Federation of Satellite Systems for Integrated Satellite-Terrestrial Networks: the 5G-HUB Project

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Abstract— **Satellite communication networks have long served as a vital connectivity backbone across Europe, particularly in remote and strategic areas. To enhance the efficiency of satellite operators in managing connectivity demands, the 5G-HUB project (within the Horizon Europe framework) aims to advance the EU's flagship GOVSATCOM initiative by developing a flexible and interoperable network management interface. This interface will link the GOVSATCOM-HUB (G-HUB) with resource providers deploying 5G core networks and microservice-based infrastructure. The project will validate G-HUB functions through three trials involving an interoperable 5G Non-Terrestrial Network (NTN) terminal operating in Ku and X bands. These trials will assess seamless resource allocation, Quality of Service (QoS) provision, and transparent traffic steering between satellite and terrestrial networks, especially in critical scenarios such as emergency and maritime operations. Additionally, the project will explore interoperability across multiple satellite network operators to support robust and resilient governmental communications.**

Keywords—Fifth Generation Systems (5G), Non-terrestrial Networks, Software-Defined Networking, Integrated Networks, Vertical Handover.

I. INTRODUCTION

The integration of Terrestrial Networks (TNs) and Non-Terrestrial Networks (NTNs) is crucial for addressing the growing demand for ubiquitous and seamless connectivity, as well as for filling the coverage gaps of these systems [1]. Integrated systems imply a form of interoperability among the networks. Currently, many satellite operators are complementing their systems by defining agreements with other operators using different orbits [e.g., Geostationary Orbit (GEO) and Low Earth Orbit (LEO), GEO and Medium Earth Orbit (MEO), etc.]. A federation of satellite systems (using the same or different orbit types) implies robust service provision, enhanced capacity, and complementary coverage. This is, for instance, the case of Viasat (GEO) and Telesat (LEO), or Eutelsat (GEO) and OneWeb (LEO), or SES (GEO) and O3b (MEO). The federation can help share the traffic load among satellite systems, thereby improving the Quality of Service (QoS). Regulations are needed to support system federation and avoid the monopoly of the satellite communications market. The 3GPP standard for 5G/6G systems plays a crucial role in enabling resource federation among different commercial operators. Further work is underway with the next Releases 19 and 20 [2]. The European approach in the field of governmental satellite communications (GOVSATCOM) is to design a GOVSATCOM-HUB (G-HUB) resource broker that matches authorized users with overall available satellite resources. The G-HUB, provided by partner INDRA Espacio, is based on a ticketing system and employs a mixed approach with fixed and dynamic capacity allocations to serve institutional users, specifically the Competent GOVSATCOM Authorities (CGAs). The G-HUB, expected to be operational by 2027, will federate the resources of several Satellite Network Operators (SNOs). In December 2024, the European Commission signed a contract with the SpaceRISE consortium (comprising three European SNOs: SES, Eutelsat, and Hispasat) to build a multi-orbit constellation of about 290 satellites (264 LEO at high altitude of 1200 km, 10 LEO at low altitude below 750 km, and 18 MEO at 8000 km altitude), known as IRIS^2 (Infrastructure for Resilience, Interconnectivity, and Security by Satellite) to be operational by 2030. IRIS^2 will be connected to the G-HUB to federate satellite resources on LEO, MEO, and GEO orbits.

This paper deals with the 5G-HUB project (coordinated by the University of Siena, Italy, with technical management carried out by CTTC, Spain) within the Horizon Europe Framework, which aims to leverage the G-HUB by integrating its resources with those of a 5G TN system to experiment with different emergency scenarios where service continuity is needed [3].

