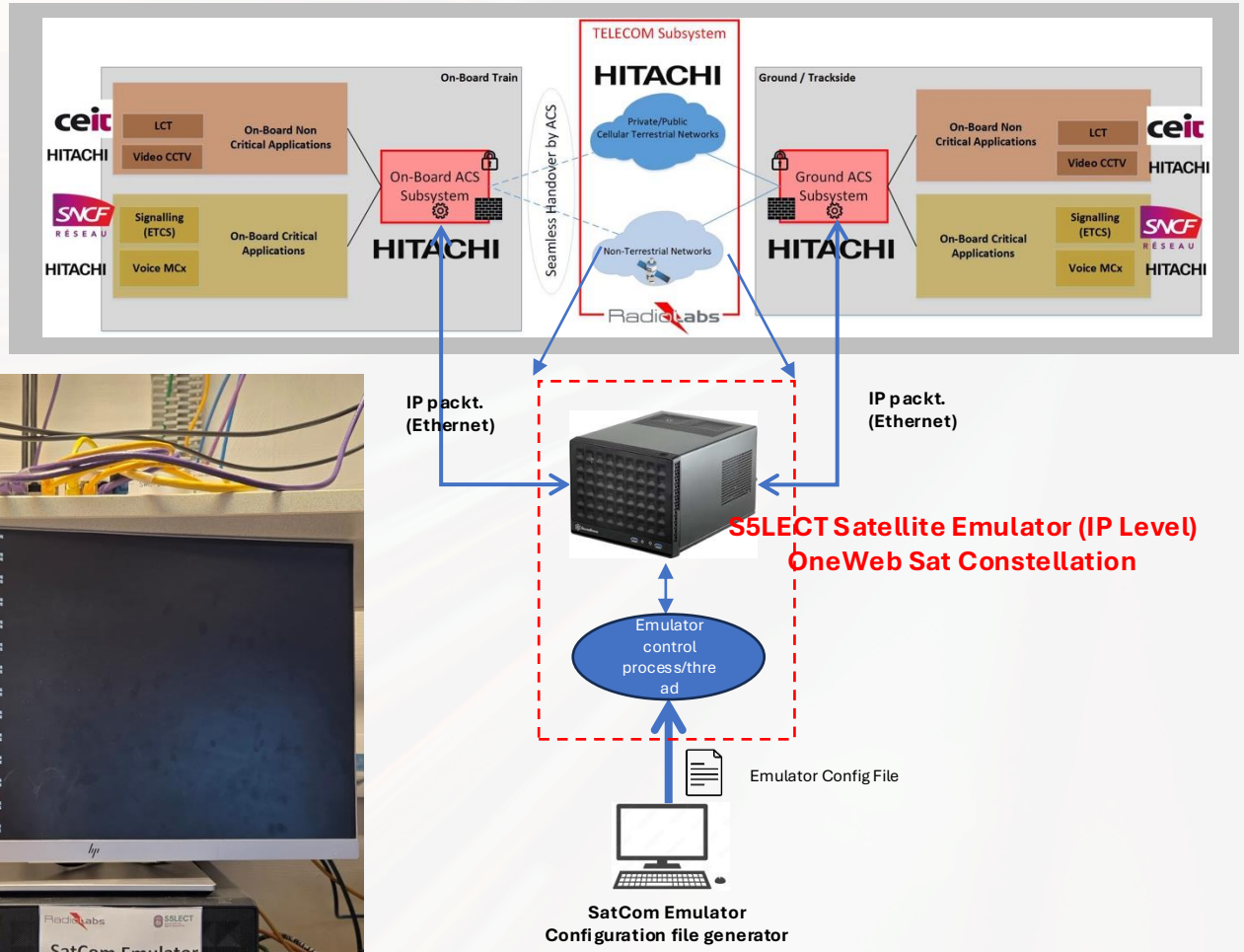
Test execution: scenario ID dispatched to each sub-system, readiness returned

S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Satellite Emulator (University of Rome Tor Vergata – Radiolabs)

Main Satellite Emulator Functions

- Emulate the LEO satellite link as seen at IP level
- Accounts for Network KPIs: latency, bandwidth, packet loss
- KPIs can be changed at run time taking into account for the:
  - Actual position of the train
  - The actual geometry of the satellite constellation as provided by the (downloadable) actual TLE file
  - The satellite beam handover and the inter satellite handover
  - Obstruction due to obstacles along the rail track
- Emulator parameters can be tuned to account for experimental data so to model real scenarios and the associated phenomena.
  - One example, has been considered using the results obtained by Hitachi during the experimental campaign over the selected railway track.
- Can be remotely controlled with APIs



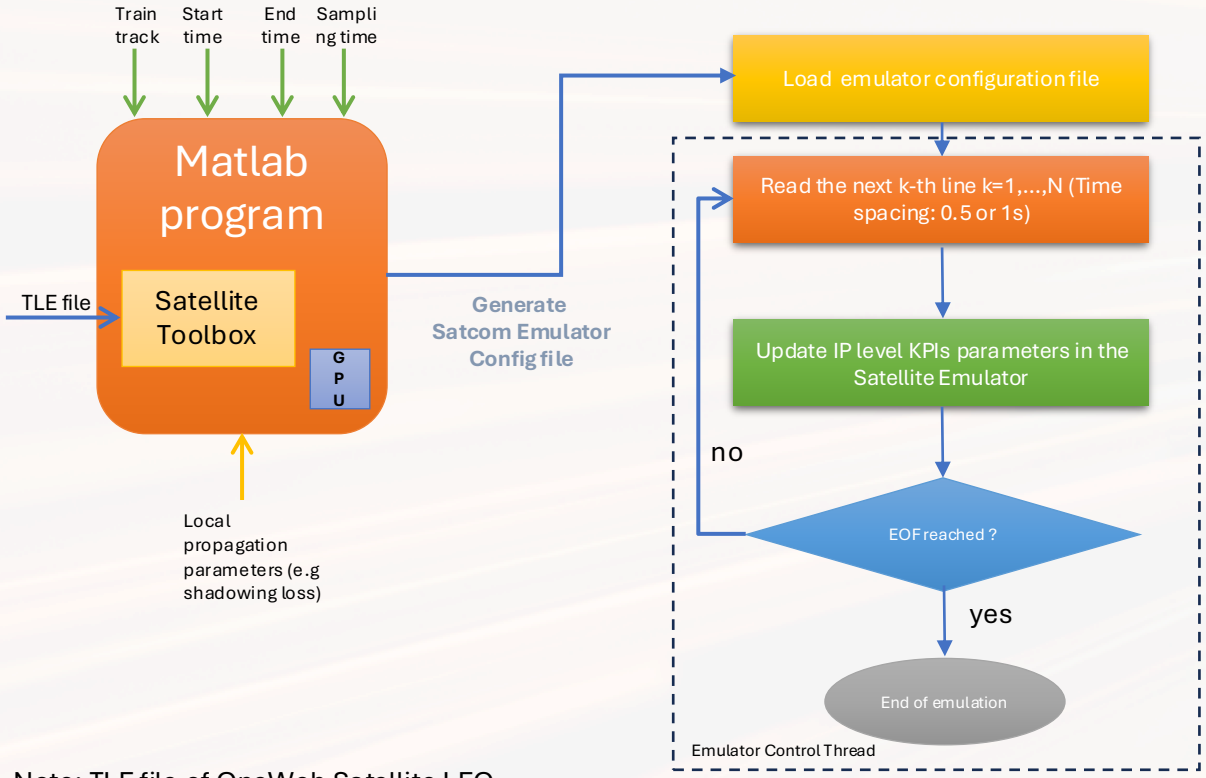


SatCom emulator inside the Hitachi Lab

S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Satellite Emulator - Operations

