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DONUTS deliverable D1.1 - Use cases: applications and requirements

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DONUTS deliverable D1.1

Use cases: applications and requirements

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Executive summary

The DONUTS project aims to deliver seamless, resilient communication services across the integrated space-air-ground networking continuum. Future digital services will increasingly rely on heterogeneous network infrastructures combining terrestrial, aerial, and satellite components to provide ubiquitous coverage, service continuity, and robustness against dynamic and disruptive conditions. In this context, a clear identification of relevant application scenarios and their associated requirements is essential to steer the project's architectural and technological development.

This deliverable establishes the reference use cases and derives the corresponding functional and performance requirements that guide DONUTS research and innovation activities. After introducing the overall project vision and key challenges, three representative use cases are defined. The first addresses seamless connectivity in large-scale mobile events, where dense user populations and highly dynamic topologies require adaptive resource management and mobility-aware orchestration. The second focuses on ubiquitous logistics connectivity across multimodal transportation chains, emphasizing reliable end-to-end communication and minimized latency to support real-time tracking, coordination, and control of moving assets. The third considers direct-to-device emergency connectivity, highlighting resilience and rapid service provisioning when terrestrial infrastructure is damaged or unavailable.

Building upon these scenarios, the deliverable outlines preliminary requirements and aligns the planned project tasks with the identified use cases. It lays the foundation for subsequent work packages on the design of the multi-layer space-air-ground architecture, the definition of control and management mechanisms, the development of the network digital twin, and the elaboration of evaluation scenarios.

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List of Acronyms

3GPP 3rd Generation Partnership Project.

AGV Automated Guided Vehicle.

AP Access Point.

ATSSS Access Traffic Steering, Switching, and Splitting.

DONUTS Design and mOdeling of multiscale multitechnologies Networks of the fUture: from cellular 5G/6G to non Terrestrial networks.

GEO Geostationary Earth Orbit.

gNB Next-generation Nobe-B.

GNSS Global Navigation Satellite Systems.

HAP High-Altitude Platform.

ISL Inter-Satellite Link.

LEO Low Earth Orbit.

LIDAR Light Detection And Ranging.

MEO Medium Earth Orbit.

NDT Network Digital Twin.

NTN Non-Terrestrial Networks.

QoS Quality of Service.

RAT Radio Access Technologies.

SAGIN Space-Air-Ground Integrated Network.

TN Terrestrial Networks.

TSN Time Sensitive Networking.

UAV Uncrewed Aerial Vehicle.

UPF User Plane Function.

VNF Virtual Network Function.

1 Introduction

This deliverable D1.1 reports the outcomes of the activity carried out in Task 1.1 of the DONUTS project, focusing on establishing the use cases and requirements that guide the technical trajectories of DONUTS (Design and mOdeling of multiscale multitechnologies Networks of the fUture: from cellular 5G/6G to non Terrestrial networkS (DONUTS)). This document is aligned with ongoing European research on non-terrestrial and integrated networks, and draws inspiration from the 6G-NTN project, in particular from Deliverable D2.1 “Use Cases Definition” [10].

The rapid evolution of communication systems toward increasingly heterogeneous, dynamic, and highly mobile environments is redefining the requirements for next-generation network architectures. Emerging applications demand unprecedented levels of reliability, coverage, adaptability, and service continuity. Traditional Terrestrial Networks (TN) alone are no longer sufficient to meet these expectations. Instead, future connectivity depends on the seamless convergence of space, air, and ground infrastructures into a unified and intelligent communication fabric. The DONUTS project is conceived in this context, aiming to design, evaluate, and validate a holistic space-air-ground integrated network (SAGIN) architecture [6,7] that ensures seamless, efficient, and robust connectivity across highly diverse environments and operational conditions.

DONUTS seeks an ambitious vision: leveraging satellites in multiple orbits, high-altitude platforms, Uncrewed Aerial Vehicles (UAVs), and beyond-5G/6G terrestrial systems to form a multi-layered, adaptive continuum. Achieving this vision requires addressing several intertwined challenges, including dynamic multi-technology resource management, continuous and disruption-free mobility support, optimized placement of network functions across distributed infrastructures, time synchronization across heterogeneous network segments, and control mechanisms capable of responding to constantly changing topologies and Quality of Service (QoS) requirements. A key enabler for these goals is the development of a multi-technology Network Digital Twin (NDT) [3, 11] that provides a consistent, real-time representation of the integrated network, supporting informed decision-making and forecasting while maintaining manageable computational complexity.

Beyond these challenges, the DONUTS architecture must also ensure high service availability, leveraging Non-Terrestrial Networks (NTN) to maintain connectivity even when terrestrial infrastructure is congested, damaged, or unreachable. At the same time, the system must support service versatility, intelligently combining TN and NTN resources to deliver the most suitable service profile depending on context, user demand, and network conditions. This seamless interplay between terrestrial and non-terrestrial segments is essential to fully exploit the flexibility of the space-air-ground continuum. Taking into account these cross-cutting requirements, we have identified three representative and impactful use cases:

- **UC1 – Seamless connectivity: handling large scale mobile events**, highlighting the need for real-time, high-capacity, and resilient communication under extreme user density and mobility, remote areas, infrastructure mobility, and rapid fluctuations in demand.
- **UC2 – Ubiquitous connectivity: enhancing worldwide logistics**, emphasizing reliable tracking, coordination, and data exchange across multimodal and geographically diverse transport operations.
- **UC3 – Resilient connectivity: facing emergency situations**, addressing unpredictable events and the crucial requirement for immediate, infrastructure-independent communication services when terrestrial networks are damaged or unavailable.

Together, these use cases form the basis for deriving functional, architectural, and performance requirements that will influence the design choices made in the subsequent work packages.

The remainder of this deliverable is organized as follows. Sections 2, 3, and 4 present the three use cases, Section 5 aligns the project tasks with the identified use cases, and Section 6 summarizes the main outcomes of this deliverable and draws concluding remarks.