TABLE I. COMPARISON WITH OTHER PROJECTS

Project	Technology/Platform	Key Contributions	Benefits/Findings
VITAL [6]	Vendor-independent SDN/NFV ground segment	Proposed softwarization for hybrid satellite-terrestrial backhaul.	Enabled flexible traffic routing across mixed paths.
Sat5G [7]	OpenStack, OpenDaylight	First end-to-end virtualized satellite trial with live HD video streaming over GEO using MEC.	Validated satellite-terrestrial integration and latency mitigation.
5G-ALLSTAR [8]	SDN RAN Controller, mmWave + Ku-band	Realized multi-connectivity with load balancing across satellite and terrestrial networks.	Demonstrated SDN-driven handover and blockage-aware performance indicators.
IAC-24 [9]	SDN Architecture, Kubernetes-native 3-tier controller hierarchy	Distributed control: onboard satellites, gateways, and edge.	Reduced control-plane latency by 37%; retained efficiency.
CloudSat [10]	OpenStack, OpenDaylight	Lab-tested full satellite-terrestrial softwarization; provided a roadmap for virtualized satellite systems in 5G.	Identified benefits and deployment challenges for 5G NTN.
5G-HUB	Open5GS, G-HUB , Smart Gateway; Ku/X band UE terminals; 3GPP Rel-17	Integration of G-HUB into 5G NTN architecture; resource federation across SNOs (e.g., Hispasat, Hisdesat); seamless TN/NTN handover via Smart Gateway.	Federated multi-operator satellite access, seamless vertical handover with service continuity, dual-band (Ku/X) UE design.

Network softwarization and open interfaces will be adopted to enable dynamic control and centralized management of resources, thereby adapting to the unique challenges of NTN. The 5G-HUB project, under the responsibility of the European Union Agency for the Space Programme (EUSPA), enables features such as dynamic routing, bandwidth allocation, and mobility support. The 5G-HUB project aims to validate the G-HUB functions over 5G TN and NTN in trials with the initial development of a unified terminal.

The 5G-HUB project addresses the open challenges faced in the initial deployment of G-HUB and the need to create all elements across it, ranging from the ground segment to the user terminals. Network automation is necessary for SNOs to benefit from the use of G-HUB, but significant work remains to be done to achieve this goal. 5G-HUB plans to evaluate a set of interface virtual functions of an early demonstrator of G-HUB with two SNOs: Hispasat (a commercial SNO in Ku band) and Hisdesat (a governmental SNO in X band).

Mobility between TN and NTN domains poses a significant challenge, particularly in maintaining service continuity. The approach adopted in the 5G-HUB project is to complement the functions of the G-HUB with a new network element called Smart GateWay (SGW), involving a client operating on the user side and a server operating on the service provider side. The SGW will facilitate a seamless Vertical Handover (VHO) between TN and NTN, a key requirement of the 5G-HUB project.

The 5G-HUB will test MCx services in the context of Public Safety and Disaster Relief (PPDR), both on land (e.g., emergency management for earthquakes) and at sea (e.g., humanitarian aid) [4]. These services have stringent requirements in terms of capacity, reliability, and latency. The Italian Red Cross (CRI) and Open Arms (OARMS) will be involved in the experiments of MCx through the integrated TN-NTN system. The 5G-HUB project utilizes the Mobitrust platform (developed by One Source, ONE) to provide secure MCx [5]. Mobitrust enhances situational awareness in safety and emergency response scenarios, offering a robust and user-friendly interface for managing MCx communications and video streams in real-time. In 5G-HUB, the Mobitrust platform is being extended to interoperate with both TN and NTN. In collaboration with end-users, such as the CRI and OARMS, ONE will showcase Mobitrust's ability to maintain communication flows and service orchestration across TN-NTN domains. Table I compares the novelty of the 5G-HUB approach with other projects, including VITAL [6], SaT5G [7], 5G-ALLSTAR [8], the study presented in reference [9], and the CloudSat project [10].

II. USE CASES

This section outlines the use cases of the 5G-HUB system and details the associated service requirements.

A. Maritime Search and Rescue Mission, and Provision of Humanitarian Aid in Conflict Zones

Open Arms conducts Search and Rescue (SAR) and humanitarian missions in the Central Mediterranean, often over 200 nautical miles offshore. Missions follow a five-phase structure:

1. **Departure & Transit**: The vessel departs based on intelligence and forecasts, with robust communication systems (e.g., satellite links, the Automatic Identification System, AIS).
2. **Detection of Distress**: Alerts are received from various sources. The crew prepares for intervention using encrypted communications and satellite data.
3. **SAR Deployment**: Drones and rescue boats locate and assist people in distress. High-bandwidth, multi-channel communication ensures coordination.
4. **Onboard Medical Support**: Survivors receive medical and psychological triage. IoT devices and telemedicine tools enable remote diagnostics and secure data sharing.
5. **Return & Handover**: Communications transition from satellite to terrestrial networks when the ship returns, requiring the sending of reports and data for follow-up.

