Multi-Access Edge Computing (MEC) over NTN

for beyond 5G & 6G

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3 Abbreviations

3GPP – 3rd Generation Partnership Project
A2X – Aerial to Everything
ADS-B – Automatic Dependent Surveillance–Broadcast
AGL – Above Ground Level
AI/ML – Artificial Intelligence / Machine Learning
ARC – Air Risk Class
ARFCN – New Absolute Radio Frequency Channel Number
B5G – Beyond 5G
BVLOS – Beyond Visual Line of Sight
C2 – Command and Control
CASA – Civil Aviation Safety Authority
CMAS – Commercial Mobile Alert System
DT – Digital Twin
DRB – Data Radio Bearer
EASA – European Union Aviation Safety Agency
ECI – E-UTRAN Cell Identifier
eCFR -Electronic Code of Federal Regulations
EIRP – Effective Isotropic Radiated Power
eMBB – Enhanced Mobile Broadband
ETWS – Earthquake and Tsunami Warning System
FAA – Federal Aviation Administration
FANET – Flying Ad hoc Network
FCC – Federal Communications Commission
FDD – Frequency Division Duplex
FL – Flight Level
FRIA – FAA-Recognized Identification Area
GCS – Ground Control Station
GEO - Geostationary Earth Orbit
GNSS – Global Navigation Satellite Systems
gNB – Next Generation Node B
HAPS – High-altitude Platforms
HARQ – Hybrid Automatic Repeat and Request
IAB – Integrated Access and Backhaul
ICAO – International Civil Aviation Organization
ICIC – Inter-cell Interference Coordination
IEEE – Institute of Electrical and Electronics Engineers
IETF – Internet Engineering Task Force
IoT – Internet of Things
ITU – International Telecommunication Union
KPI – Key Performance Indicator
KPM – Key-Performance Metrics
LEO – Low Earth Orbit
LOS – Line of Sight
LTE – Long Term Evolution
MANET – Mobile Ad hoc Network
MBS – Multicast Broadcast Services
MEC – Multi-access Edge Computing
NG-RAN – Next-Generation RAN
NTN – Non-terrestrial Network
NWDAF – Network Data Analytics Function
OTIC – Open Test and Integration Centers
O-RAN – Open RAN
PCI – Physical Cell Identifier
PLF – Polarization Loss Factor
PQI – Packet Quality Indicator

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PRB – Physical Resource Block
PWS – Public Warning Systems
QoS – Quality of Service
RAN – Radio Access Network
RAT – Radio Access Technology
RF – Radiofrequency
RIC – RAN Intelligent Controller
RSRP – Reference Signal Received Power
RSRQ – Reference Signal Received Quality
RX – Receiver
SDN – Software Defined Network
SF – Speed Factor
SINR – Signal Interference + Noise Ratio
SMO – Service Management and Orchestration
SWaP – Size, Weight, and Power Consumption
TDD – Time Division Duplex
TMZ – Transponder Mandatory Zone
TN – Terrestrial Network
TS – Technical Specifications (3GPP)
TX – Transmitter
UAS – Unmanned Aerial System
UAV – Unmanned Aerial Vehicle
UE – User Equipment
UMEC – UAV as MEC
URLLC – Ultra Reliable Low-Latency Channel
UTM – Unmanned Traffic Management
UTC – Coordinated Universal Time
V2X – Vehicle to Everything
VANET – Vehicular Ad hoc Network
VTOL – Vertical Take-Off and Landing

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1 Introduction

1.1 Objectives and Expected Outcomes

Rural and remote areas across the world face persistent gaps in information and communication technology (ICT) infrastructure and access. While urban connectivity has advanced rapidly, billions of people in sparsely populated or hard-to-reach regions remain unconnected or underserved. As of 2023, approximately 33% of the global population (2.6 billion people) remains offline [1]. Worldwide, 81% of urban residents use the Internet compared to only about 50% of rural residents which highlights a significant urban-rural digital divide [1]. Bridging this divide is critical for inclusive economic development, social equality, and achieving global sustainable development goals. This document provides a global perspective on rural, remote, and aerial ICT infrastructure gaps, the challenges involved in closing these gaps, and potential solutions drawn from best practices across different regions. We retain a formal technical analysis style, expanding the focus beyond Europe to include North America, Latin America, Africa, Asia-Pacific, and other regions. We also integrate aerial connectivity approaches (including unmanned aerial vehicles and satellite communications) as key emerging solutions for remote areas. The aim is to inform technical and policy stakeholders of the current state of rural connectivity worldwide and the mix of strategies needed to achieve universal access.

2 Overview of Existing ICT Infrastructure

This section provides an overview of the ICT infrastructure currently available or deployed in rural and remote areas, including the technologies that enable aerial (UAV) connectivity. It categorises the infrastructure into three broad segments: **terrestrial networks**, **Wi-Fi and Fixed Wireless Access (FWA)**, and **satellite communications**. For each category, we discuss the typical architecture, coverage, capacity, and limitations in the context of sparsely populated or hard-to-reach regions.

Access to reliable internet and mobile communications in rural and remote areas lags significantly behind urban centres globally. These gaps are particularly significant in low-income and developing regions.

Global Penetration Disparities: In high-income countries, internet usage has reached near-universal levels (over 90% of the population online), whereas in low-income countries, only about 27% of the population uses the Internet [1]. This disparity is magnified in rural areas. As of 2023, roughly half of the world's rural population was online, compared to over 80% of the urban population [1]. The urban-rural gap is smallest in regions with high overall connectivity (for instance, Europe's rural internet usage is only slightly lower than its urban usage) and largest in regions with low connectivity. In Africa, only about 23% of people in rural areas use the Internet, versus 57% in urban areas – a ratio gap of roughly 2.5 to 1 [1]. Similar gaps are observed in parts of South Asia and the Arab States. Latin America and the Asia-Pacific region have intermediate gaps (ratios of 1.5), reflecting progress in extending access outside cities but still leaving many remote communities offline [1].

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A major reason for low internet usage in rural areas is the lack of underlying network infrastructure. Mobile broadband (3G or above) is the primary (and often only) means of internet access in developing regions. Globally, mobile broadband coverage now reaches about 95% of the population, yet the remaining 5% – roughly 400 million people – live in areas with no mobile internet coverage at all [2]. This "coverage gap" has proven challenging to close, as it mostly consists of remote, sparsely populated, or hard-to-serve areas. Since 2018, global 3G/4G coverage has grown modestly despite major network rollouts, indicating that the last few percent of population coverage is challenging [2]. Rural areas account for the bulk of those uncovered. Virtually all urban areas of the world are covered by at least a basic mobile network, whereas many rural regions are not. In the Americas, an estimated 22% of the rural population has no mobile signal at all, and an additional 5% has only 2G voice/SMS service. This means that about 27% of rural inhabitants lack mobile internet access [2]. In Africa, the situation is even worse compared to the rest of the world: around 15% of the rural population has zero coverage and another 14% is limited to 2G, in total nearly 29% without mobile data service [2].

2.1 Key Challenges in Rural Wireless Connectivity

Geographical barriers such as difficult terrains, including mountains, forests, and vast open spaces, complicate the deployment of traditional wireless infrastructure. In rural areas, the need for more towers over larger distances significantly increases costs compared to urban networks. This challenge not only affects the feasibility of extending services to remote locations but also impacts the overall efficiency of wireless communications in less populated regions.