Operations of Satellite Emulator



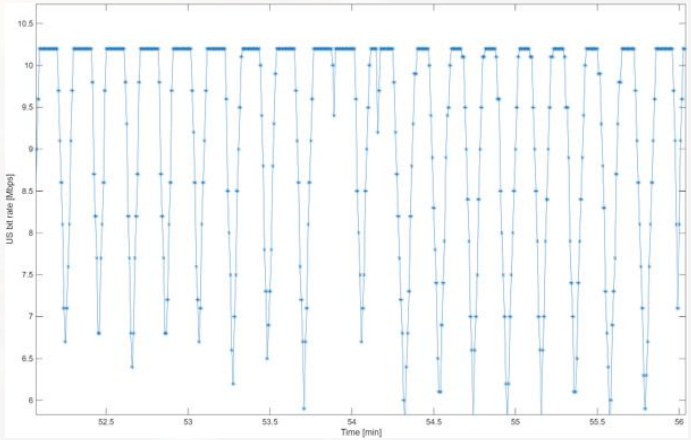
Note: TLE file of OneWeb Satellite LEO constellation

Example of Emulator Configuration File

time	latitude	longitude	speed	pk	idsat	e2eDelay	RateU2G	RateG2U	BurstU2G	BurstG2U	LimitU2G	LimitG2U
2026-01-25T08:12:43.235000Z	48,7429	2,44446	0,033	13	233	50	11,1	50,5	3040	12464	12160	21584
2026-01-25T08:12:43.735000Z	48,7429	2,44446	0,033	13	233	73,2	11,1	50,5	3040	12464	12160	21584
2026-01-25T08:12:44.235000Z	48,7429	2,44446	0,115	13	233	76,9	18,8	50,5	4560	12464	13680	21584
2026-01-25T08:12:44.735000Z	48,7429	2,44446	0,115	13	233	73,5	18,8	50,5	4560	12464	13680	21584
2026-01-25T08:12:45.235000Z	48,7429	2,44446	0,109	13	233	66,1	14,1	50,5	3344	12464	12464	21584
2026-01-25T08:12:45.735000Z	48,7429	2,44446	0,109	13	233	48,2	14,1	50,5	3344	12464	12464	21584
2026-01-25T08:12:46.235000Z	48,7429	2,44446	0,015	13	233	49	11,7	50,5	3040	12464	12160	21584
2026-01-25T08:12:46.735000Z	48,7429	2,44446	0,015	13	233	48,9	11,7	50,5	3040	12464	12160	21584
2026-01-25T08:12:47.235000Z	48,7429	2,44446	0,311	13	233	49	11,8	50,5	3040	12464	12160	21584
2026-01-25T08:12:47.735000Z	48,7429	2,44446	0,311	13	233	48	11,8	50,5	3040	12464	12160	21584
2026-01-25T08:12:48.235000Z	48,7429	2,44446	0,47	13	233	48,7	12,8	50,5	3040	12464	12160	21584
2026-01-25T08:12:48.735000Z	48,7429	2,44446	0,47	13	233	48,7	12,8	50,5	3040	12464	12160	21584
2026-01-25T08:12:49.235000Z	48,7429	2,44446	0,482	13	233	48,8	14,6	50,5	3648	12464	12768	21584

S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Example of Results: upstream LEO satellite link capacity Considered Train track from Hitachi

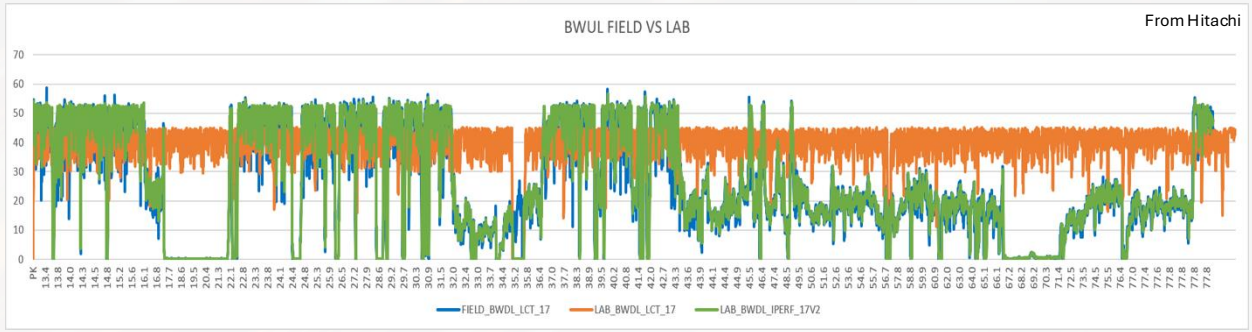


Upstream US bit rate (clipped to account for OneWeb profile at 10 Mbps on average (NO osbtacles and no shadowing)

Effects due to beam and satellite handovers are evidenced

Introduced shadowing correction factor to account for obstacles along the rail track.

- Shadowing correction can be generated using stochastic models or from experimental data (downstream scenario)



The derivation of the shadowing correction factor from experimental data (blue curve) permits:

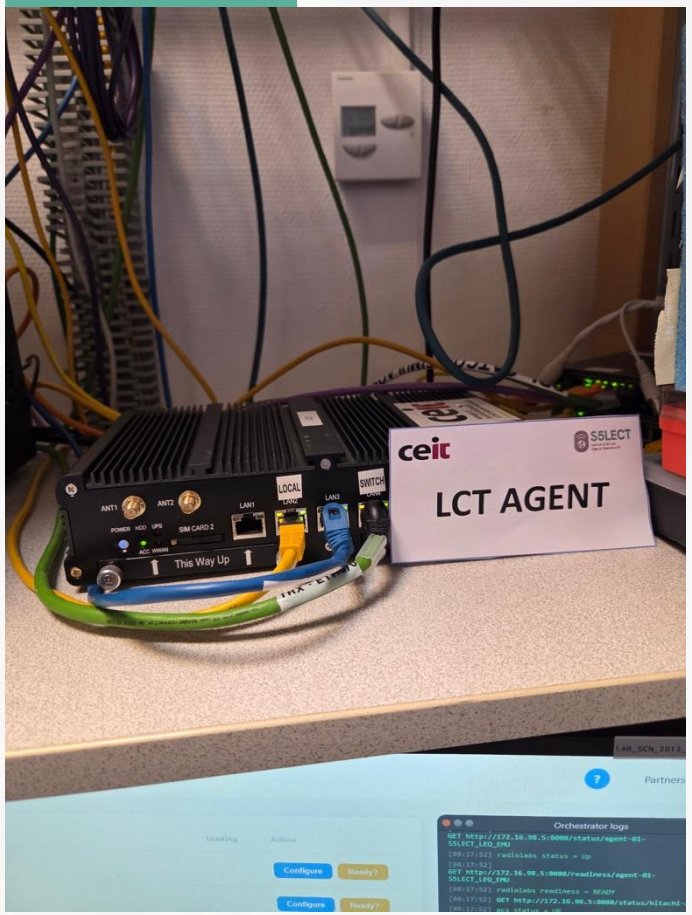
- To properly tune emulator parameters (i.e. the IP level KPIs) to the real propagation scenario (green curve generated by the Matlab program) with respect to the no obstacles case (orange curve generated by the same Matlab program)
- To derive a **signature** of the obstacles along the track that can impair satellite propagation in mobile scenarios.