2 UC1 – Seamless connectivity: handling large-scale mobile events

2.1 Scenario overview

One illustrative and high-impact scenario for space-air-ground integrated networks is the coverage of a grand cycling race, such as the “Tour de France”. This use case exemplifies the need for seamless, resilient, and adaptive connectivity across diverse terrains and highly mobile environments that could be locally dense. Riders traverse hundreds of kilometers daily, often passing through mountainous regions where terrestrial infrastructure is sparse or unavailable. Moreover, as the race crosses multiple national borders, mobility management becomes increasingly challenging due to limited interoperability and coordination among different mobile network operators. To ensure uninterrupted communication and services – ranging from live video broadcasting to critical health monitoring and operational coordination – a multi-layered network composed of unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), and low-Earth orbit (LEO) satellites must be orchestrated. This scenario encapsulates a rich set of applications with heterogeneous QoS requirements, highlighting the importance of infrastructure mobility (in particular to cope with group mobility), dynamic adaptation to multi-access connectivity, and vertical integration of non-terrestrial and terrestrial components, all core challenges addressed by the DONUTS project. This scenario is illustrated in Figure 1.

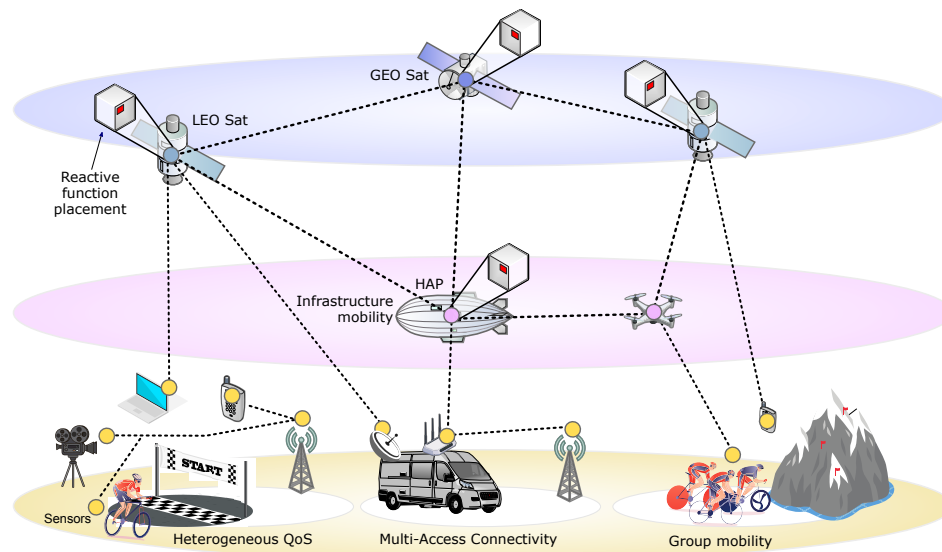


Figure 1: Illustration of UC1: seamless connectivity for a large-scale mobile event, such as a grand cycling race.

2.2 Applications and QoS requirements

This cycling race scenario involves a heterogeneous set of applications, each with distinct service requirements in terms of throughput, latency, reliability, and scalability.

1. Live broadcasting and media coverage

- **Description:** High-definition, low-latency video streams are transmitted from drones, motorcycles, and roadside cameras to production centers. Connectivity should be maintained during the race.
- **QoS requirements:**
 - High throughput (≥ 50 Mbps per stream)
 - End-to-end latency ≤ 200 ms.

- High reliability and jitter control for uninterrupted video quality.
- Up to 200 concurrent HD video streams.

2. Athlete monitoring and safety

- **Description:** IoT-enabled wearables continuously transmit riders' biometrics (heart rate, oxygen level, hydration, etc.), geolocation, and crash alerts.
- **QoS requirements:**
 - Low throughput (≤ 1 Mbps per rider).
 - Deterministic latency (a few ms) for emergency alerts
 - Ultra-high reliability ($\geq 99.99999\%$).
 - Up to 1500-2000 biometric/IoT devices (on riders, vehicles, safety infrastructure...).

3. Race coordination and logistics

- **Description:** Communication between race officials, team vehicles, medical staff, and safety personnel.
- **QoS requirements:**
 - Medium throughput (1–10 Mbps).
 - Low latency for voice/video calls (≤ 50 ms).
 - High reliability and guaranteed availability across all segments.
 - Up to several hundred simultaneous operational users.

4. Spectator connectivity

- **Description:** Broadband Internet access for on-site spectators, journalists, and event staff.
- **QoS requirements:**
 - Best-effort capacity, scaling dynamically with demand.
 - Latency ≤ 100 ms for interactive services.
 - Up to 100 000 concurrent users in dense hotspots.

2.3 Challenges and expected results

This use case introduces several research and engineering challenges, driven by the dynamic, heterogeneous, and large-scale nature of the environment. To enable seamless connectivity in such an environment, several technical challenges must be addressed. The DONUTS project aims to address these challenges through innovative solutions for mobility management, QoS-aware resource allocation, and resilience across the space–air–ground continuum.

Seamless Mobility Management. The mobility of end-users (e.g., cyclists, vehicles, media teams) combined with the infrastructure mobility of UAVs and HAPs requires a paradigm shift in how handovers and session continuity are managed. Traditional mobility protocols are inadequate to cope with frequent topology changes, varying link conditions, and the collective movement of user groups. Supporting such group mobility requires coordinated handover strategies and predictive mobility models that track and manage clusters of users and network elements moving together. DONUTS aims to design cross-layer mobility management mechanisms capable of ensuring uninterrupted service continuity and minimal handover latency, even when transitioning between terrestrial and non-terrestrial links.