Many rural regions face significant **infrastructure limitations**, lacking essential services such as electricity, roads, and wired internet. These deficiencies complicate and increase the cost of deploying wireless networks, creating additional challenges for service providers. The smaller potential customer bases in these areas further diminish the financial incentives for companies to invest in improving connectivity.

Economic constraints in rural communities, characterized by lower population densities and reduced disposable incomes, pose significant challenges for providers aiming to achieve a return on investment. This economic reality not only discourages infrastructure expansion but also exacerbates the existing digital divide, making it increasingly difficult for these communities to access essential digital services. As a result, the gap between urban and rural areas in terms of connectivity and technological resources continues to widen, highlighting the need for targeted interventions to address these disparities.

Technological Challenges:

Outdated network technologies in rural areas result in slow and unreliable connections. Limited access to modern networks like 5G deepens the gap between rural and urban areas.

Regulatory and Policy Hurdles:

Inconsistent or restrictive regulations, bureaucratic delays in licensing, and lack of coordinated governmental efforts create additional obstacles to rural network deployment.

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2.2 Terrestrial and Cellular Networks

Terrestrial networks encompass fixed wired infrastructure (like fiber-optic or copper lines) as well as cellular mobile networks (e.g. 4G/LTE, 5G) that deliver broadband to end-users. In Europe, fixed broadband coverage is high overall but remains slightly lower in rural areas – for instance, as of mid-2022, about 91.4% of rural EU households were passed by a fixed broadband network, compared to 97.3% nationally [3]. However, these figures include basic DSL; the gap is wider for high-speed connectivity. Many rural communities lack Next-Generation Access (NGA) technologies (30 Mbps or above): in 2021, only ~67.5% of rural homes had high-speed coverage, which was 22.6 percentage points below the overall population's coverage [4]. This shortfall is largely due to the economics of network deployment – rolling out fibre or dense cell sites in low-density areas is costly. Deploying mobile networks in thinly populated rural zones can cost up to 80% more than in urban zones, because infrastructure (towers, backhaul) must cover larger areas with fewer paying subscribers.

Terrestrial cellular networks are often the primary internet source in rural and remote areas where fixed lines are absent. Mobile operators typically prioritize coverage in towns and transport corridors, meaning rural users may only have access to older or lower-bandwidth technologies [5]. It is common, for example, for villages to have basic 3G or limited 4G coverage, while 5G new deployments focus on cities. As one study notes, operators often "limit the countryside to lower bandwidth" connectivity, reducing speeds available to rural users [5]. The most remote areas might even have no reliable signal from any operator. To improve this, some countries have taken measures like network sharing agreements. For instance, in the UK several operators jointly implemented a rural national roaming scheme, allowing a user's phone to switch to the strongest available signal from any carrier when their own provider has no coverage [5]. Infrastructure sharing is a practical step to extend terrestrial coverage in underserved zones.

On the wired side, fiber backbones often extend to rural towns, but the "last-mile" to individual premises may still be old copper or even wireless links. Many rural exchanges have been upgraded to VDSL or fiber-to-the-cabinet, but fiber-to-the-home (FTTH) lags – rural FTTP (fiber to the premises) coverage in the EU is only around 34%, much lower than urban areas [4]. Nonetheless, ongoing national broadband plans and EU funding aim to increase rural fiber reach. Some remote villages are served by microwave radio links that bring connectivity to a local ISP or cellular tower, which then distributes service to users. In general, terrestrial networks in rural areas typically exhibit lower capacity and higher latency compared to those in urban settings, due to longer distances, older technology, and congestion from limited backhaul. Additionally, the newer 5G networks – which promise gigabit speeds and millisecond latency – are often not yet present outside major population centers. As of the early 2020s, "5G services are not considered for the countryside yet" in many regions [5], meaning rural IoT and mobile broadband must rely on 4G or even legacy 3G networks. This reality sets the stage for a digital divide, wherein rural inhabitants experience markedly different network performance than urban users.

Terrestrial fixed broadband infrastructure (like fiber-optic cables or DSL) is extremely limited in most rural areas of developing countries, and even in developed countries remote regions often lack high-speed fixed access. Laying fiber to every village can be prohibitively expensive. For instance, in the European Union (which has comparatively advanced infrastructure), only about 60% of rural households had access to next-generation broadband (100 Mbps or higher) as of the late 2010s, versus nearly 90-100% of urban households – despite extensive EU investment programs to expand rural coverage. North America faces similar gaps: in the United States, an estimated **14 to 19 million Americans in rural areas** still lacked access to baseline broadband (25 Mbps down/3 Mbps up) as of the late 2010s, and rural home broadband adoption rates (around 63% in 2019) lag urban rates (75%) [6]. In Canada, as recently as 2019 only 45% of rural households had access to high-speed broadband (50 Mbps service), compared to ~98% of urban households, though programs are underway to improve this. In developing regions, fixed broadband to homes is rare outside major towns; instead, connectivity, if available at all, often comes from shared/community facilities or wireless. The lack of fiber backhaul to rural and remote cell sites is also a limiting factor – many base stations in Africa or remote parts of Asia are still backhauled via microwave links or satellites with limited capacity, which constrains the bandwidth available to end users.

2.3 Fixed Wireless Access (FWA)

Wi-Fi and Fixed Wireless Access are pivotal in connecting rural and remote communities, often filling gaps left by limited wired infrastructure. In many sparsely populated areas, local entrepreneurs or community networks use point-to-point wireless links and Wi-Fi technology to deliver broadband where traditional ISPs do not operate. These setups typically involve radio transmitters on towers, silos, or high elevation points that beam internet connectivity (using unlicensed bands or licensed fixed wireless spectrum) to customer premises receivers. Such **FWA** systems can use technologies ranging from Wi-Fi (802.11) equipment to LTE-based solutions dedicated for fixed access. Modern 4G/5G FWA solutions can achieve tens or even hundreds of Mbps under good conditions, essentially providing a wireless last-mile alternative to cable or DSL. For example, 5G-based FWA has demonstrated speeds over 100 Mbps, making it a viable option for delivering high-speed internet to rural homes where laying fiber is impractical.

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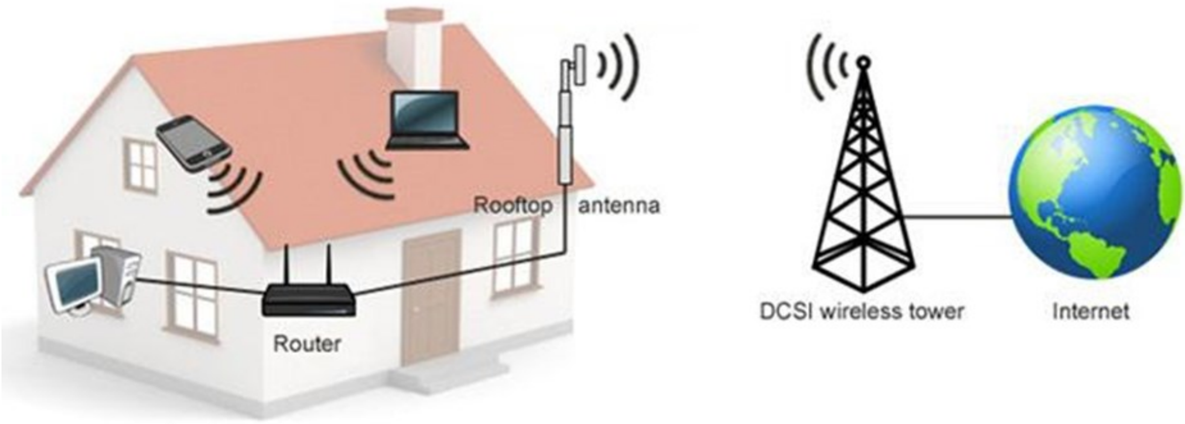