LCT Agent

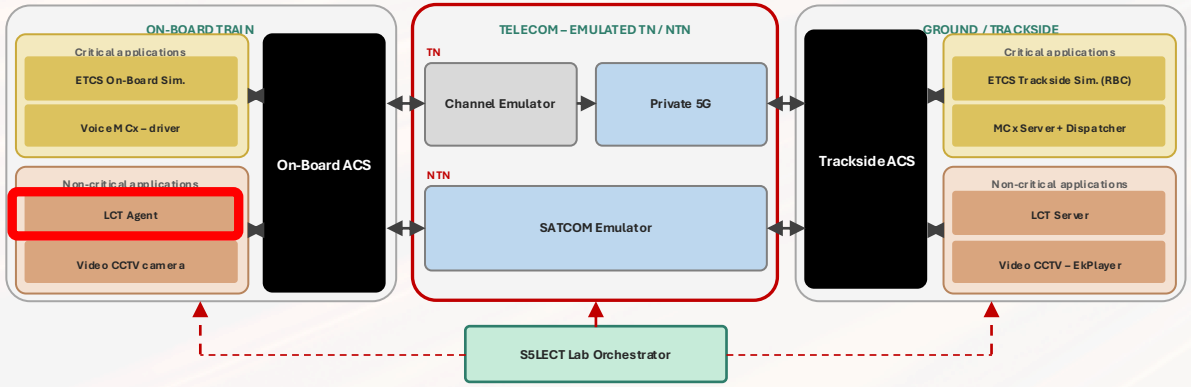
Functions

- On-board part connected to the ACS-oboard
- Responsible for obtaining the train position and for monitoring the IP and RF parameters together with the LCT Server.
- It allows the measurement of different communication channels in terms of IP QoS parameters and RF parameters along a given track with a specific location.

On lab



On Architecture

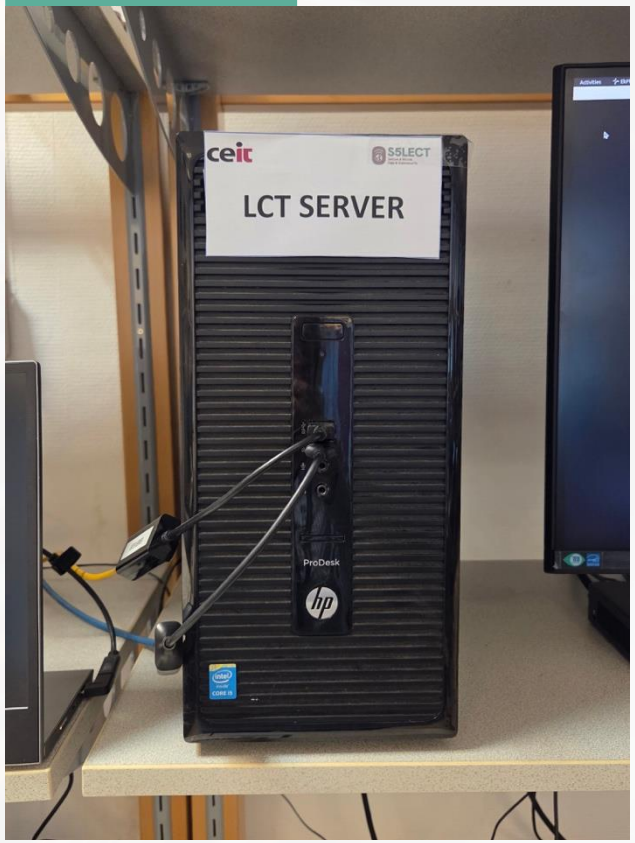


LCT Server

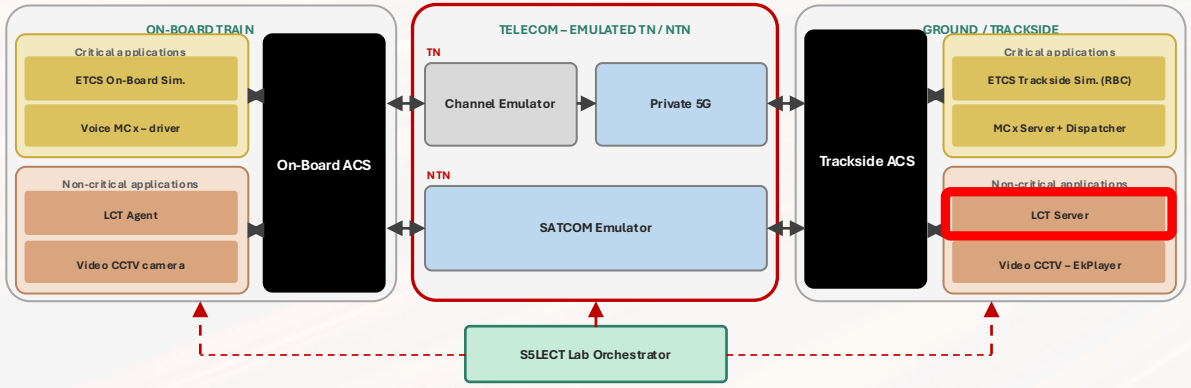
Functions

- Subsystem located on the trackside.
- Responsible for monitoring the IP parameters of the different communication technologies together with the LCT Agent.