Multi-Access Communication and Transport Interoperability. Covering a large-scale, fast-moving event requires leveraging all available radio access technologies (RATs) to maintain continuous, high-quality connectivity. Riders, vehicles, and mobile production units may simultaneously be in range of terrestrial 5G cells, aerial relays (e.g., HAPs), and LEO satellite links, each offering highly variable and intermittent performance. This diversity calls for advanced multi-access management strategies capable of exploiting multiple paths while coping with rapid changes in link quality and availability. The 3GPP Access Traffic Steering, Switching, and Splitting (ATSSS) framework [1] enables devices to use multiple network interfaces concurrently, but its effective operation in the space–air–ground continuum requires tight coordination with multipath transport protocols [5, 8]. Multipath operation also requires congestion control and scheduling algorithms that can adapt to highly heterogeneous path characteristics such as large latency differentials, intermittent connectivity, and variable error rates, without destabilizing performance. The DONUTS project will investigate cross-layer methods to make these multipath decisions both robust and efficient across the full space–air–ground continuum. This includes identifying complementary paths, leveraging multiple User Plane Functions (UPFs) to provide redundant and flexible routing at the core network level, limiting unnecessary packet duplication while preserving redundancy, ensuring that the combined use of multiple RATs maintains the QoS required for heterogeneous flows, and enriching steering and scheduling functions with not only performance metrics but also policy constraints such as trust considerations or environmental impact.

Infrastructure Mobility. The use of mobile network infrastructure elements, such as HAPs acting as aerial base stations or relays, introduces new challenges in topology control and service continuity. Beyond the physical repositioning of these assets, infrastructure mobility also encompasses the logical mobility of network functions. To sustain service quality and reduce latency, virtualized network functions (e.g., core network function, user plane functions, DNS resolvers, or caching entities) may need to be dynamically instantiated, migrated, or scaled across aerial and satellite platforms. This calls for a lightweight orchestration framework capable of handling limited on-board resources and intermittent backhaul connectivity. The project will investigate adaptive placement to dynamically reposition and configure these assets in response to user movement, channel variability, and demand hotspots, ensuring sustained coverage and capacity.

Adaptive Control and Forecasting. Given the rapidly changing network topology and traffic patterns, adaptive control mechanisms that enable proactive decision-making are essential. The use of forecasting algorithms within the network digital twin will enable the prediction of mobility patterns, link quality, and demand variations, thereby enabling preemptive resource reallocation and improved network stability.

Summary of Expected Outcomes

The introduction of this use case is expected to yield several key outcomes contributing to the DONUTS vision:

- **Advanced mobility management framework** supporting both individual and group mobility across terrestrial, aerial, and satellite segments, ensuring seamless and predictive handovers.
- **Cross-layer multi-access communication mechanisms** integrating ATSSS and multipath transport protocols to enable efficient traffic steering, switching, and splitting across heterogeneous links.
- **Dynamic infrastructure orchestration** capabilities for the placement and migration of virtualized network functions on aerial and satellite platforms to enhance coverage, latency, and resilience.
- **AI-driven resource management and forecasting tools** for adaptive, QoS-aware allocation of network resources across the space–air–ground continuum.
- **Resilient and self-adaptive network operation** validated through the DONUTS Network Digital Twin, providing a robust foundation for real-time monitoring, prediction, and optimization.

3 UC2 – Ubiquitous connectivity: enhancing worldwide logistics

3.1 Scenario overview

The overwhelming importance of very good logistics services in the supply chain management has been absolutely recognized for the implied benefit on everyday life, ranging from reduced latency for delivery to the availability of tracking applications. Nonetheless, the availability of an interoperable network infrastructure integrating multiple wireless technologies each featured by a specific maximum transmission range, unlocks the development of novel services and applications. In fact, while technologies like Wi-Fi can safely satisfy the needs of logistics applications in indoor environments, typical 5G networks address such needs in outdoor environments. However, the inherent limit to the scope of logistics applications is given by the unavailability of Internet connectivity over remote and inaccessible areas, like oceans, mountains, etc. With the recent emergence of Internet connectivity brought by LEO satellites, the management of the supply chain will benefit from a pervasive logistics availability on any spot on Earth. The network scenario envisaged for this use case is illustrated in Figure 2.

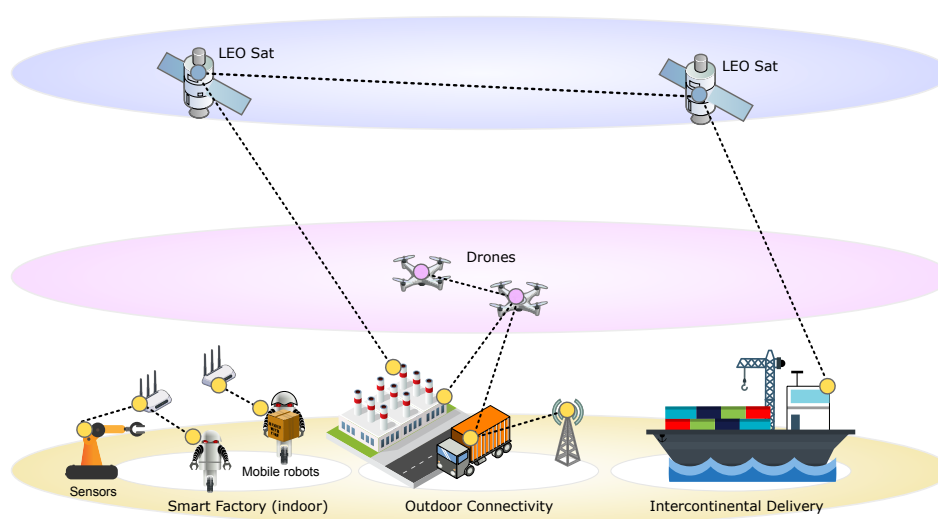


Figure 2: Illustration of UC2: ubiquitous logistics connectivity across indoor, outdoor, and remote environments.

This scenario, illustrated in Figure 2, operates both within indoor locations (the smart factory) and outdoor areas. To ensure seamless connectivity, we need to rely on various communication technologies (e.g., Wi-Fi, public and/or private 5G, and LEO satellites). In the smart factory, a fleet of mobile and connected robots, possibly equipped with UHD cameras, a number of workers with augmented reality and Automated Guided Vehicles (AGVs), sensors, actuators and cameras for security surveillance, may require a high demand in throughput, and possibly delay constraints. These robots navigate within a warehouse equipped with Wi-Fi access points and must select the access point to associate with. Outside the smart factory, the connectivity of the connected trucks transporting the assets, that must be geolocalized for tracking purposes, must be prolonged using a different technology. In particular, we envision 5G (private or public) as well as LEO satellites. In case the assets travel over long distance, LEO satellite communications may represent the only option for connection.