Figure 1: FWA architectural diagram

Community-driven networks are a noteworthy phenomenon in this category. In Catalonia (Spain), the **Guifi.net** project is a famous example: volunteers and local IT enthusiasts built a large mesh of Wi-Fi nodes to connect rural areas. As of 2021, Guifi.net had installed over **40,000 active nodes** reaching around **100,000 rural inhabitants**, using a collaborative model of shared infrastructure [7]. Such community networks demonstrate that with modest wireless equipment and shared effort, broadband can be brought to remote villages that commercial operators deemed non-profitable. Wi-Fi-based networks often use line-of-sight links (2.4 GHz or 5 GHz bands, or even 60 GHz for short links) between rooftops and towers to extend connectivity from a fibre point in a nearby town. While cost-effective, they face challenges like interference (in unlicensed bands), weather impacts, and the need for technical upkeep by the community or local ISP. Nonetheless, they provide essential connectivity for education, e-health, and commerce in areas that would otherwise be offline.

Fixed Wireless Access is also provided by some telecom operators as a product – for instance, a 4G/5G router installed in a rural home that connects to the mobile network as an alternative to DSL. This approach has gained traction as 4G coverage is ubiquitous; it can immediately upgrade a customer from sub-10 Mbps DSL to 50+ Mbps via LTE, assuming the cell tower has capacity. In the future, as 5G rolls out more widely, FWA could deliver fiber-like speeds to rural users (through technologies like millimetre-wave in small villages, or sub-6 GHz 5G with high-gain antennas). However, the performance of FWA in remote settings depends heavily on backhaul and spectrum availability – a rural cell serving FWA must have a robust backhaul (often satellite or microwave if fiber is absent). Without that, adding FWA users can just share the limited capacity. Thus, Wi-Fi and FWA are critical stop-gaps and complementary solutions: they are quicker to deploy than cables and can cover difficult terrain (hills, islands) by wireless relays.

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2.4 Satellite Communications (GEO, MEO, LEO)

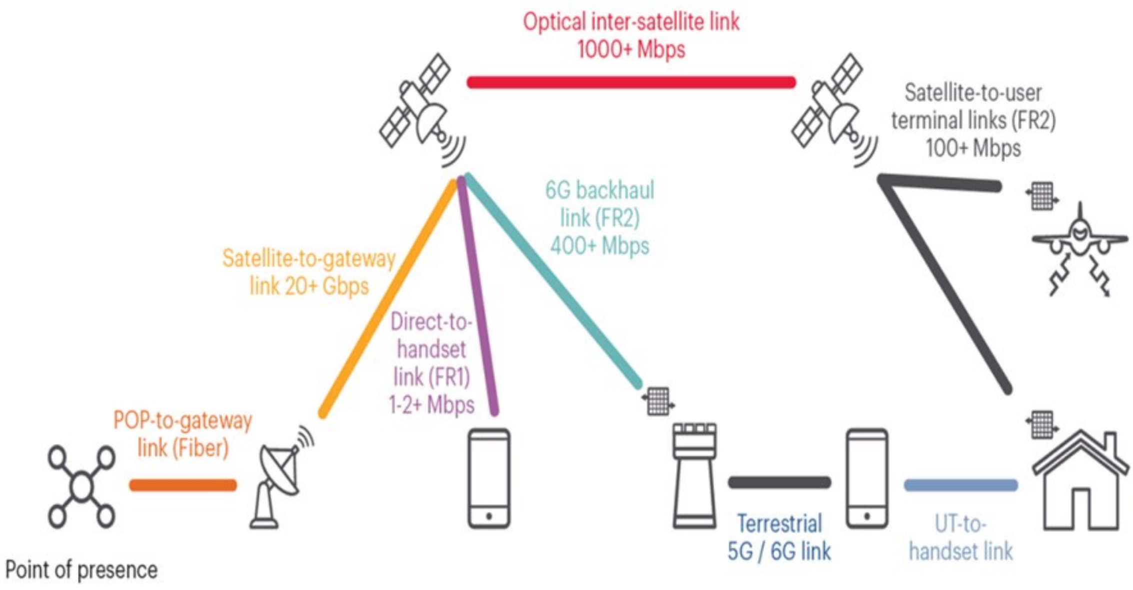

Figure 2: TN and NTN link budgets diagram

Satellite communications (SatCom) are essential for connectivity for both remote terrestrial areas and aerial platforms. Satellites can provide coverage in regions where no other infrastructure exists, effectively bypassing geographic barriers. Traditional satellite internet services via **geostationary (GEO) satellites** have long served remote villages, ships, or research outposts – albeit with limitations like high latency (~600 ms round-trip) and limited bandwidth. GEO satellites (such as those at 36,000 km altitude) can cover large areas (entire countries or continents) and have been used to backhaul rural cellular base stations and community Wi-Fi hubs. Experts note that in many cases **satellite backhaul is the only feasible way to connect rural and remote sites** because running fiber or microwave across rough terrain for just a small population is cost-prohibitive [8]. By using one satellite link to a cluster of remote sites (either directly to users or to local network nodes), service providers can reach hundreds of communities that would otherwise be inaccessible. This makes satellite an indispensable part of any strategy to close the rural connectivity gap [8].

In recent years, satellite broadband has revolutionised with the advent of **Low Earth Orbit (LEO) constellations**. Systems like SpaceX's Starlink and OneWeb deploy hundreds to thousands of satellites orbiting much closer to Earth (~500-1200 km). These LEO networks achieve much lower latency – typically **20 to 40 ms**, comparable to terrestrial broadband [9] – and higher throughput per user (50–150 Mbps or more) by using newer technology and frequency reuse. For example, Starlink users often see ~100 Mbps downloads and latency under 50 ms in 2023, a game changer compared to earlier satellite services [9] . The low latency enables real-time applications like video calls, online gaming, and UAV remote control that GEO latency made difficult. However, LEO constellations require a dense network of satellites and ground stations; they are being rolled out commercially with an initial focus on rural consumers and mobility applications. From a European perspective, these emerging non-terrestrial

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networks integrate with 5G/6G plans. 3GPP has standardised support for **Non-Terrestrial Networks (NTN)** in Release 17 and beyond, which lays the groundwork for ordinary 5G devices to connect via satellite when out of range of cell towers. The goal is seamless coverage: a smartphone or an IoT device in a remote farm could automatically use satellite connectivity when no terrestrial signal is available, thereby ensuring continuous service.

Satellite communications are also **highly relevant for aerial systems** such as UAVs (drones), especially for beyond-visual-line-of-sight missions. When a drone flies beyond the range of its operator's direct radio link or outside cellular coverage, satellites can provide the control and data link. For instance, LEO satellite networks like **Iridium** have been used to enable BVLOS (Beyond Visual Line-of-Sight) command and control for UAVs anywhere in the world. Iridium's LEO satellites, with truly global reach, allow a pilot to control a drone "regardless of how far away the vehicle is", delivering low-latency connectivity that makes near real-time control possible [10]. This is crucial for applications like long-range delivery drones, search-and-rescue UAVs in remote wilderness, or high-altitude platforms that roam far from any ground station.