On lab

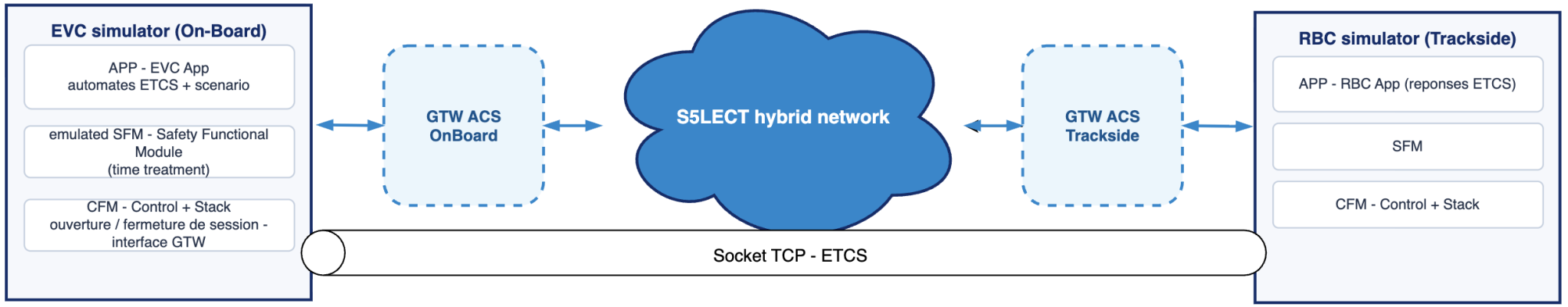


On Architecture

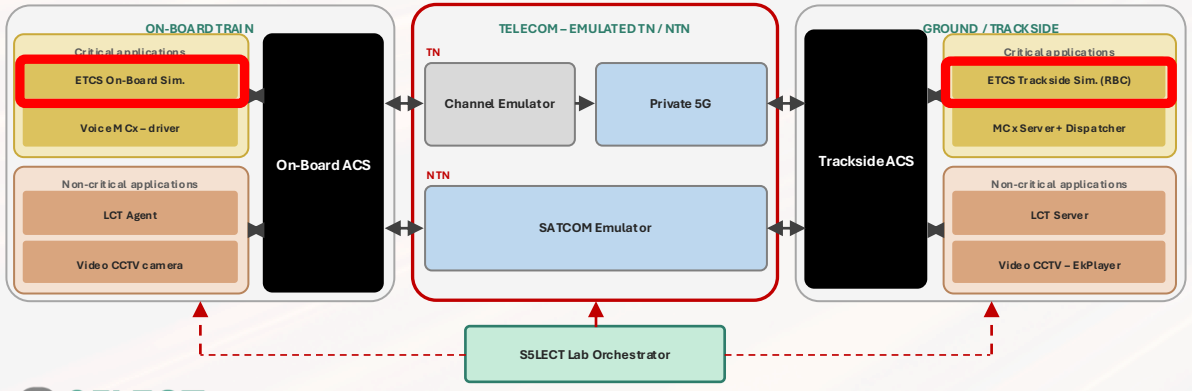


ETCS2 emulator

Functions



On Architecture



Cybersecurity Demonstrator

Functions

Security-state impact evaluation

A controlled security state is applied to the project communication conditions, and its consequence on the railway service is measured.

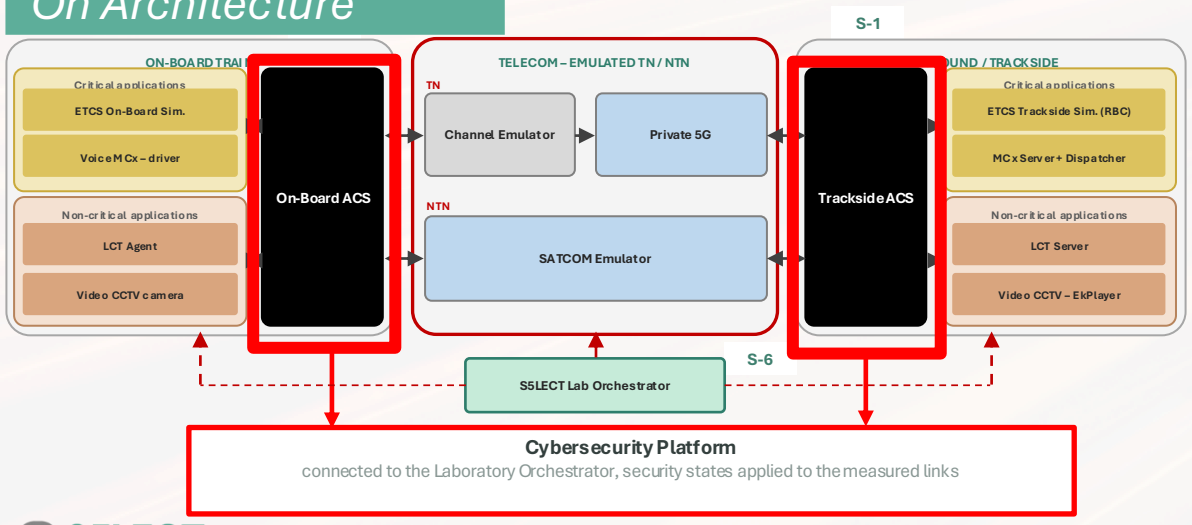
- **D3.3 risk scenarios**

  platform built on the D3.3 framework; Scenarios 1 and S-6 demonstrated quantitatively.
- **Controlled security state**

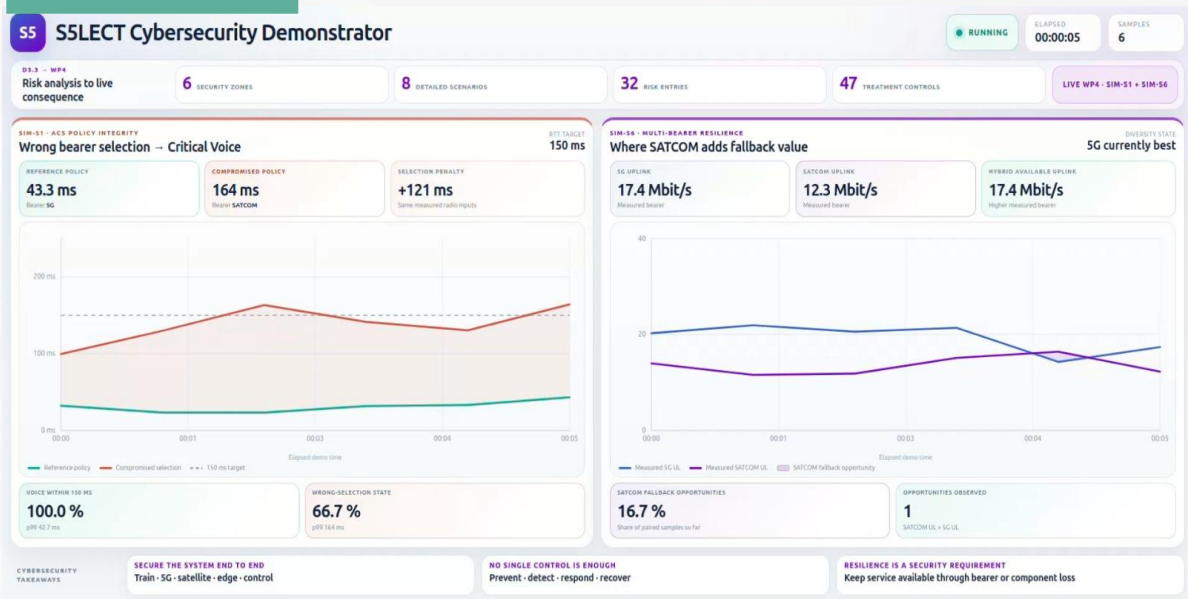
  reference vs compromised, identical communication input.
- **Service consequence**

  voice compliance, SATCOM fallback opportunities.