In such a scenario, frequent reconfigurations of the networks (including vertical and horizontal handovers) may be needed (e.g., mobile robots must choose their access point, however, the nearest access point may not be the best option if this latter is overloaded). To address these issues, we expect to rely on the sampling of collected measurements (e.g., various KPIs and topology indices), adequate performance models and a digital twin that will enable a controller to anticipate potential performance issues (e.g., connectivity losses) and mitigate their impact by reconfiguring the network (e.g., switching from Wi-Fi to 5G).

3.2 Applications and QoS requirements

1. Video flows for safety and edge-assisted guidance

- **Description:** High-definition, low-latency video streams are transmitted both indoor and outdoor by some of the AGVs and robots to offload the computation to the edge. At the edge, these videos are processed and often fused (more likely with other sensor data such as LiDAR) to perform complex tasks such as path computation or object identification. Time-critical guidance and operation commands are then sent back to AGVs and robots.
- **QoS requirements:**
 - Medium throughput (\geq several Mbps per stream).
 - Low end-to-end latency (≤ 10 ms) and bounded deterministic latency for closed-loop remote controls.
 - Jitter control to ensure uninterrupted video quality.
 - High reliability.
 - microsecond-level time precision to enable accurate data fusion at the edge.
 - Up to 50 robots and AGVs concurrent video streams.

2. Control flows to instruct robots, AGVs, and workers

- **Description:** Small flows of data are transmitted to robots and AGVs to notify them of their tasks.
- **QoS requirements:**
 - Small throughput (\geq several kbps per stream).
 - Large end-to-end latency (≤ 1 s).
 - High reliability.
 - Up to 200 *always-on* control and telemetry flows for robots, AGVs and Workers.

3. Surveillance flows for security purposes

- **Description:** Small flows of data from surveillance cameras or sensors to alert any incidents.
- **QoS requirements:**
 - Small to medium throughput (\geq several kbps to several Mbps per stream).
 - Medium end-to-end latency (≤ 200 ms).
 - High reliability.
 - Up to 80 concurrent surveillance flows from cameras and sensors.

4. Tracking flows to monitor the location of assets

- **Description:** Small flows of data to track the location of assets on their journey to and in the warehouse.
- **QoS requirements:**
 - Small throughput (\geq several kbps per stream).
 - Large end-to-end latency (≤ 1 s).
 - High reliability.
 - Up to 500 tracking devices concurrent streams.

5. Tracking flows to monitor the location of workers, AGVs, etc.

- **Description:** Small stream of data to track the location of the different robot and workers in and around the warehouse. The location is used for safety reasons (i.e., collision prevention).
- **QoS requirements:**
 - Small throughput (≥ 100 bps per stream).
 - Small end-to-end latency (≤ 15 ms).
 - High reliability.
 - Up to 200 concurrent streams for tracking devices.

6. Resilient cold chain monitoring for intercontinental delivery

- **Description:** Monitoring data about the maintenance of ideal temperature for goods delivered from factory to retail stores over transcontinental paths.
- **QoS requirements:**
 - Small throughput (≥ 100 bps per stream).
 - Large end-to-end latency (≤ 1 s).
 - Medium reliability (possibility of cumulative data transmissions).
 - Up to 500 sensors concurrent streams.

3.3 Challenges and expected results

Low Overhead Direct Access for Small Packets Fine grain asset tracking as well as cold chain monitoring incurs regular transmission of small data packets from many senders. Moreover, these senders may be energy-constrained, in part because they would need to be cheap and thus simple. This combination of relatively massive accesses with short payloads at a low cost is reminiscent of LPWAN problematics and they are not well aligned with the procedures implemented by cellular radio technologies. In DONUTS we want to investigate means to transmit small chunks of data with low overhead even in the context of high sender density, in particular through the use of the Aloha access channel for such traffic.

Seamless multi-connectivity handover In highly dynamic smart factory environments, many devices can rely on multi-connectivity through heterogeneous wireless technologies such as Wi-Fi 6/7 and private 5G. Ensuring seamless vertical (Wi-Fi to/from 5G) and horizontal (AP to AP, gNB to gNB) handovers remains a key challenge, as link conditions vary rapidly due to mobility, interference, and the RF complexity of industrial spaces. Traditional handover mechanisms often cause latency spikes, throughput drops, or packet loss that violate the strict QoS requirements of industrial control and real-time videos. This motivates the need for intelligent, predictive, and context-aware handover strategies that can anticipate performance degradation and proactively select the optimal access technology.

Adaptive TSN Scheduling with RL in 5G/6G Autonomous robots, AGVs, and AI-driven systems in 5G/6G networks require low-latency and deterministic communication to support real-time operations, as they continuously transmit high-definition video and sensor data to edge controllers for real-time decision-making. While 5G/6G networks provide low-latency connectivity via URLLC and network slicing, they cannot ensure fully end-to-end deterministic communications. Time Sensitive Networking (TSN), defined by IEEE 802.1 standards, addresses these challenges by providing time-synchronized, low-latency, and highly reliable communication. In TSN, IEEE 802.1Qbv schedules traffic to ensure critical data meets strict latency and reliability requirements [4]. TSN traditionally uses static schedules, fixed routes, and replication, unable to adapt to changing traffic or bursts from robots and

autonomous systems. TSN/5G integration current approaches remain limited because they rely on static, offline-calculated TSN configurations [2]. This challenge becomes even more pronounced in 6G networks, where factors such as user mobility, dynamic traffic flows, and cloud-native architectures make static configurations ineffective. To address these issues, the DONUTS project will investigate the use of reinforcement learning (RL) to dynamically compute TSN configurations, including optimal scheduling, routing, and replication strategies, enabling the network to adapt in real time to changing conditions. RL does not alter the inherent determinism of TSN but instead optimizes network configurations that maintain deterministic guarantees. By continuously learning from network performance, RL-based TSN configuration computation is expected to enhance adherence to deterministic constraints, and maintains bounded latency for mission-critical applications.