Besides LEO networks, GEO satellites (e.g., Inmarsat) also support UAV connectivity for certain use cases, though with higher latency; these can be sufficient for non-time-critical data or as backup links. From an infrastructure standpoint, a satellite communication setup for rural or aerial use involves user terminals – VSAT dishes for villages, or compact satellite modems/antennas on UAVs – communicating to satellites, which then link to ground gateways connected to the internet. Advances in antenna technology (like flat-panel phased arrays) are making it easier to equip vehicles or even drones with satellite terminals that can track moving LEO satellites. Satellite capacity and QoS have also improved: modern high-throughput satellites (HTS) and LEO constellations use frequency reuse and spot beams to deliver more Mbps per user and manage interference. For example, the 3GPP NTN standards envision satellite links providing not just backhaul but also direct broadband and even voice service to standard phones, with techniques to handle Doppler shift and long delay [11]. One trade-off with satellite remains the cost of the equipment (like a Starlink dish) and service fees can be expensive, which is a barrier in low-income rural communities. Also, environmental factors (rain fade for Ka-band, etc.) can affect reliability. Despite these challenges, satellite communications are a critical enabler for connectivity in scenarios where terrestrial networks alone cannot suffice, including the emerging aerial communications domain. This has also been elaborated in the deliverable 2.2.

2.5 Aerial Systems Introduction

Satellite communications play a crucial role in ensuring continuous and reliable communication for highly mobile aerial systems such as drones and planes. In urban areas, drones support ultra-dense networks, providing vital services during events, in smart cities, and in high-traffic zones. On the other hand, in remote areas, UAVs can be essential for disaster recovery efforts, maritime surveillance and infrastructure monitoring. Relying solely on terrestrial networks

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proves insufficient in these scenarios due to limitations such as range, congestion, and lack of available infrastructure, highlighting the necessity of satellite communications for effective operation in diverse environments.

UAVs serve multiple pivotal roles within NTN. One potential application of UAVs is to act as relays, extending NTN signals to regions with limited TN coverage or high interference — an approach being explored in the MECON project under Task 3.3.. Additionally, UAVs can attach as terminal (UE) by communicating directly with LEO satellites, facilitating real-time data exchange that is crucial for mobile aerial platforms. Furthermore, UAVs can operate as temporary base stations, establishing airborne networks in urban locations—such as during event coverage—or in remote areas, particularly for disaster relief efforts.
Challenges and Considerations: Latency vs. Bandwidth Trade-offs: LEO satellites offer low latency, however, due to their rapid orbital movement, they need frequent handovers. Energy Constraints: As satellite relays, UAVs face the challenge of balancing limited power resources with the need to maintain efficient connectivity.. Interference and Congestion: Urban UAV operations must proficiently manage spectrum sharing with terrestrial networks and effectively mitigate signal degradation.
In conclusion, it is imperative to emphasize the critical role of satellite communication in facilitating UAV operations across both urban and remote environments. Additionally, hybrid networks, which encompass terrestrial, NTN, and UAV-based communication layers, represent the most resilient and scalable framework. A detailed discussion on UAV-satellite integration can be found in Deliverables 2.3 and 3.3 of the project..

3 Socio-Economic Context and Challenges

Technical infrastructure alone does not tell the full story of the digital divide. The socio-economic context in rural and remote regions significantly influences both the demand for connectivity and the viability of solutions. This chapter discusses how demographic and economic factors, as well as regulatory frameworks (particularly for UAV operations), impact connectivity in the target scenarios. Understanding these factors is crucial for designing approaches that are not only technically feasible but also socially equitable and compliant with policy.

3.1 Rural Communities and Digital Divide

Rural and remote communities often face a **“double divide”**: they are sparsely populated and economically less attractive to network investors, and the people living there may also have lower digital literacy and/or income that affects adoption. On the supply side, private telecom operators have no interest in investing in heavy infrastructure in low-density areas because the return on investment is low. This market failure leads to **under-provisioned networks** e.g. villages left with only slow DSL or inconsistent mobile coverage. Governments and the EU have invested in subsidies and programs (such as national broadband plans, EU structural funds, or the Connecting Europe Facility to encourage the rollout of rural broadband.

Despite these efforts, serious disparities remain. According to recent data, in 2021 **over 60% of Europe's rural households still had no access to Very High-Capacity Networks (VHCN)** (e.g., fiber or DOCSIS cable) [12]. This is more than double the proportion of urban households without VHCN, highlighting a significant rural gap in access to high-speed internet. The EU's Digital Decade goals for 2030 include ensuring every household (rural included) has gigabit connectivity and 5G coverage but reaching that will require overcoming both technical and financial hurdles.

Affordability can also be an issue; rural households often have lower incomes, and if the only option is an expensive satellite subscription, they might remain offline. This underscores that socio-economic development and connectivity go hand in hand. Numerous studies have found positive correlations between broadband access and economic growth, job creation, and social inclusion [13]. High-speed internet enables e-learning, e-health (telemedicine), e-government services, and remote work opportunities that can **revitalise rural economies** and improve quality of life. Conversely, lack of connectivity worsens urban-rural disparities, leading to rural businesses being less competitive and youths moving to cities.

Additionally, rural areas have specific use cases – such as **precision agriculture**, smart farming, and environmental monitoring – that are increasingly data-driven. Farmers now use IoT sensors, drones, and online platforms to improve yields and reduce costs. Rural industries cannot fully leverage these innovations without reliable connectivity, potentially affecting food supply chains and environmental management. It became clear that "it is not the same to be well connected in a rural area as in a crowded city" when it comes to accessing opportunities and services. This has increased political will to address rural connectivity as a matter of inclusion and resilience.

Another socio-economic consideration is the role of **local initiatives and cooperatives**. As seen with community networks like Guifi.net or other wireless commons projects [14] empowering local communities to build and maintain networks can be a viable model, especially when traditional operators are absent. These initiatives often require a collaboration between citizens, municipalities, and sometimes alternative operators, and they foster local expertise and ownership. European Union rural development programs have begun to acknowledge bottom-up approaches as complementing top-down infrastructure projects.

In **remote regions** (like mountain hamlets, Arctic areas, or outer islands), the socio-economic context might involve indigenous communities or very isolated populations. For them, connectivity can be literally a lifeline – enabling telemedicine consultations, access to government services without days of travel, or simply the ability to connect with relatives and preserve culture. The EU has special programs for its outermost regions and an increasing focus on **"no one left behind"** in the digital society. Yet

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remote areas often require customised solutions (like satellite-based community Wi-Fi hubs, etc.) that must be coupled with training and maintenance support to be sustainable.

In summary, the socio-economic context emphasises that bridging the rural/remote digital divide is not just a technical challenge but also a matter of **policy, economics, and community engagement**. Any approach to improve connectivity must consider affordability, relevance of content/services, and capacity building for users – otherwise new networks might go underutilised. Likewise, the benefits of connectivity – from improved education to increased GDP – provide a strong economic rationale for public investment in rural broadband. The imperative for social inclusion is evident: digital connectivity has become an essential requirement for comprehensive participation in contemporary society. Consequently, it is imperative to ensure that citizens residing in rural and remote areas are afforded equitable access in comparison to their urban counterparts.

4 Requirements Analysis for Rural and Aerial Connectivity

In rural areas, connectivity requirements are increasingly like those in urban areas in terms of basic internet usage – residents need to browse, stream video, use cloud services, and participate in video calls. The **European Gigabit Society goals** [Ref] set a benchmark of every household having access to at least 100 Mbps (upgradable to gigabit) connectivity. Thus, a key requirement is **high throughput broadband** to homes, schools, businesses and farms. Practically, this means networks should deliver downstream speeds of tens of Mbps (50-100 Mbps baseline, ideally) per user and upstream speeds in the multi-Mbps range (to enable uploading documents, HD video conferencing, etc.). Latency in rural broadband is also important, especially as applications like interactive learning, telemedicine, or even online gaming become common in rural communities. While super-low latency (1-5 ms) is not critical for general use, the connection should ideally keep latency under ~50 ms for a good experience on real-time apps.