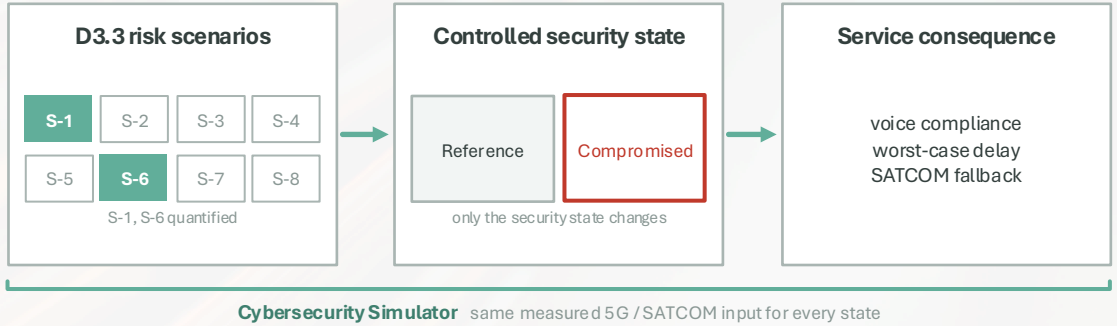
On Architecture



On lab



How it works



S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Edge Computing Platform

Functions

Service-aware Edge evaluation

An Edge evaluation platform that replays the project communication conditions and compares service-aware Edge configurations.

- **Network-level placement**

  national cloud, regional or base-station Edge, with measured compute cost

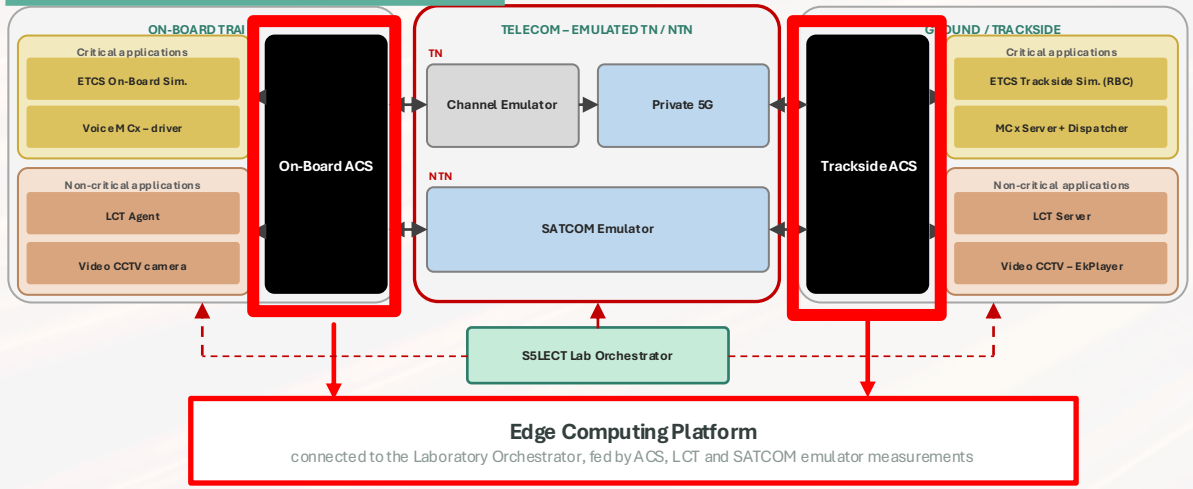
- **Application-level video processing**

  filtering, aggregation, rate adaptation

- **Voice / Video evaluation**

  latency against 150 ms, load against SATCOM capacity

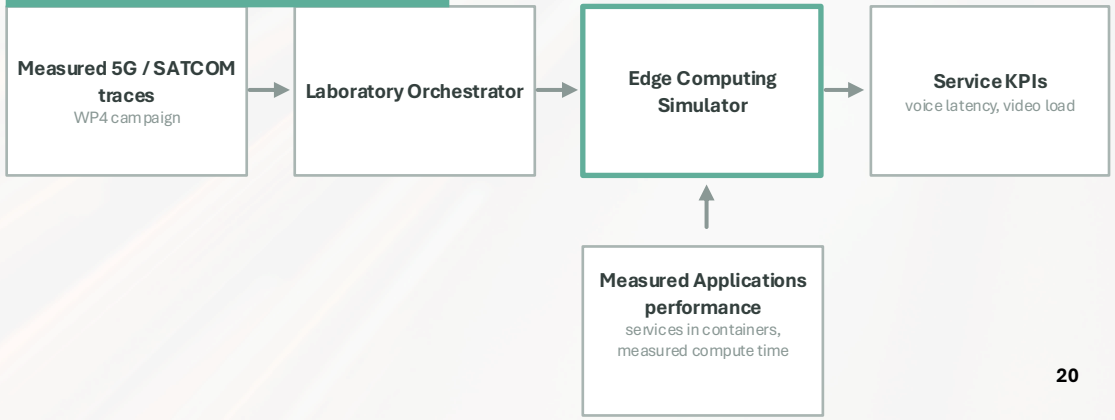
On Architecture



On lab



How it works



S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Overall Lab

Laboratory Presentation



S5LECT
SatCom & 5G Link, Edge & CyberseCuriTy

Test Methodology

1 Simulators & emulators

Install and configure each element: private 5G + channel emulator, SATCOM emulator, ETCS, LCT, MCx and video.

2 Orchestrator

Connect every element through its REST API and load the replay scenarios built from the field runs.

3 Validate the simulators

Compare lab and field (throughput, latency, RSRP) and adjust the scenarios.

4 Test the hybridisation

Run the ACS modes (manual, automatic, geographic) with different parameters: LQI tuning, SATCOM zones.

Output: Validated lab conditions and hybridisation results (see Test Results).