Multipath Connectivity as a TSN Enabler The robots and AGVs continuously stream high-definition video and sensor data to edge controllers, where this information is fused to compute trajectories, detect obstacles, or identify objects. These computations then drive closed-loop control commands that must be delivered back to the robots within strict and predictable deadlines to ensure safe motion, collision avoidance, and coordinated operations with human workers. Such end-to-end determinism can only be offered by TSN [9], but meeting these constraints over a single path in a heterogeneous wireless environment is often impossible. Multipath operation, including the use of multiple RATs and redundant User Plane Functions (UPFs) in the core network, can enable TSN by minimizing latency and jitter through dynamic path selection, enhancing reliability via controlled redundancy, and applying deadline-aware scheduling. The DONUTS project will investigate how to orchestrate these concurrent paths in a TSN-aware manner, determining when and how to duplicate traffic and UPFs, where to place UPFs in the network to minimize latency and ensure resilience, and exploiting digital-twin insights to anticipate performance degradation. By integrating these mechanisms into a unified control framework, DONUTS aims to provide robust, predictable, and energy-efficient multipath connectivity that sustains TSN-grade performance throughout the smart warehouse.

Achieving high-precision data synchronization In this use case, the Digital Twin relies on sampling of collected measurements to anticipate potential performance issues. To be effective, this model needs a perfectly correlated view of the entire system. For instance, it must know the exact state of AGV1, AGV2, and Access Points in use at the same microsecond. In the absence of a precise time synchronization, data/measurements arrive at the digital twin with different unknown delays, making it impossible to build an accurate, time-coherent Digital Twin of the real system. To overcome this challenge, DONUTS project will investigate how TSN can be implemented over wireless (Wi-Fi/5G) networks, ensuring the precision clock synchronization level necessary to maintain fidelity between the real system and its Digital Twin.

Role of the Digital Twin In this use case, the Network Digital Twin (NDT) acts as a real-time mirror of the networks involved in this use case, integrating data from robots, workers, AGVs, cameras, sensors, assets, etc. and instructing operations (e.g., resource reconfigurations) on the networks. By continuously integrating measurements and forecasting traffic, mobility, and link conditions, the NDT provides a predictive view of network behavior under various scenarios (e.g., anticipating congestion or coverage gaps). This enables the testing of proactive and continuous reconfigurations (e.g., reshuffling the devices and access point associations) and an energy-aware orchestration of the resources before applying them on the real network.

GNSS-free connectivity to LEO satellites. The need of resilient IoT connectivity in the context of 3GPP standards translates in removing the requirement of GNSS capabilities on Narrow Band IoT devices. Currently, GNSS is needed as a means for low power devices to compensate the Doppler effect on communications with LEO satellites. While GNSS can be safely replaced by a pre-configured position on low power devices meant to be fixed, the changing position of IoT devices linked to goods being delivered throughout the planet raises a research challenge, i.e., insuring that NB-IoT Direct-to-Satellite connectivity does not depend on another satellite-based positioning service: GNSS is power hungry and can be subject to jamming or outages. In this sense, DONUTS will help in shedding some light on the actual possibility to enable GNSS-free connectivity to LEO satellites.

Summary of Expected Outcomes

This use case is anticipated to deliver the following key outcomes:

- **Low-overhead uplink mechanisms** enabling massive transmission of small packets from energy-constrained devices with significantly reduced signaling (to and from the DT, etc.) and contention overhead.
- **Intelligent, predictive handover strategies** that ensure seamless vertical and horizontal mobility across heterogeneous wireless systems without violating industrial QoS constraints.
- **TSN-grade multipath orchestration frameworks** that provide deterministic latency, jitter minimization, and controlled redundancy across multiple radio access technologies and UPFs.
- **High-precision wireless time synchronization mechanisms** that enable microsecond-level temporal alignment required for accurate and coherent Digital Twin operation.
- **A Network Digital Twin** capable of proactive optimization, leveraging real-time data and predictive models to test and enforce energy-efficient reconfigurations before deployment.
- **GNSS-free NB-IoT direct-to-LEO connectivity techniques** allowing resilient satellite communication without reliance on external positioning systems.

4 UC3 – Resilient connectivity: facing emergency situations

4.1 Scenario overview

Natural disasters, such as earthquakes, floods, or large-scale power outages, often disrupt terrestrial communication infrastructure. In such emergency scenarios, the rapid restoration of connectivity is crucial for public safety, rescue coordination, and the dissemination of information.

This use case focuses on **Direct-to-Device (D2D)** access provided by aerial and satellite platforms (see Figure 3). D2D is emerging as a cornerstone of 6G, enabling global, infrastructure-independent connectivity by extending cellular services directly to smartphones worldwide. We consider two contrasting D2D contexts:

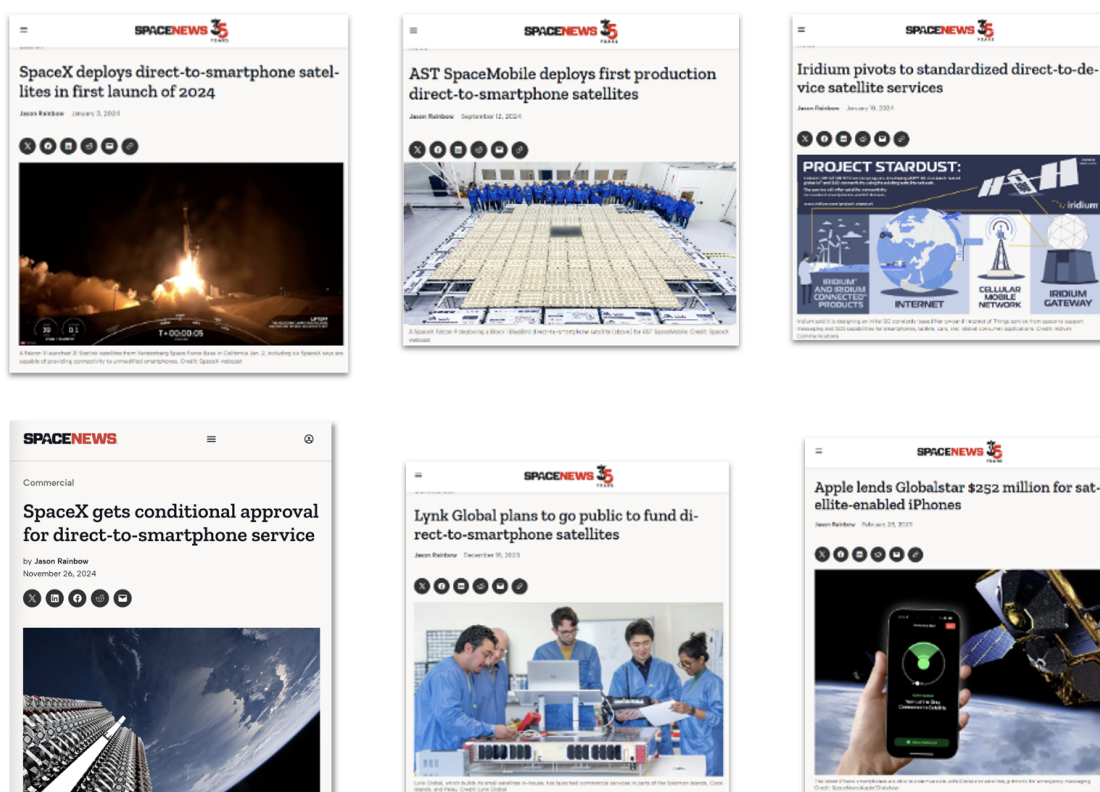


Figure 3: Ecosystem of direct-to-device (D2D) satellite connectivity highlighting major actors and recent trends. Key industrial players (e.g., SpaceX, AST SpaceMobile, Lynk Global, Globalstar, Iridium) are actively deploying or planning large-scale D2D services, often in partnership with smartphone manufacturers (e.g., Apple). Recent developments include satellite-enabled smartphones, conditional service approvals, and dedicated emergency connectivity features.

- **High-density urban zones** with massive, sudden demand for connectivity (e.g., earthquake in a city).
- **Low-density remote zones** where terrestrial infrastructure is non-existent or destroyed (e.g., rural villages, mountainous areas).

Both scenarios demand rapid deployment of communication capabilities with minimal human intervention, seamless support for diverse applications, and context-aware orchestration of network functions (see Figure 4). DONUTS leverages the space-air-ground continuum to ensure connectivity, availability, and continuity, even in adverse or unpredictable conditions.

4.2 Applications and QoS requirements

Application	Description	QoS Requirements
SOS / Alert Messaging	Civilians broadcasting location and emergency status via smartphones or terminals.	High reliability; latency < 5s; scalable to thousands of users.
Rescue Operations Coordination	Secure, real-time voice and data exchange between first responders (fire, police, medical teams).	Low latency (< 50ms); high reliability; localized backhaul.
Telemetry for Search Devices	Sensor data from drones, robots, or deployed detectors (e.g., survivor heatmaps, building stability).	Moderate latency ($\leq 30s$); low throughput; energy-efficient transmission.
Public Broadcasts	Government or agency alerts via satellite or aerial multicast.	Delay-tolerant; scalable multicast; wide-area reach.

Table 1: Applications and QoS requirements for UC3

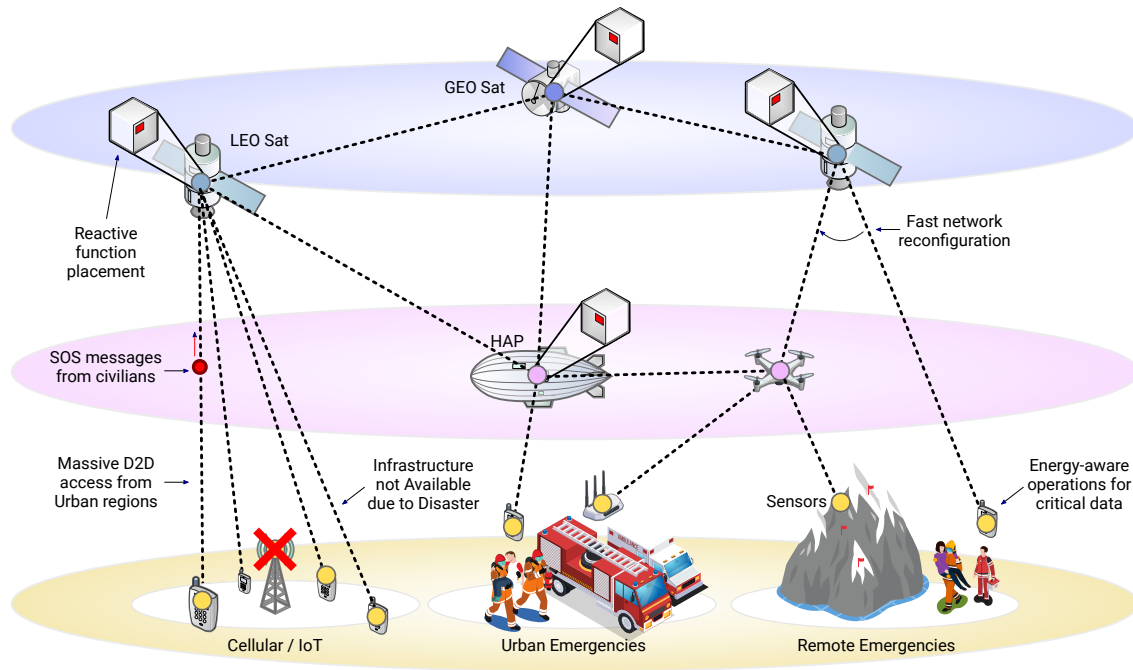


Figure 4: Illustration of UC3: Direct-to-Device emergency connectivity for disaster recovery. LEO satellites and aerial relays (UAVs, HAPs) provide immediate communication links to civilians and first responders when terrestrial infrastructure is damaged or unavailable. This enables SOS alerts, coordination of rescue operations, and dissemination of critical information.