Another requirement is **reliability and continuity** of service. Rural areas often have fewer alternative options, so the network serving them should have high uptime and resilience. Power outages, backhaul failures, or weather events can isolate a rural community entirely if there is only one link. Therefore, requirements may include backup paths or redundancy (for example, a cellular network with a satellite backhaul might have a secondary link or battery backup on towers to maintain service during outages). A target often cited is **99.9% availability** (which corresponds to about 8 hours downtime per year) or better for critical connectivity, though many current rural solutions fall short of this.

Coverage is a fundamental requirement – the network must reach scattered farms and settlements, not just the village center. For mobile connectivity, this means strong signal over many kilometers, possibly requiring high-gain antennas or lower frequency bands that propagate far. For fixed broadband, it means every house (even down a country road) should have a feasible connection method (be it fiber, wireless link, etc.). The EU has metrics for coverage: e.g., 100% of rural households covered by 5G by 2030.

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Achieving that implies that either 5G cells reach far rural corners, which seems impossible, or satellites fill in the gap.

When it comes to **specific rural use cases**, some additional requirements emerge:

- **Precision Agriculture and IoT**: Farms deploying IoT sensors (soil moisture, livestock trackers) and drones for monitoring need wide-area coverage across fields. This implies networks with good outdoor coverage (including in open fields and near ground) and support for potentially thousands of low-power devices (massive Machine-Type Communication). Bandwidth per IoT device is low, but reliability and coverage are key. Latency is moderate (seconds can be fine for sensor reports, but for drone control in farming, sub-second latency is needed).
- **Remote Education and Healthcare**: A rural clinic doing telemedicine consults will require stable video at high resolution – so perhaps 5-10 Mbps with low jitter and latency <100 ms to not disrupt conversation. Remote education (e-learning) similarly needs stable video and access to online resources; during the pandemic, multiple simultaneous video streams (for different family members) became a requirement in households.
- **Public safety and emergency services**: Rural first responders (fire, police, EMS) increasingly rely on connectivity (for GIS maps, communication, etc.). So the network should also support prioritized communication. This requires coverage even in forest or mountainous spots and the ability to handle a sudden surge of usage (during a crisis).

Finally, **affordability** and ease of use are sometimes considered requirements in a project context – the solution must be not just technically sound but economically sustainable for rural users. If a network meets technical specs but costs too much for locals, the effective requirement (affordable access) is not met.

4.1 Technical Requirements

NTNs complement terrestrial networks by filling coverage gaps, providing redundancy, and enabling new use cases in agriculture, environmental monitoring, and public safety. As satellite technology advances and costs decrease, NTNs are becoming a practical and scalable solution for achieving ubiquitous rural connectivity. Here are the technical requirements for using satcom to fill the noted gaps.

4.1.1 Main Technical Requirements for Rural/Remote Indoor and Outdoor Coverage

For effective coverage in rural or far areas, the technical requirements focus heavily on coverage and signal strength. For Indoor coverage of TN (Terrestrial Networks), utilizing low-frequency spectrum, typically below 1 GHz, is helpful because these frequencies travel further and penetrate obstacles such as walls and vegetation better than higher frequencies. This reduces the number of TN based base stations required to cover large, sparsely populated areas. Proper placement of base stations is also critical to maximize coverage, especially in regions with challenging terrain like hills, forests, or valleys.

Infrastructure deployment must be cost-effective, often involving shared infrastructure such as tower sharing among operators to reduce capital and operational expenditures. In many rural cases, integrating terrestrial cellular networks with non-terrestrial solutions like satellite communications (NTN) ensures continuous service where terrestrial infrastructure is sparse or impractical. NTNs, particularly those using Low Earth Orbit (LEO) satellites, can provide wide-area coverage and reach locations that are otherwise inaccessible, such as remote villages, mountainous regions, or areas affected by natural disasters. Integration of terrestrial and NTN systems requires seamless handover mechanisms, efficient spectrum management, and robust backhaul solutions to maintain service quality.
Power supply considerations are also paramount, as rural areas frequently lack stable electricity grids. Therefore, reliable and sometimes off-grid power solutions like solar panels or battery backups are necessary to maintain uninterrupted network operation, both for terrestrial and NTN ground infrastructure such as satellite gateways and user terminals.

“Remote” scenarios refer to extremely isolated areas – such as alpine huts, remote islands, maritime scenarios (offshore facilities), or other areas with no nearby infrastructure. The requirements here often prioritize **basic connectivity and robustness** over ultra-high speed. Some remote scenarios have very specialized use cases (e.g., an offshore wind farm that needs connectivity for sensor data and crew welfare, or a scientific base in a mountain that needs data links).

The fundamental requirement for remote communities is to provide **basic broadband access** where none exists. Even a steady 10-30 Mbps could be transformative in such a context. **Latency** can be more tolerant if the use cases are mostly asynchronous (emails, downloads), but for any integration with modern services, aiming for <100 ms is preferable. If only GEO satellites are available, then mitigation like local edge caching or delay-tolerant applications might be required to work with 600 ms latency.

Coverage and range requirements in remote scenarios often translate to long link distances. For instance, a single satellite beam might cover a whole region; or a high-altitude platform could serve an area with 50 km radius. If using terrestrial radio (like a mountain top tower), it needs to cover large expanses (which might require lower frequencies or high power).

Remote industrial sites (like **oil rigs, mines, or wind farms**) have additional requirements:

- **Low latency and high reliability** for control systems (if they want to operate machinery remotely). This touches on **ultra-reliable low-latency communication (URLLC)** requirements defined in 5G: often <10 ms latency and >99.999% reliability for critical control loops. Achieving this remotely is very challenging, but certain functions might require it (e.g., remote control of a drone inspecting a pipeline).
- **High capacity** for data-intensive tasks: e.g., if a scientific station wants to transfer research data, or if there are high-definition surveillance cameras streaming.
- **Mobility** if vehicles are involved (e.g., a truck driving in a remote mining area should stay connected throughout the site – implying some form of local network coverage across the area).

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In emergency or disaster scenarios (where normally an area has no one, but during an operation many responders come), the requirement is for **rapid deployability** – meaning solutions like mobile satellite terminals or drone-mounted relays that can be set up quickly. While not a steady-state requirement, it's a scenario-driven need.

4.1.2 NTN-Specific Considerations

NTNs, especially those using Low Earth Orbit (LEO) satellites, are increasingly vital for extending coverage to rural and remote areas. They deliver service in locations where terrestrial networks are impractical or too costly. NTN integration requires seamless handover between terrestrial and satellite links, efficient spectrum management, and robust backhaul. LEO satellites offer lower latency (typically 30–100 ms one-way) and higher capacity than older geostationary systems, making them suitable for broadband and IoT applications in rural areas. However, NTN latency is still generally higher than terrestrial networks, and throughput may be lower, but both are improving with new satellite constellations.