S5LECT Laboratory video

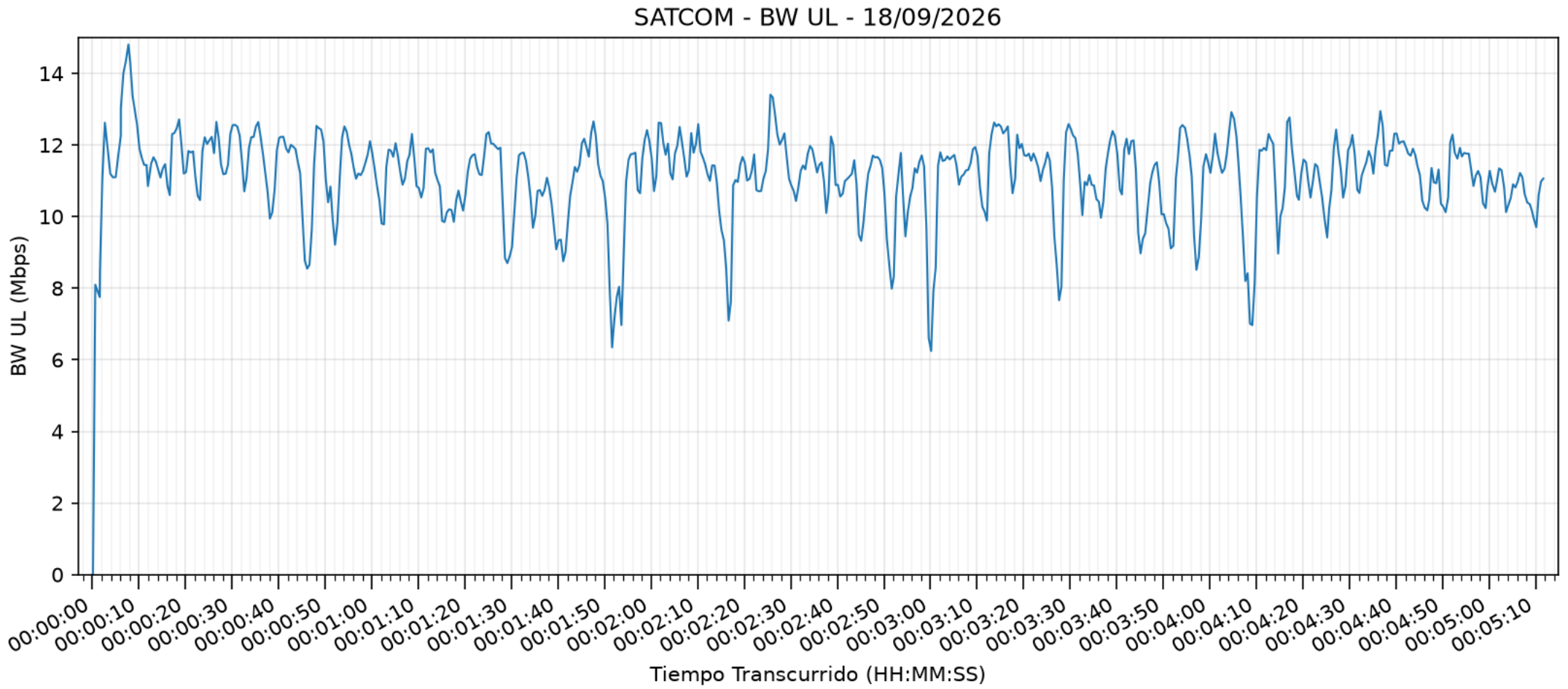


Demonstrations

1. Demo 01 - Telemetry by LCT (Live)
2. Demo 02 - Hybridisation – Automatic (Live)
3. Demo 03 - Hybridisation – Geographic (Live)
4. Demo 04 - ETCS over ACS
5. Demo 05 – MCX over ACS
6. Demo 06 - Cybersecurity for ACS
7. Demo 07 - Edge for ACS

Demo 01 - Telemetry by LCT (Live)

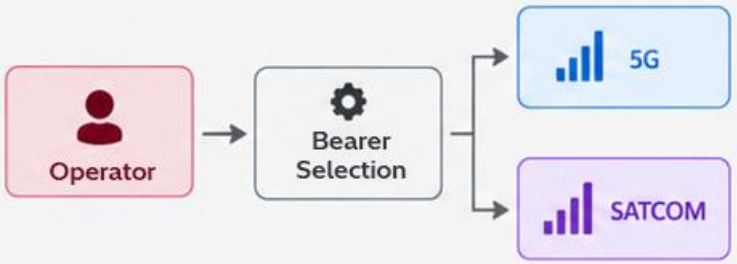
Demo 01 - Telemetry by LCT (Result)



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.



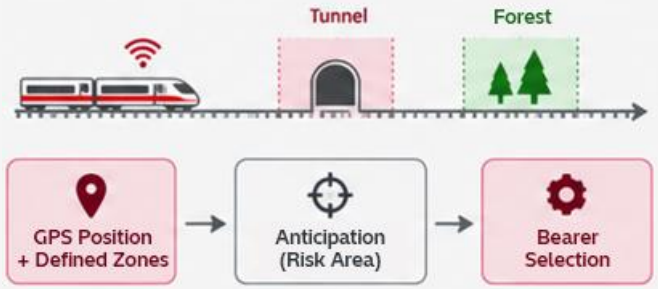
Automatic

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.



Demo 02 - Hybridisation – Automatic (Live)

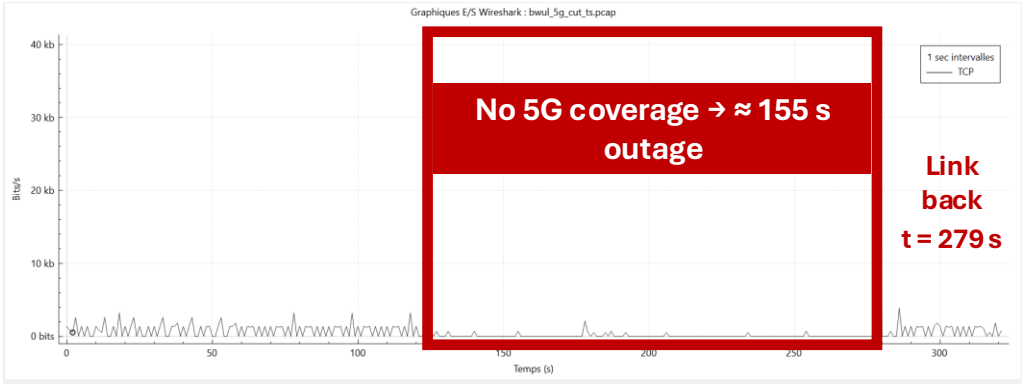
Demo 03 - Hybridisation – Geo (Live)

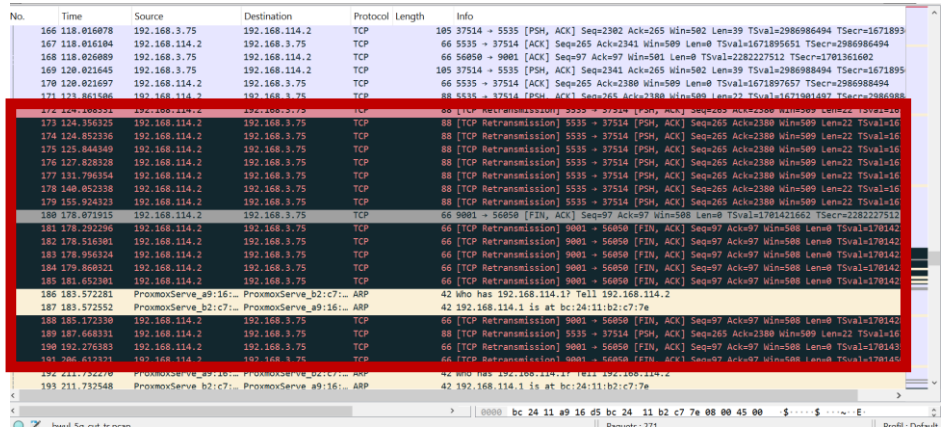
Demo 04 – ETCS over ACS

Demonstration - ETCS over ACS 1/2

Scenario 1 - 5G only + coverage cut

- Link cut at t ≈ 124 s
- 19 TCP retransmissions (124 → 254 s), exponential back-off
- Session 9001 closed (FIN) and re-opened at t ≈ 279 s
- ≈ 155 s without ETCS exchange





Retransmissions from trackside, never acknowledged (link down)

✕ ETCS session lost

- Wireshark captures: ETCS On-Board (192.168.3.75) ↔ ETCS Trackside (192.168.114.2), TCP 5535 & 9001