4.3 Challenges and expected results

Dynamic Network Function Placement and Orchestration The urgent nature of disasters requires that virtualized network functions (e.g., gateways, UPFs, DNS) be dynamically instantiated on-demand on aerial or satellite platforms. DONUTS will explore automated orchestration mechanisms for deploying and migrating functions based on user density, traffic type, and infrastructure availability.

Rapid Network Reconfiguration Quick changes in demand and topology require real-time network monitoring and reconfiguration. This includes forecasting population movement, pre-allocating resources, and implementing proactive handover strategies. DONUTS aims to support predictive models integrated with a network digital twin to drive adaptive reconfiguration.

Mobility management of rescue teams In disaster scenario, first responders are deployed to the target area. First responders could operate as small groups of rescue teams, where the connectivity inside the group, and the connectivity between the group and the center of operation should be maintained, leading to a particular attention on mobility management of users (individually and by group).

Energy-Aware Operation Battery-powered user devices and field infrastructure must optimize communication energy. Network function placement and scheduling must consider energy consumption in function orchestration and data forwarding.

Air-Space Cross-Layer Transfer As shown in Figure 4, enabling D2D emergency connectivity for disaster recovery requires data transport across the Air (HAPS, drones) and Space layers (LEO, MEO, GEO). HAPS and drones can be rapidly deployed over disaster areas to provide immediate local coverage, while satellites act as the backbone to offload data to the wider Internet. This cross-layer transfer combines local responsiveness with global reach, ensuring continuity of communications even when terrestrial infrastructure is impaired.

Role of the Digital Twin In this use case, the Network Digital Twin (NDT) acts as a real-time mirror of the deployed emergency network, integrating data from aerial platforms, satellites, and user devices. By continuously ingesting measurements and forecasting traffic, mobility, and link conditions, the NDT provides a predictive view of network behavior under disaster dynamics. This enables proactive reconfiguration (e.g., anticipating congestion or coverage gaps), energy-aware orchestration, and validation of emergency response strategies before applying them in the field.

Summary of Expected Outcomes

This use case will validate DONUTS capabilities in:

- Intelligent, context-aware network function deployment.
- Robustness under degraded infrastructure and volatile conditions.
- Seamless integration of direct-to-device satellite communication with dynamic terrestrial/aerial components.
- Fast and energy-efficient deployment of emergency communication services.

5 Alignment of project tasks with use cases

As illustrated in Figure 5, the DONUTS project is structured into four technical tasks (Tasks 1, 2, 3, and 4) and one task dedicated to global integration and experimental validation through the development of a demonstrator (Task 5). The three use cases presented in this document will shape the design of DONUTS's space-air-ground network architecture in SubTask 1.2. Moreover, Task 2 on multi-technology and multiscale resource management, Task 3 on adaptive control, and Task 4 on the network digital twin will also be impacted by the requirements extracted from these use cases.

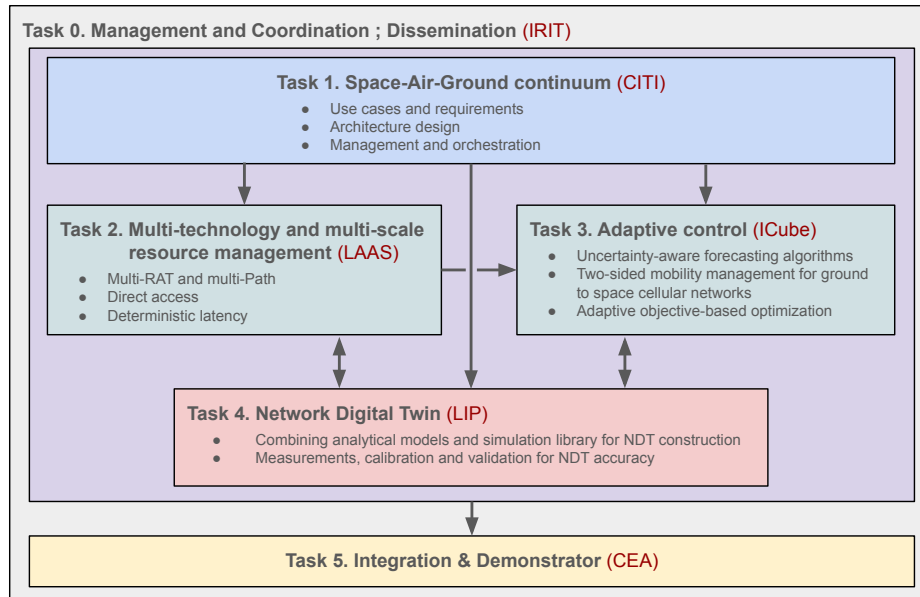


Figure 5: General overview of DONUTS tasks.

Table 2 positions the different project tasks with respect to the identified use cases, highlighting the scope of each task, and the involved partners. Each use case is addressed by multiple project tasks and partners, reflecting the integrated and collaborative nature of the project.

Task	UC1	UC2	UC3
T1.2 Architecture design / recommendation	✓	✓	✓
T1.3 Network function placement and orchestration	CITI		CITI
T2.1 Multi-RAT and multi-path	IRIT, ICUBE	ICUBE	IRIT
T2.2 Direct access		LAAS, LIG	
T2.3 Deterministic latency / TSN		CEA	
T3.1 Uncertainty-aware forecasting algorithms		ICUBE	
T3.2 Two-sided mobility management	CITI, IRIT		CITI
T3.3 Adaptive objective-based optimization		ICUBE	
T4.1 Construction of a multi-technology NDT	LAAS	LIP, ICUBE, LAAS	
T4.2 Measurements, calibration ... for the accuracy of NDT	LAAS	ICUBE, LAAS	

Table 2: Tasks and partner involvement per use case

Discussion on network digital twins (NDTs)

Developing a scalable, robust, and accurate Network Digital Twin (NDT) is a key scientific objective of the DONUTS project. Such a tool can serve as a crucial asset for efficiently reallocating resources within actual networks. To achieve this, DONUTS will create a tailored methodology designed to address the frequent inherent issues of NDTs, such as large datasets and computational complexity.