4.1.3 3GPP standardized Spectrums for NTN

One of the key issues for operation of NTN is the operational Spectrum and bands due to Regulatory issues as well as technical issues like path loss, penetration, available BW, antenna size, beamforming performances, support of UEs etc. Below is a detailed list of the spectrum currently standardised, or actively being standardised, for 3GPP 5G NR Non-Terrestrial Networks (NTN). It distinguishes between the bands that are already frozen in Release 17 and those under extension in Releases 18–19, plus the ITU regulatory backdrop that enables their use.

Table 1: Tow approved frequency ranges

3GPP "Frequency Range"	Nominal span	Typical use-case	3GPP status
FR1-NTN	≤ 7.125 GHz (L/S bands)	Direct-to-handset, NB-IoT/eMTC, RedCap	Bands n255 & n256 frozen (Rel-17); n253 & n254 under Rel-18/19 extensions
FR2-NTN	17.3 – 30 GHz (Ka/upper Ku)	High-throughput GEO/LEO links, backhaul, aero/maritime terminals	New Ka bands n510-n512 agreed in Rel-18; Ku band work item in progress for Rel-19

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Table 2: 3GPP NR-NTN operating bands (uplink / downlink)

NR band	Duplex	Uplink	Downlink	Service allocation*	Release
n253	FDD	1668 – 1675 MHz	1518 – 1525 MHz	L-band MSS	Rel-19 WI
n254	FDD	1610 – 1626.5 MHz	2483.5 – 2500 MHz	L + S MSS (Globalstar split)	Rel-18/19 WI
n255	FDD	1626.5 – 1660.5 MHz	1525 – 1559 MHz	L-band MSS	**Rel-17 (frozen)**
n256	FDD	1980 – 2010 MHz	2170 – 2200 MHz	S-band MSS	**Rel-17 (frozen)**
n510	FDD	27.5 – 28.35 GHz	17.7 – 20.2 GHz	Ka-band FSS	Rel-18 freeze / Rel-19 enhancements
n511	FDD	28.35 – 30.0 GHz	17.7 – 20.2 GHz	Ka-band FSS	Rel-18/19 5g-tools.com
n512	FDD	27.5 – 30.0 GHz	17.7 – 20.2 GHz	Ka-band FSS	Rel-18/19

4.1.4 Key takeaways for MECON

- Commercial hardware support today is focused on n255/n256 (direct-to-device) and emerging n510-n512 VSAT terminals.
- Upcoming extensions (n253/n254 and Ku-band) aim to relieve L/S-band congestion and provide additional IoT capacity.
- Standards alignment matters – Sticking to 3GPP bands ensures UE, gNB-SAN and core-network interoperability, lowering deployment risk and shortening certification cycles.
- Regulatory due diligence – Before trials, confirm national spectrum availability (especially L-band sharing agreements) and comply with ITU filing conditions to avoid harmful interference.

4.1.5 Key Performance Indicators (KPIs)

Reliable and high-quality connectivity in rural and remote areas depends on achieving well-defined **Key Performance Indicators (KPIs)**. For **Non-Terrestrial Networks (NTN)**, and the IoT and NB-IoT services that operate on top of them, these KPIs establish the minimum technical requirements needed to support applications such as precision agriculture, livestock monitoring, eLearning, VoIP, broadband internet access, and emergency services.

The KPIs fall into four main categories:

- **Coverage and Link Budget:** Availability targets and maximum coupling loss (MCL) values ensure that users in rural and deep-indoor conditions can be reached, with NB-IoT offering up to 164 dB link budget.
- **Performance:** Metrics such as throughput, latency, and signal quality define user experience. NTN broadband aims for ≥10 Mbps downlink and low-hundreds of milliseconds latency, while

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IoT/NB-IoT devices operate at much lower bitrates (tens to hundreds of kbps) and tolerate higher delays.

- **Scalability and Efficiency:** Device capacity per cell (from tens of thousands up to 50,000 for NB-IoT) and long battery lifetimes (≥10 years) enable cost-effective large-scale deployments.
- **Reliability and Service Continuity:** Accessibility, retainability, drop rates, and network uptime (≥99%) are critical to sustaining consistent service in remote NTN environments.

A consolidated summary of the target KPI values for **Wireless/NTN broadband, general IoT, and NB-IoT services** is shown in the table below:

Table 3: KPI values for Wireless/NTN broadband, general IoT, and NB-IoT services

KPI	Wireless/NTN Target	IoT General	NB-IoT Specific
Coverage Availability	≥ 98–99%	≥ 98–99%	~99% (outdoor/light indoor), ~95% (deep indoor)
MCL	-	-	164 dB
Downlink Throughput	≥ 10 Mbps	< 100 kbps	20–250 kbps
Uplink Throughput	≥ 2–5 Mbps	< 100 kbps	20–250 kbps
Latency	≤ 100 ms terrestrial, 30–200 ms NTN	1–10 s	1–10 s
Device Capacity	-	10,000s/cell	up to 50,000/cell
Battery Life	-	≥ 10 years	≥ 10 years
Accessibility	≥ 98–99%	≥ 98–99%	≥ 98–99%
Retainability	≥ 98–99%	≥ 98–99%	≥ 98–99%
Drop Rate	≤ 1%	≤ 1%	≤ 1%
Signal Quality (RSRP/SNR)	≥ -100 dBm/≥ 10 dB	≥ -100 dBm/≥ 10 dB	≥ -120 dBm/≥ 0 dB
Network Reliability	≥ 99%	≥ 99%	≥ 99%

These figures are aligned with **3GPP Release-17 NTN specifications**, IoT/NB-IoT standards, and performance levels demonstrated by current LEO and GEO satellite systems. Together, they define the benchmark for delivering dependable NTN connectivity in rural and underserved regions.

4.2 *Requirements for FWA Deployment*

- **Infrastructure**: Base stations (existing or new towers), customer antennas (CPE) installed on rooftops, and reliable backhaul (fiber or microwave) connecting towers to core networks.

- **Spectrum**: Use of licensed (e.g., 3.5 GHz, 700 MHz) and unlicensed bands (e.g., 5 GHz Wi-Fi, mmWave) depending on coverage and capacity needs.
- **Line-of-Sight (LoS)**: Critical for high-frequency mmWave but less so for sub-6 GHz bands, which better penetrate obstacles.
- **Regulatory Compliance**: Spectrum licensing and local permits for tower installation are essential.

Advantages

- **High Speeds & Capacity**: Capable of delivering from tens of Mbps up to 1 Gbps (especially with 5G FWA).
- **Rapid & Cost-Effective Deployment**: Faster to roll out than fiber, with 50–70% lower infrastructure costs, and minimal ground disruption.
- **Scalability & Flexibility**: Easy to expand coverage by adding base stations and upgrading equipment.
- **Better Reliability than Satellite**: Less affected by weather and latency issues, especially on sub-6 GHz bands.

Challenges

- **Signal Obstruction & Range**: mmWave frequencies require clear LoS and are blocked by terrain and vegetation; sub-6 GHz bands mitigate this but offer lower speeds.
- **Spectrum Congestion & Regulation**: Unlicensed bands face interference; licensed spectrum is costly and requires regulatory approval.
- **Backhaul Limitations**: Remote towers need robust fiber or microwave links, which may be scarce or expensive to deploy.
- **Economic Viability**: Sparse rural populations reduce return on investment, often necessitating government subsidies.
- **Equipment Costs**: Customer premises equipment ranges from $100–$300, with base station upgrades costing tens of thousands of dollars.