The primary requirements of this scenario pertain to the throughput in the return link, which is the most demanding and encompasses latency and reliability considerations. The communication requirements are derived from [11], which addresses an aerial surveillance scenario utilizing a 5G system supported by drones. In this case, video streaming traffic is needed, which requires a throughput of 5-10 Mbps and latency values of up to 100 ms, aligning well with LEO orbit satellite infrastructures. Moreover, reliability has five-9s requirement to support the challenging requirements of OARMS use cases.

B. *Telemedicine and Humanitarian Aid for Crisis Management*

Italian Red Cross follows a structured approach for emergency responses (including SAR, mass disasters, public events, and international deployments), relying on sector-based coordination, real-time communication, and tactical deployment. The operation is divided into five key stages:

- **Initial Deployment and Sectorization of the teams**: Upon arrival, the area is digitally mapped and divided into sectors. Teams are assigned to sectors (i.e., Search & Rescue, Triage & Stabilization, Logistics). Involved teams are coordinated, sharing real-time geo-data, video, and sensor information with the Advanced Command Post (Italian acronym PCA).
- **Multi-Incident Activation**: Multiple emergencies (e.g., building collapse, gas leak, road blockage) occur simultaneously. Field data is escalated to the PCA, which uses real-time inputs to adjust deployments dynamically.
- **Tactical Relocation**: Overloaded sectors trigger real-time personnel reassignment (e.g., from Sector 3 to Sector 1). The 5G-HUB project ensures seamless handover and command continuity.
- **Network Disruption & Satellite Integration**: The failure of 5G TN prompts automatic failover to 5G NTN. The system maintains communication stability by switching operators (e.g., Operator A → B).
- **Strategic Data Transmission**: Key data (video, medical assessments, reports) are sent to the CRI National HQ in Rome via satellite. The HQ monitors, provides strategic input, and coordinates reinforcements or international assistance.

The throughput requirements again refer to the return link of the NTN system. The contemporary use of multiple communication services (e.g., real-time audio and video calls, IoT sensor data, telemedicine applications) may result in an aggregate throughput requirement of up to 5 Mbps per sector (15 Mbps in total for the three sectors), while the maximum acceptable latency can be as high as 250 ms [12]. Also in this use case, the highest reliability is required to support CRI operations in disaster scenarios.

III. SYSTEM ARCHITECTURE

The 5G-HUB system is based on a hybrid 5G TN/NTN environment by deploying GEO-based satellite capacity in Ku and X bands. The SNO interfaces with the G-HUB via the Common Provider Interface (CPI), supporting both static and dynamic resource allocation.

A. *Smart Gateway Architecture and Functionalities*

A central component in the 5G-HUB architecture is the SGW, consisting of:

- **Smart Gateway Client** (SGW-C): Positioned near the user equipment, responsible for monitoring TN and NTN radio link connectivity, executing access selection logic, and collecting QoS metrics.
- **Smart Gateway Server** (SGW-S): Deployed within operator domains, at neutral facilities, or co-located with the G-HUB. It manages switching logic and orchestration with the G-HUB.

B. *G-HUB and Interfaces with Network Elements*

The G-HUB plays a central role in the 5G-HUB project as a service broker, acting as a policy-driven coordination point between CGAs, satellite Resource Providers (RPs), and institutional supervisors (e.g., EC/EUSPA). Its core functionalities include internal configuration management (participants, roles, access policies), handling and validation of service requests, token assignment and management, and the standardization of these requests based on a common set of attributes (such as service type, priority, availability requirements, classification, etc.). SNOs' control centers interact with the G-HUB via the CPI interface for service orchestration, resource management, and service monitoring. Moreover, GOVSATCOM users and CGAs interact with the G-HUB through a Web interface, enabling them to submit service requests, monitor services, and check resource status. While the G-HUB centralizes and validates this functional information based on predefined attributes, the G-HUB does not participate in the technical allocation of SATCOM resources, such as satellite selection, beam assignment, or transponder configuration, which remain under the responsibility of the satellite RPs. This functional separation ensures that the G-HUB operates independently from the technical management of resources, enabling it to define and request different types of services according to the institutional roles and division of responsibilities for GOVSATCOM.