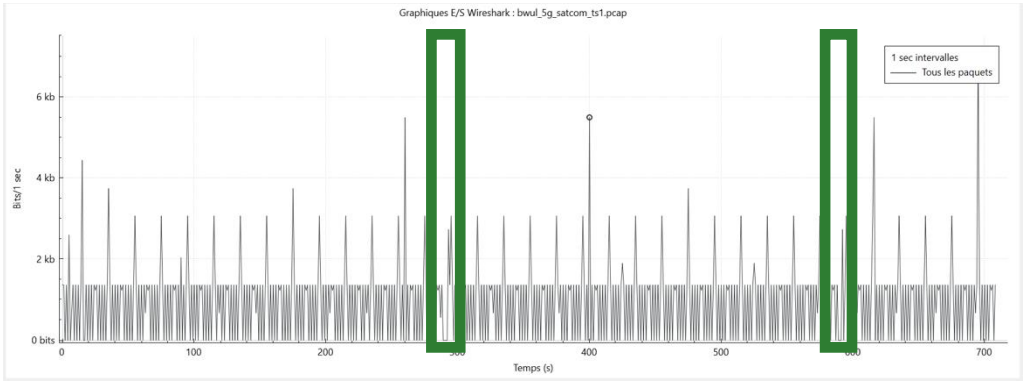
Demonstration - ETCS over ACS 2/2

- Wireshark captures: ETCS On-Board (192.168.3.75) ↔ ETCS Trackside (192.168.114.2), TCP 5535 & 9001

Scenario 2 - 5G + SATCOM, ACS hybridation

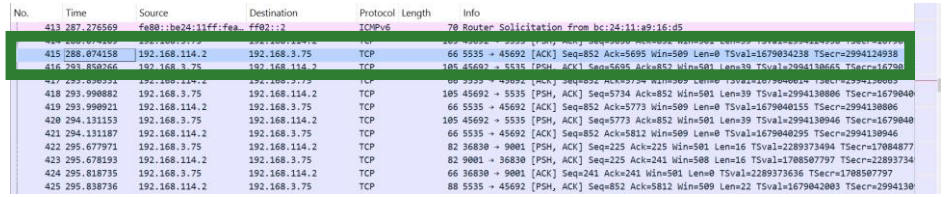
708 s test, 2 handovers (t ≈ 288 s and ≈ 592 s)

- 0 retransmission, no SYN / FIN / RST
- Same TCP sessions kept end-to-end
- Max gap between packets ≈ 5.8 s



Handover #1

Handover #2



No.	Time	Source	Destination	Protocol	Length	Info
413	287.276569	fe80::be24:11ff:fea…	ff02::2	ICMPv6	70	Router Solicitation from bc:24:11:a9:16:d5
415	288.074158	192.168.114.2	192.168.3.75	TCP	66	5535 → 45692 [ACK] Seq=852 Ack=5695 Win=509 Len=0 TSval=1679034238 TSecr=2994124938
416	293.850266	192.168.3.75	192.168.114.2	TCP	105	45692 → 5535 [PSH, ACK] Seq=5695 Ack=852 Win=501 Len=39 TSval=2994130665 TSecr=16790
418	293.990882	192.168.3.75	192.168.114.2	TCP	105	45692 → 5535 [PSH, ACK] Seq=5734 Ack=852 Win=501 Len=39 TSval=2994130806 TSecr=1679040
419	293.990921	192.168.114.2	192.168.3.75	TCP	66	5535 → 45692 [ACK] Seq=852 Ack=5773 Win=509 Len=0 TSval=1679040155 TSecr=2994130806
420	294.131153	192.168.3.75	192.168.114.2	TCP	105	45692 → 5535 [PSH, ACK] Seq=5773 Ack=852 Win=501 Len=39 TSval=2994130946 TSecr=1679040
421	294.131187	192.168.114.2	192.168.3.75	TCP	66	5535 → 45692 [ACK] Seq=852 Ack=5812 Win=509 Len=0 TSval=1679040295 TSecr=2994130946
422	295.677971	192.168.3.75	192.168.114.2	TCP	82	36830 → 9001 [PSH, ACK] Seq=225 Ack=225 Win=501 Len=16 TSval=2289373494 TSecr=17084877
423	295.678193	192.168.114.2	192.168.3.75	TCP	82	9001 → 36830 [PSH, ACK] Seq=225 Ack=241 Win=508 Len=16 TSval=1708507797 TSecr=22893734
424	295.818735	192.168.3.75	192.168.114.2	TCP	66	36830 → 9001 [ACK] Seq=241 Ack=241 Win=501 Len=0 TSval=2289373636 TSecr=1708507797
425	295.838736	192.168.114.2	192.168.3.75	TCP	88	5535 → 45692 [PSH, ACK] Seq=852 Ack=5812 Win=509 Len=22 TSval=1679042003 TSecr=2994130

Handover #1: 288.07 s → 293.85 s

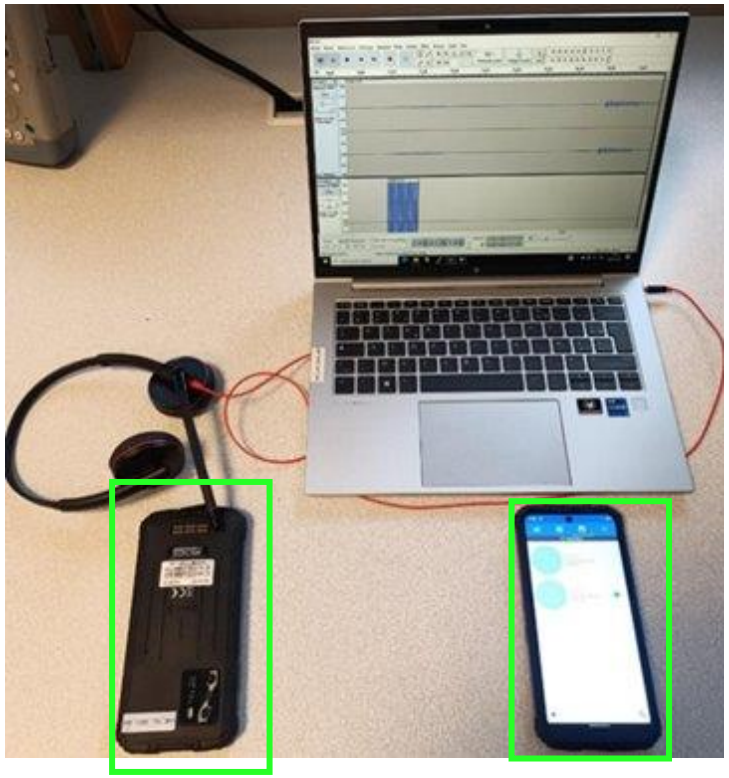
Same session (port 45692), sequence numbers continue (Seq 5656 → 5695), no retransmission

✓ ETCS session maintained

Demo 05 - Hybridisation – Geo (Live)