Cost Overview

- **Customer Equipment (CPE)**: $100–$300 per household (often subsidized).
- **Monthly Service Plans**: Typically $50–$150 depending on speed and data allowances.
- **Base Station Upgrades**: $15,000–$50,000 for existing towers; new tower construction costs more.
- **Backhaul Infrastructure**: Fiber installation costs vary widely ($10,000–$100,000 per mile), with microwave links as a cheaper alternative.

Solutions & Opportunities

- **Hybrid Networks**: Combining FWA with fiber backhaul ensures high capacity and reliability.
- **Government Support**: Subsidies and grants (e.g., USDA ReConnect, IIJA) are critical to offset costs and incentivize providers.
- **Advanced Tech**: Beamforming, Massive MIMO, and AI-driven network optimization improve coverage and efficiency.
- **Alternative Spectrum**: TV White Space (TVWS) offers promising non-LoS coverage in challenging terrains.
- **Community Partnerships**: Local ISPs and cooperatives can leverage shared infrastructure to reduce costs.

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4.3 Requirements for aerial systems

Regulatory frameworks play a crucial role in ensuring the safe operation of UAVs, as they establish necessary standards designed to protect both users and the surrounding environment. However, these frameworks can also impose restrictions that limit operational flexibility, particularly for UAVs. Since UAVs often transmit from locations far from the UEs, higher transmission power is required. In some cases, the only viable option is to use licensed spectrum that is not actively used in that area. However, obtaining legal access to such bands is typically not feasible within the short timeframes required to deploy and launch a UAV operation. . Limitations on transmission power and frequency usage can impair UAV communications, reducing signal quality for ground users and constraining airborne performance, especially in unlicensed spectrum.. Additionally, the slow authorization process for accessing licensed spectrum poses a significant challenge, further complicating rapid deployment scenarios. Therefore, while regulatory and safety standards are essential for safeguarding UAV operations, they can also create obstacles that affect the operational efficiency of UAV services.

Regulatory bodies impose strict power limits on UAV transmissions to avoid interference with existing terrestrial networks, which significantly affects the ability of ground terminals (GUEs) to establish reliable connections with UAVs. Weaker signals result in a shorter coverage range, thereby reducing the effectiveness of UAV-based networks. Additionally, these limitations lead to higher packet loss, which degrades the quality of service (QoS) for applications that require stable connections. When comparing the impact of low-power UAV relays versus high-power terrestrial base stations, it becomes clear that power restrictions can render UAV networks less viable in certain scenarios, highlighting a critical challenge in the development and deployment of these systems.

Frequency Band Regulations are also one of the significant challenges for UAV networks, this is especially relevant for unlicensed bands like 2.4 GHz and 5 GHz, where certain sub-bands are commonly used for terrestrial Wi-Fi and IoT, but are not authorized for aerial use in many European countries.. Additionally, operators are compelled to rely on licensed bands that can be costly and difficult to obtain, further delaying the deployment of UAVs. This regulatory inconsistency across different regions complicates cross-border UAV operations, as varying approaches to frequency band regulations create a fragmented operational landscape for drones.

Challenges with Licensed Spectrum Allocation for UAVs arise due to the need for special authorization when operating in licensed bands. This requirement can be bureaucratic and time-consuming, rendering it impractical for emergency deployments. Furthermore, the process is not scalable for temporary or mobile operations, as each new location may necessitate fresh approvals. This situation significantly impacts rapid response scenarios, such as disaster recovery efforts where UAV networks must be established instantly, or the creation of pop-up communication networks for events or military operations that demand quick access to spectrum. Although some countries have proposed dedicated UAV spectrum to address these issues, the adoption of such measures remains slow, consequently limiting their real-world application.

In conclusion, while regulatory constraints are essential for ensuring safety and managing interference, they also impose significant limitations on UAV service offerings by restricting power levels, frequency choices, and deployment speed. To address these issues, there is a pressing need for flexible spectrum policies that enable UAVs to utilize adaptive power control for optimized coverage without causing interference. Additionally, granting access to certain unlicensed bands for aerial use would reduce the dependency on slow licensing processes. Implementing expedited licensing processes for urgent deployments is also vital. Ultimately, future regulatory adaptations will be crucial for fostering scalable, efficient, and globally standardized UAV communication networks.

5 Identification of ICT Gaps in Rural and Remote Scenarios

In this chapter, we identify the gaps between the **requirements** outlined and the **capabilities** of current ICT infrastructures in the rural, remote, and aerial scenarios. “Gaps” refer to aspects where the existing technologies and deployments do not fully meet the needs, leading to underserved communities or limitations in UAV operations. The gap analysis is organised per scenario to highlight the specific shortfalls in each context.

5.1 Gaps and Challenges in High Mobility Aerial Connectivity

5.1.1 5G Service categories delivery through NTN

The integration of Non-Terrestrial Networks (NTNs)—including satellite systems, High-Altitude Platform Stations (HAPS), and Unmanned Aerial Vehicles (UAVs)—with Terrestrial Networks (TNs) is a key enabler of universal 5G and future 6G communications. These integrated networks promise to extend connectivity to remote and underserved areas, offering enhanced resilience and coverage. While Ultra-Reliable and Low-Latency Communication (URLLC) is a well-established use case in TNs, it remains infeasible in most satellite-based NTN scenarios due to high propagation delays and dynamic channel characteristics. In response, the International Telecommunication Union (ITU-R) has introduced Highly Reliable Communication (HRC) in IMT-2020 Recommendation M.2514-0 as a practical alternative to URLLC in NTN environments.

This report addresses delay-aware traffic management techniques for HRC, Enhanced Mobile Broadband (eMBB), and Massive Machine-Type Communications (mMTC) in NTN-TN integrated

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networks. We analyse architectural approaches such as network slicing, traffic offloading, and edge computing, and examine enabling technologies including ultra-massive MIMO, THz communications, Reconfigurable Intelligent Surfaces (RIS), and AI-driven optimisation. Furthermore, we explore critical open challenges in areas such as Doppler shift mitigation, spectrum sharing, seamless mobility, and energy efficiency.

The convergence of Non-Terrestrial Networks (NTNs) and Terrestrial Networks (TNs) forms the foundation of global 5G and emerging 6G architectures. NTNs consist of geostationary (GEO), medium-earth orbit (MEO), and low-earth orbit (LEO) satellites, as well as airborne platforms such as HAPS and UAVs. These elements collectively support a multi-tier communication infrastructure known as the Space-Air-Ground Integrated Network.

The ITU and 3GPP define three primary service categories for 5G:

- Enhanced Mobile Broadband (eMBB): High-throughput, delay-tolerant applications such as 4K/8K video, AR/VR, and cloud gaming.
- Massive Machine-Type Communications (mMTC): Scalable access for billions of low-power, low-rate devices in IoT scenarios.
- Ultra-Reliable Low-Latency Communications (URLLC): Requires ≤1 ms latency and ≥99.999% reliability for mission-critical use, e.g., autonomous driving, industrial automation.

However, URLLC is not feasible over most satellite-based NTN links due to inherent long propagation delays and dynamic radio environments. GEO satellites display one-way latencies around 250 ms, while even LEO satellites introduce delays ranging from 20 to 50 ms. These delay values exceed allowable thresholds for URLLC and lead to service degradation when applied naively. Also, NTN channels suffer from fast Doppler shifts, intermittent obstructions, and limited support for fast retransmission, complicating URLLC use cases further.

As a result, the IMT-2020 ITU-R introduced Highly Reliable Communication (HRC) in Recommendation M.2514-0 to accommodate the reality of satellite-based communication. HRC aims to provide strong reliability guarantees for mission-critical applications but permits less strict latency bounds, making it feasible for NTNs in emergency, military, or IoT monitoring tasks.