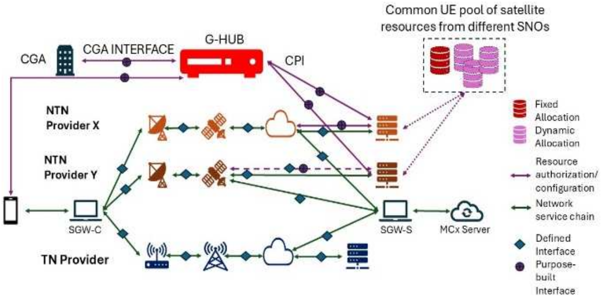

Fig. 1. 5G-HUB architecture (and interfaces) with alternative SNOs because of resource federation and TN-NTN integration.

C. *Security Considerations*

The TN-NTN integration envisioned in the 5G-HUB project adopts encrypted communications between SGW components using Virtual Private Networks (VPNs). Additionally, a broader security strategy must be considered. All interfaces introduced (such as those connecting the G-HUB with the SNOs) should be secured using strong authentication and encryption to mitigate risks such as configuration injection. Furthermore, all transactions should be permanently logged to support non-repudiation and auditability. These logs can also feed real-time AI/ML-based anomaly detection systems, enabling the detection of unauthorized or malicious activity. Robust authorization mechanisms are also crucial to ensure that each component accesses only the resources required, adhering to the principle of least privilege. These security measures must be complemented by considering threats and attack surfaces that may be introduced by the new architecture. For instance, the introduction of external SGW and G-HUB could create potential targets for attackers if not hardened. A possible approach is to use bidirectional authentication among G-HUB, SGW, and network operators, so that only trusted entities can initiate resource requests.

D. System Challenges

A key challenge for this system is the development of a dual-mode 5G UE terminal capable of connecting to both TN (typically using 3.5 GHz bands) and NTN (using Ku and X bands). Another challenge for this system is to keep the same IP address during VHO for both the UE and the MCx server to achieve service continuity (seamless VHO), a key requirement for the use cases envisaged by the 5G-HUB project. Current 3GPP specifications do not support VHO; they consider, for the moment, only idle mode mobility from TN and NTN. Another challenge for VHO concerns the complexity of achieving interoperability among TN and NTN of different operators, even when adopting the 5G standard; this is due to business and security concerns that prevent direct interactions among their networks. Finally, there is the challenge posed by the impact of satellite latency on the VHO interruption time when a break-before-make handover is adopted. Future challenges to be addressed include the adoption of the Network Exposure Function (NEF) and AI-enhanced decision logic that leverages cross-domain Key Performance Indicators (KPIs), enabling more intelligent and adaptive operations of the G-HUB.

IV. USER TERMINAL DESIGN

Within the context of the 5G-HUB project, a unified TN/NTN user terminal (compliant with Release 17) is proposed to facilitate the integration of both network segments, as illustrated in Figure 2.

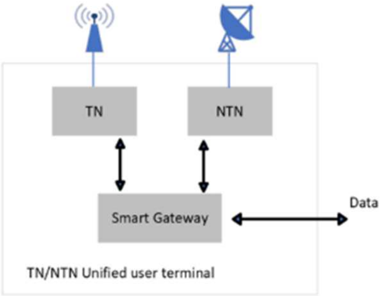

Fig. 2. Block diagram of the unified user terminal with TN and NTN radios.

To implement the 5G NTN terminal, the necessary modifications to the 5G protocol stack are:

- Enhancing random-access procedures.
- Pre-compensate for large propagation delays and Doppler frequency shifts.
- Disable or enhance the Hybrid Automated Repeat reQuest (HARQ) process.
- Using System Information Block 19 (SIB19).
- Updating timers and buffers.