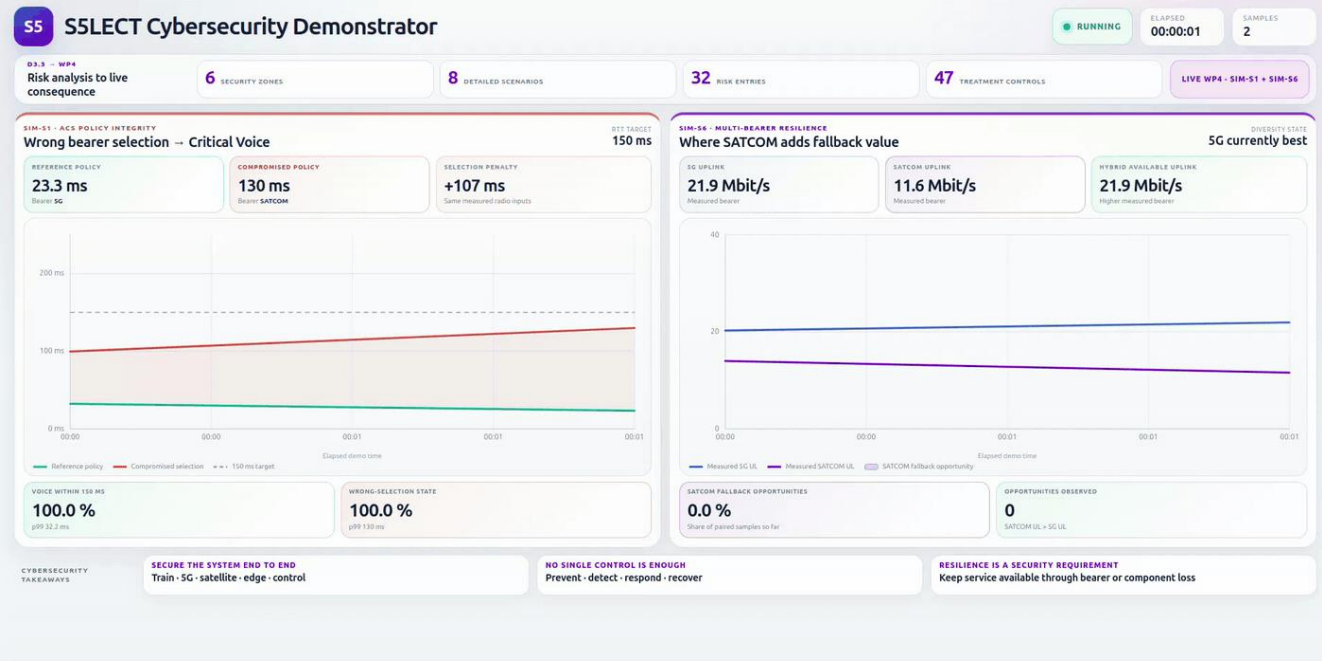
MCX over ACS – Demo

[GIF / video]



Test setup

Cybersecurity Demonstration



Security must be judged on the service, not on the network:
link selection must be protected as a critical function, and hybridization itself monitored, since losing one link does not show in average performance.

What the demonstration shows

Laboratory evaluation on the replayed WP4 trace, indicative values

1 Can an attack hurt the service without touching the network?

Yes: forcing the wrong link degrades voice calls while 5G and satellite are perfectly healthy.

S-1 · calls within 150 ms: about 100 % → 80-85 %

2 Does the damage depend on when it happens?

Strongly: the same compromise can go almost unnoticed or be severe, depending on the moment.

S-1 · calls within 150 ms: about 80 % to 98 %, depending on timing

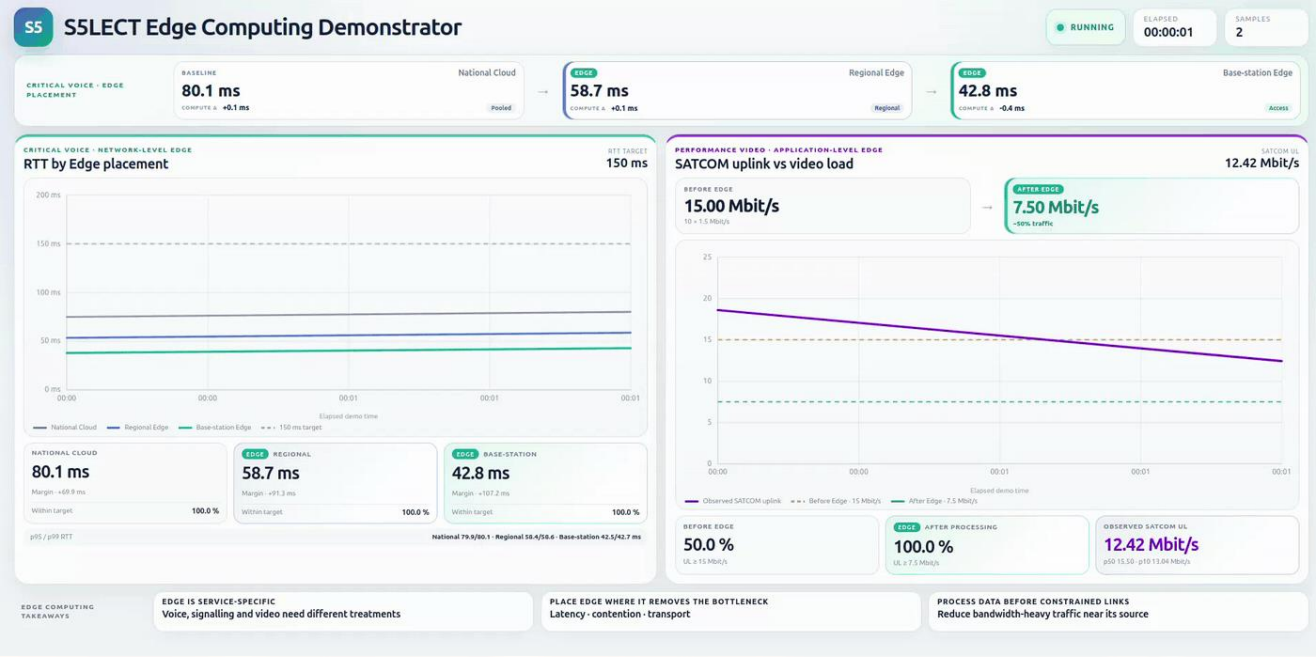
3 Would we notice if an attack disabled the satellite link?

Not with usual metrics: delays do not move, yet the system silently stops being hybrid and loses every moment where satellite was the better link.

S-6 · satellite was the better link in about 8 % of samples

S5LECT
SatCom & 5G Link, Edge & CybersecuriTy

Edge Demonstration



Edge must target the actual bottleneck: placement where transport delay dominates, on-board processing where link capacity does.
Neither removes radio-access limits, which remain a matter of multi-link connectivity.

What the demonstration shows

Laboratory evaluation on the replayed WP4 trace

1 Does moving computing closer to the train always help?

For voice, it buys margin rather than compliance: latency drops by tens of milliseconds, but calls were already on time and radio-link peaks remain.

Calls within 150 ms: about 99.4 % → 99.8 %

2 Where does Edge make the real difference?

For video: processing on board, before the satellite link, makes a saturated link usable again.

10 trains, video halved on board: link sufficient about 1 % → 90 % of the time

3 How far does it scale?

With video reduced on board, the same satellite capacity serves many more trains.

4× reduction: about 20 trains served 90 % of the time



S5LECT
SatCom & 5G Link,
Edge & CybersecuriTy

www.s5lect-project.eu