The initial focus of the NDT in the DONUTS project will be on Use Case 2, which presents a simpler technological context compared to Use Cases 1 and 3, while still considering multi-technology and heterogeneity aspects. By starting with this use case, we aim to establish a solid foundation for the NDT methodology.

As the DONUTS project progresses, the next objective will be to adapt and apply the NDT methodology to Use Cases 1 and 3. We would have already addressed the heterogeneity issues in Use Case 2 to pave the way toward these more complex uses cases. Indeed, these use cases present additional challenges, with Use Case 1 characterized by greater dynamicity and Use Case 3 by a larger scale. By successfully addressing these challenges, DONUTS aims to demonstrate the versatility and robustness of its NDT methodology across a range of complex scenarios.

6 Summary and conclusion

This deliverable has established the foundational use cases and requirements that steer the scientific and technical direction of the DONUTS project. Starting from the project vision of a seamless space-air-ground networking continuum, we have identified the key challenges that next-generation communication systems must address, including dynamic heterogeneity, extreme mobility, service continuity, and resilience under disrupted or infrastructure-scarce conditions. Within this context, three representative use cases have been defined to capture diverse yet complementary operational scenarios.

The first use case focuses on seamless connectivity for large-scale mobile events, highlighting the need for highly adaptive resource management and mobility-aware orchestration in environments characterized by dense user populations and rapidly changing topologies. The second use case addresses ubiquitous logistics connectivity, emphasizing reliable and continuous communication across multimodal transportation chains and geographically distributed operations, while also stressing the importance of minimizing end-to-end latency to support real-time tracking, coordination, and control of moving assets. The third use case considers direct-to-device emergency connectivity, stressing network resilience and rapid service provisioning when terrestrial infrastructure is damaged or unavailable. Together, these use cases provide a comprehensive view of the functional and performance expectations that DONUTS must fulfill.

Building upon these scenarios, this deliverable has derived preliminary requirements and has aligned the planned project tasks with the identified use cases. This alignment ensures that architectural design, algorithmic development, and system validation activities in subsequent work packages remain grounded in realistic and high-impact operational needs.

In conclusion, the use cases and requirements presented here form a coherent reference framework for the DONUTS project. They will guide the design of the envisioned multi-layer space-air-ground architecture, the definition of control and management mechanisms, the development of the network digital twin, as well as the evaluation scenarios to be adopted throughout the project. Furthermore, these use cases will serve as benchmarks for assessing technical achievements and ensuring that DONUTS delivers tangible advancements toward truly seamless and resilient future networks.

Acknowledgment

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References

- [1] 3GPP. System Architecture for the 5G System. Technical Report TS 23.501, 3rd Generation Partnership Project (3GPP), 2021.
- [2] Muhammad Adil, Tie Qiu, Xiaobo Zhou, Danish Javeed, Zhenrui Cao, and Dapeng Oliver Wu. Integrated 5G and Time Sensitive Networking for Emerging Applications: A Survey of Advancements, Challenges, and Future Directions. *IEEE Communications Surveys & Tutorials*, 28:4016–4050, 2026.
- [3] Paul Almasan, Miquel Ferriol-Galmés, Jordi Paillisse, José Suárez-Varela, Diego Perino, Diego López, Antonio Agustin Pastor Perales, Paul Harvey, Laurent Ciavaglia, Leon Wong, et al. Digital twin network: Opportunities and challenges. *arXiv preprint arXiv:2201.01144*, 2022.
- [4] European Commission. Deterministic end-to-end communication with 6G. Technical Report Grant Agreement No.101096504, European Union, Horizon Europe Programme, 2022.
- [5] Alan Ford, Costin Raiciu, Mark J. Handley, Olivier Bonaventure, and Christoph Paasch. TCP Extensions for Multipath Operation with Multiple Addresses. RFC 8684, March 2020.
- [6] Juan A. Fraire, Oana Iova, and Fabrice Valois. Space-terrestrial integrated internet of things: Challenges and opportunities. *IEEE Communications Magazine*, 60(12):64–70, 2022.
- [7] Jiajia Liu, Yongpeng Shi, Zubair Md. Fadlullah, and Nei Kato. Space-Air-Ground Integrated Network: A Survey. *IEEE Communications Surveys & Tutorials*, 20(4):2714–2741, 2018.
- [8] Yanmei Liu, Yunfei Ma, Quentin De Coninck, Olivier Bonaventure, Christian Huitema, and Mirja Kühlewind. Managing multiple paths for a QUIC connection. Internet-Draft draft-ietf-quic-multipath-19, Internet Engineering Task Force, January 2026. Work in Progress.
- [9] Ahmed Nasrallah, Amarendra Thyagaturu, Ziyad Alharbi, Cuixiang Wang, Xing Shao, Martin Reisslein, and Hesham ElBakoury. Ultra-Low Latency (ULL) Networks: The IEEE TSN and IETF DetNet Standards and Related 5G ULL Research. *IEEE Communications Surveys & Tutorials*, 21(1):88–145, 2019.
- [10] Fanny Parzysz, Christos Politis, Joel Grotz, Laurent Reynaud, Volker Breuer, Florian Denzin, Ji Lianghai, Jun Ma, Mohamad Sayed Hassan, Zheng Li, Nicolas Chuberre, Matilde Voltolini, Monique Calisti, and Miguel Ángel Vázquez. D2.1: Use cases definition. Technical Report D2.1, 6G-NTN Project, March 2023.
- [11] Yiwen Wu, Ke Zhang, and Yan Zhang. Digital twin networks: A survey. *IEEE Internet of Things Journal*, 8(18):13789–13804, 2021.