The 5G NTN terminal implementation uses the srsRAN_4G project as a baseline [13]. It provides an open, standalone implementation of several 5G features for user terminals. Then, the 5G NTN radio will be able to connect to a satellite network through a GEO constellation and a transparent architecture where the service and feeder links are considered. Processing of the SIB19 field by the 5G NTN terminal is essential for it to access the resources of the satellite network. Using this, the gNB can spread relevant information about satellite position and feeder link in its serving area. The SIB19 is composed of three main elements: satellite ephemerides, timestamp, and feeder link-related parameters. Ephemerides contain information about satellite position and velocity, and are used to estimate the distance between the satellite and the UE, as well as the Doppler frequency shift on the service link. The timestamp indicates the epoch time of the provided ephemerides.

Additionally, the 5G NTN terminal will be capable of operating in both Ku and X frequency bands. For Ku-band connectivity, a Kymeta 8u antenna will be used, which features electronically steerable capabilities. The pointing mechanism is performed via the Open-AMIP protocol, which will be incorporated as a submodule of the 5G NTN terminal. This protocol relies on signal quality measurements, combined with GNSS data and the satellite's position. For X-band connectivity, an IDR TXN-10 antenna will be used, which is suitable for maritime on-the-move environments. At the same time, the 5G TN terminal will operate in one of the available commercial 5G systems. The unified TN/NTN UE will be built by implementing each of its components on the Software-Defined Radio (SDR) platform E320, which has high processing capacity and incorporates a baseband processing module based on the Xilinx Zynq-7045 SoC.

The design challenges and limitations on the implementation of 5G NTN terminals are quite demanding at the physical layer due to the impairments of the satellite channel, which presents large propagation delays, high Doppler shifts, and high path loss. Moreover, we have to consider time and frequency synchronization, duplexing modes, and the use of robust modulation schemes. The Round-Trip Time (RTT) in LEO/MEO/GEO systems can be up to 50 ms/150 ms/600 ms, respectively: large RTT values limit the applicability of HARQ schemes.

V. NETWORK MANAGEMENT DESIGN

The key approach for integrating TN and NTN networks is based on the softwarization and disaggregation of monolithic 5G Network Functions (NFs), the separation of control and user planes, and the use of open interfaces. The adoption of appropriate Management and Orchestration (MANO) procedures, like those proposed by ETSI Network Function Virtualization (NFV) and ETSI Zero Touch Network and Service Management (ZSM), provide flexibility and dynamicity to perform automated lifecycle management of mobile network deployments, thus overcoming current manual management procedures at Mobile Network Operators (MNOs) and SNOs. In our integrated vision, depicted in Figure 3, each SNO will employ a MANO framework component in its Operations Support System/Business Support System (OSS/BSS), enabling it to host and configure satellite 5G-based communication service requests originating from the G-HUB.

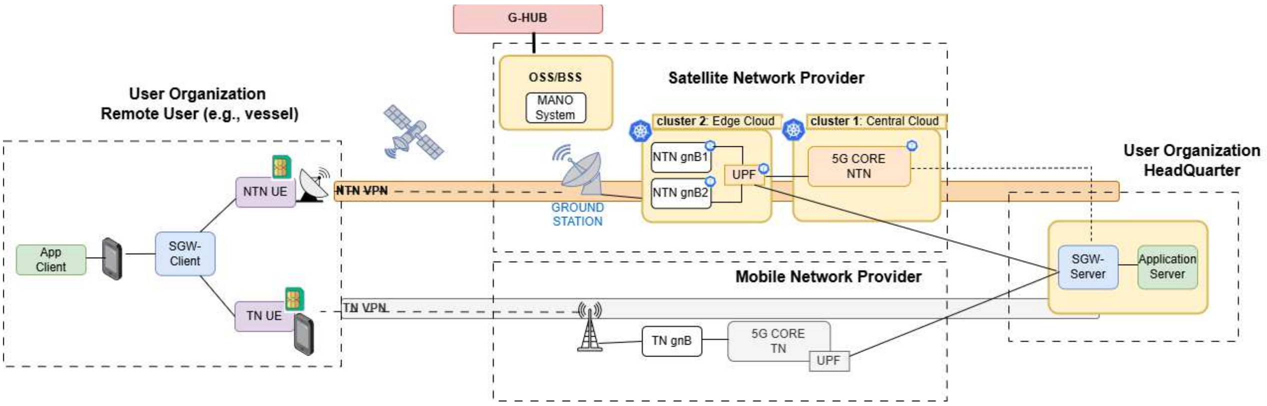

Fig. 3: 5G-HUB network management design embracing a cloud-native approach at the SNO to introduce automation.

To deploy such a mobile core instance, we consider a cloud-native approach based on Open5GS open-source software. This software is aligned with 3GPP Release 17 specifications and provides an appropriate testing framework for the intended NTN-TN integration. The mobile core can be deployed, separating the Control Plane (CP) and User Plane (UP). The CP functions can be deployed in a centralized Point of Presence (PoP). In contrast, User-Plane Function (UPF) instances can be deployed on demand at edge locations [14]. The UPF provides a connection from the mobile network to external data networks, such as those of vertical application servers. With this approach, a UPF instance can be placed close to a gNB instance running in a given ground station, thereby establishing a local breakout point to reduce round-trip latencies if application servers are co-located, as shown in Figure 3.

Regarding the RAN segment, the MANO system at the SNO will process incoming G-HUB requests of 5G-based communications by launching dedicated NTN gNB instances and connecting them to the available mobile core owned by the SNO. For such deployments of RAN components, we also propose using a cloud-native approach, such as in [15]. MANO procedures based on cloud-native artifacts enable the seamless and automated deployment of network functions across diverse environments, facilitating resource management and enhancing network performance. Figure 4 shows a boxplot representing the times required to start an instance of the CP part of a 5G core network, a UPF, and a gNB in a Kubernetes cluster, using Open5GS and srsRAN open-source software. As can be observed, the time required for each entity is around 32 s, providing significant agility and flexibility to the process, as the lifecycle management of such gNB instances is tailored to the length of the service request made by G-HUB.

The remaining components to integrate in the envisioned dynamic and automated management scheme are SGW-S (one per each user organization) and SGW-C (one per end user). As previously mentioned, they provide a seamless interoperability process transparent to end-users between TN and NTN/s networks. This is achieved by following the strategy inspired by [16] (see Figure 3), which utilizes VPNs. These VPNs are established once the TN and/or NTN connections are operational, being independent from the involved MNOs and SNOs, and the VPNs allow end-to-end communications between the end user and the MCx application server.

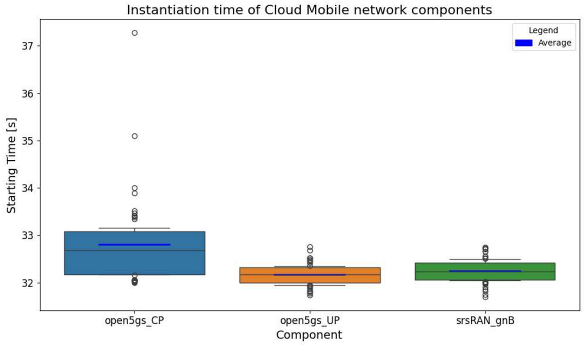

Fig. 4. Instantiation time of cloud-native mobile network components.

Currently, SGW-C collects real-time network metrics from NTN and TN and, based on configured VHO policies, triggers a VHO when necessary, by interacting with the SGW-S through a RESTful API via the new interface G0, which supports control commands for VPN management, connection authorization, and VHO-related traffic path updates (re-routing). If the CP functions of the NTN mobile core provide exposure capabilities [e.g., interaction with Policy Control Function (PCF) through NEF)], they could be exploited by the SGW-S instance available at user organization, working as a 3GPP Application Function (AF), for policy control and enforcement to implement flow control policies towards application servers.

If the TN connection degrades in terms of Signal-to-Interference and Noise Ratio (SINR) measurements, the SGW-C of the unified UE can detect this issue and initiate a VHO procedure that requires synchronizing the routing path on both SGW-S and SGW-C. This approach deviates from conventional 3GPP handovers, where decisions are made by the gNB. In particular, SGW-C and SGW-S function like routers, switching traffic along one path (TN VPN) or another path (NTN VPN) to perform the VHO. In this way, the VHO occurs without changing the IP addresses of the end-user and the application server, thus maintaining service continuity. Performance can be assessed using KPIs such as VHO failure rate and VHO ping-pong rate. Moreover, the proposed VPN scheme allows the system to be scaled by adding additional network interfaces at the SGW-C. This introduces a challenge to the VHO algorithm, which needs to be enhanced considering the availability of multiple NTN 5G-based connections. 5G-based connections via NTN are activated upon demand because they are expensive and need to be used only for the necessary time. This is why dynamic resource allocation on the satellite side via G-HUB is important. We do not consider a single subscription for the UE since this would imply using a single core for both TN and NTN. We aim for a more general approach that allows the possibility of federating independent SNOs and MNOs, including those from different countries.

VI. PROJECT DEMOS

The solution developed during the project will undergo an experimental phase aimed at validating its effectiveness, measuring KPIs, and collecting insights to guide future research and development efforts. This phase will commence with a lab-scale trial conducted at the CTTC facilities, allowing for initial testing and fine-tuning in a controlled environment. Following laboratory validation, the solution will be assessed in two real-world demonstration scenarios, as outlined in the following subsections.

A. *Demo in Spain for Telemedicine and Humanitarian Aid at Sea*

The telemedicine humanitarian aid demonstration will take place in a maritime environment at a location in Spain (e.g., the Port of Barcelona). It will focus on the system's ability to ensure seamless VHO between 5G TN and 5G NTN. The demonstration scenario involves a vessel equipped with telemedicine communication systems moving progressively away from shore (see Figure 5). As the vessel transitions into an area where terrestrial connectivity begins to degrade, the system will autonomously manage the VHO to a 5G-NTN connection, which has been pre-authorized via G-HUB negotiation. Key objectives of the demo include: (*i*) Ensuring service continuity across heterogeneous network domains; (*ii*) Demonstrating the system's resilience and mobility management capabilities in real-time operational conditions, where service continuity is essential for remote medical consultations, diagnostics, and assistance.

Fig. 5. Scenario envisaged for the demo in Spain: OARMS ship with telemedicine equipment.

B. *Demo in Italy for Crisis Management Caused by Earthquake*

The crisis management demonstration (see Figure 6) will be conducted in mainland Italy using the CRI facilities in Bresso, Italy. It will evaluate the capabilities of the 5G NTN to ensure reliable emergency communications in scenarios where terrestrial connectivity is unavailable or degraded, due to natural disasters or conflict-related disruptions. Following a simulated failure or congestion of the 5G TN, the Italian Red Cross operational field team will establish connectivity to an MCx application server via the 5G NTN. This connection will be enabled using resources pre-allocated by an NTN resource provider, selected and assigned through G-HUB negotiation mechanisms. The demonstration will focus on the ability to: (*i*) Enable immediate and seamless switchover to the NTN with minimal service interruption; (*ii*) Support comprehensive MCx services, including real-time video and audio communications, which are critical for operational coordination, situational awareness, and the effective management of emergency response efforts.

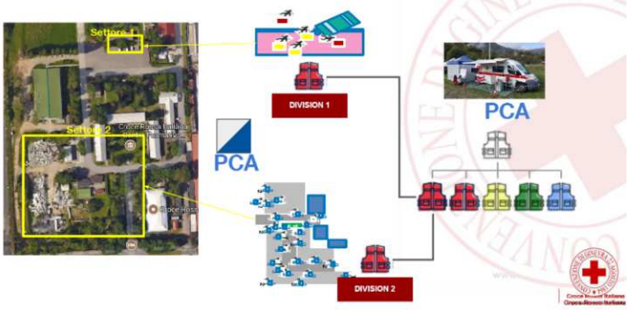

Fig. 6. Scenario of the demo in Italy to be carried out at the Preparedness Centre (Bresso, Milan) with a rubble field simulating an earthquake.

VII. KPIS AND PRELIMINARY RESULTS

Following the use case scenarios investigated in Section II, the numerical KPIs of the project have been summarized in Table II.

TABLE II. MAIN REQUIREMENTS FOR PROJECT USE CASES

KPI	Requirement	Justification
Packet Loss Rate	≤1% (Good), 1-5% (Acceptable), > 5% (Bad)	Packet loss above 5% affects communication quality
Service Interruption Time	⩽ 110 ms [17]	VHO is not seamless if the interruption is larger than this time
Authentication Success Rate	≥ 99%	Ensures legitimate access to the service without problems (e.g., an NTN UE terminal can attach to the network).
Percentage of the Time the Throughput ≥ CIR	≥ 99.999%	CIR is the minimum bit-rate value to guarantee an acceptable service level
Service Reliability	≥ 99.999%	Percentage of time the service is available
Minimum SINR requirement	−5 dB	Minimum SINR value below which our UE is unable to provide reliable connectivity with TN and NTN radios
VHO Failure Rate	< 5%	Percentage of failure in performing the VHO
VHO Ping-Pong Rate	< 10%	Percentage of Ping-Pong VHOs versus Total Number of VHOs

A preliminary investigation has been carried out to evaluate the VHO performance in terms of VHO failure rate and VHO ping-pong rate, where the TN system is modeled according to rural macro-A propagation conditions and the NTN segment is based on a 600 km altitude quasi-polar LEO constellation with earth-moving cells and details provided in set-1 of TR 38.821 [18]. In particular, we have investigated the TN-to-NTN VHO case, considering two alternative SINR-based triggering conditions (named following the names of handover events in 5G systems), where the SINR values of both TN and NTN have been filtered at L1 to L3 to remove, in part, fluctuations that can cause some problems and early or late VHO decisions. In particular, the L3 smoothing filter is based on a parameter β to weigh current SINR values (updated every 150 ms). The first VHO scheme is denoted as A2, where VHO is triggered before SINR goes below a minimum value. Here, a Handover Margin (HOM), denoted as HOM_1, is adopted to anticipate the disconnection event, and another handover margin with value HOM_2 is used to introduce hysteresis against the ping-pong effect. The VHO triggering condition has to persist for a certain Time-to-Trigger (TTT) before the VHO is decided. More details on this scheme are provided in [19]. The second VHO scheme is denoted as A3, where the SINR values of TN and NTN are compared, and the VHO is decided when the SNIR of TN goes below the SINR of NTN (plus a margin denoted as HOM) for more than TTT time. The VHO performance results are shown in Figure 7, adopting the following heuristically optimized settings: (*i*) A2 with $HOM_1 = 5$ dB, $HOM_2 = 3$ dB, $TTT_1 = 2$ s, $TTT_2 = 5$ s; (*ii*) A3 with HOM = 4 dB, TTT = 5 s. In both cases, the L3 filter has $\beta = 1/30$. We can see that the A3 scheme, with the selected parameters, meets the requirements outlined in Table II.

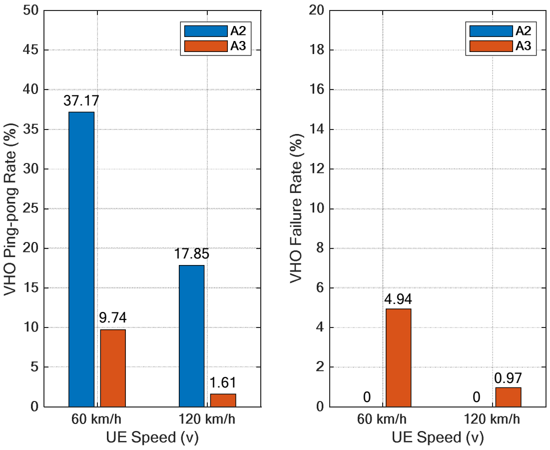

Fig. 7. VHO ping-pong rate and VHO failure rate for an integrated TN-NTN system.

VIII. CONCLUSIONS

The 5G-HUB project enables seamless integration of terrestrial and non-terrestrial networks for mission-critical applications under the EU GOVSATCOM framework. By combining the G-HUB's federated resource management with Smart Gateway-based VHO, the system ensures service continuity across TN and NTN domains. Key innovations include a unified Ku/X-band NTN user terminal, softwarized network functions, and dynamic orchestration aligned with 3GPP Release 17 standards. The project will conduct two real-world demonstrations (disaster response and maritime telemedicine) to assess QoS, VHO performance, and interoperability, thereby reinforcing 5G-HUB's role in delivering resilient, scalable NTN-TN solutions for governmental services. The project is also expected to provide contributions to 3GPP and ETSI standardization.

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