5.1.2 Handover and QoS in Drone Swarms or High-Speed Platforms

- Ensuring seamless handover between UAVs, satellites, and terrestrial networks is critical for maintaining Quality of Service (QoS) in high-mobility environments, such as UAVs as terminals of ground user terminals (vehicles, high-speed trains...)
- UAVs operating in swarms or as relays must switch between NTN beams or terrestrial connections without excessive latency, packet loss, or service interruptions. This task can be hard, and if the UAVs are being used as relays, they may have a buffer of critical information to send to the destination handover node so there is no information loss.
- Traditional terrestrial handover strategies may not be efficient in aerial NTN contexts, requiring new beam-switching and predictive mobility models, adding complexity to the network and processing on the UE site.

5.1.3 Real-Time Service Requirements vs. Satellite Latency Constraints

- Real-time applications such as command-and-control (C2) communications, surveillance, and video streaming require ultra-low latency. This requirement is harder to achieve while relying on satellite communications.
- Balancing latency-sensitive UAV missions with available NTN infrastructures is a key challenge, requiring hybrid architectures that integrate multiple connectivity layers, such as, UAV as relays, LEO satellites and ground gNBs.

5.1.4 Interference Between UAV C2, Streaming Communications, and Ground Users in Unlicensed Bands – Relation w/ 4.2 chapter

- When UAVs rely on unlicensed frequency bands (e.g., 2.4 GHz, 5 GHz), interference with ground-based networks can degrade both command-and-control (C2) signals and real-time video/data streaming.
- The problem of interference in urban environments and ultra-dense areas, where spectrum congestion can cause communication failures or delays in UAV operations.
- Dynamic spectrum management, prioritisation of C2 traffic, or specialized aerial frequency allocations on licensed bands as possible solutions. This requirement asking for frequencies licensed is long, thus, when there is a need to quickly mobilize UAVs to a remote area, there is not the time to license these bands, and unlicensed bands must be used.

5.1.5 Coordination Between Satellite Footprints, UAV Relays, and Beamforming Challenges

- UAVs acting as NTN relays must align with satellite footprints and beams, ensuring continuous coverage and efficient routing of signals to ground users.
- However, coordination becomes difficult due to dynamic movement of UAVs and satellite beams, requiring real-time tracking and adaptive beam steering andotential conflicts between NTN satellite beams and UAV communication generated beams, leading to signal degradation or inefficient coverage zones.
- When UAVs operate as relays or base stations, they effectively create dynamic cells, adding complexity to network management. AI-driven algorithms can provide a solution by enabling real-time, adaptive control, particularly in urban environments where demand fluctuates rapidly and in remote areas where connectivity needs shift over large distances. In such cases, UAVs should be dynamically repositioned to form new network cells, ensuring continuous and efficient coverage based on evolving requirements.

5.1.6 Path Loss and Shadow Fading in High-Altitude UAV Operations

- UAVs operating at high altitudes face significant path loss, impacting signal strength and overall network efficiency.
- Shadow fading effects from atmospheric conditions, cloud layers, and urban obstructions can degrade connectivity.
- In urban environments, scattering and multipath propagation introduce further complexity, requiring advanced adaptive modulation and diversity techniques.

5.1.7 Lack of Cloud-Based UAV Control Platforms and NTN Integration

- Cloud-based UAV control platforms have gained traction for enabling centralized drone fleet management, AI-driven decision-making, and real-time monitoring.
- Current cloud solutions are mostly optimized for terrestrial infrastructure and are not fully integrated with NTN-based UAV operations.
- Key challenges include:
    - Latency in cloud commands due to satellite uplinks, affecting real-time UAV maneuvers.
    - Synchronization between UAVs, cloud processing, and satellite links to enable autonomous drone decision-making.
    - Scalability issues for real-time UAV orchestration, especially in large swarms operating in remote areas.

5.1.8 Lack of Research on Swarm Leadership and Role Assignment

- UAV swarms require hierarchical coordination, where certain UAVs take leadership roles to manage movement, communication, and network stability.
- Lack of research on defining optimal swarm leadership structures.
- Open challenges:
    - Selecting leader drones dynamically based on battery life, processing power, or signal strength.
    - Failover mechanisms when a swarm leader fails or loses connectivity.
    - Efficient role assignment that balances workload across swarm members while optimizing energy consumption.

6 Potential Approaches to Address ICT Gaps

Potential integrated solution concepts for rural and aerial connectivity: combining terrestrial towers, high-altitude platforms (HAPS), low-altitude platforms (LAP) such as tethered balloons, UAV relays, and satellites (LEO) to provide seamless coverage across challenging.

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6.1 Technical and regulatory Solutions

6.1.1 Rural centric solutions

To close the rural connectivity gap, a mix of **infrastructure upgrades** and innovative deployment models is required:

- **Fiber Extension and Upgrade Projects**: The most direct solution is to extend fiber-optic networks deeper into rural areas (fiber-to-the-home or to community Wi-Fi points). The EU and national governments can continue to subsidize rural fiber deployments, focusing on the remaining unserved areas. Where full FTTH is too costly, **fiber-to-the-village** plus high-capacity wireless distribution can be a compromise – e.g., lay fiber to a village and then use Wi-Fi 6 or 5G small cells to cover the premises. New techniques like **hollow core fiber** or cheaper aerial fiber cables can reduce costs. Also, utilising existing infrastructure rights-of-way (power lines, water pipes for fibre) can help.
- **5G for Rural (including FWA)**: With 5G becoming mainstream, ensuring that rural areas benefit is key. One approach is deploying **5G base stations with low-band spectrum (e.g., 700 MHz)** that cover large areas and upgrading existing rural towers. 5G has features like massive MIMO and carrier aggregation that can significantly boost capacity even in low-density areas. For communities just outside fiber reach, **5G Fixed Wireless Access (FWA)** can deliver high speeds. Operators can provide outdoor CPE (Customer Premise Equipment) that connects to 5G and gives Wi-Fi inside the home. To make this effective, sufficient backhaul is needed – which might be solved by either microwave backhaul upgrades or leveraging satellite backhaul as discussed later. There are already examples where multi-connectivity (combining 5G and satellite) was tested and showed near 99% network availability for rural IoT use cases [15], meaning coupling 5G and satellite can meet strict uptime and throughput requirements.
- **Network Sharing and Collaborative Models**: To address the economics, **infrastructure sharing** among operators can be expanded. The UK's rural network sharing was one example [16]. In an EU context, regulators can encourage or mandate that operators pool resources in rural areas – e.g., a single wholesale network in rural zones that all operators use, thus spreading costs. Another model is **community-public partnerships**: local communities co-invest (like Guifi.net style) and perhaps own passive infrastructure (towers, fiber ducts) which operators then use to provide service at lower cost. This has been seen in some European broadband PPPs where municipalities help fund fiber and an operator lights it.
- **Use of TV White Spaces and Unlicensed Band**: The underutilized TV spectrum in rural areas can be tapped using cognitive radio or license-exempt frameworks. TV White Space devices can cover several kilometers with decent bandwidth (though lower than 4G/5G). Projects in some countries have used this to connect remote schools or farms. It's not a panacea but can

be part of the toolkit, especially where regulatory conditions allow unlicensed use of sub-GHz spectrum.

- **High Altitude Platforms (HAPS)**: Although Google Loon ended, the concept of high-altitude platforms (airships, balloons, stratospheric drones) is still being pursued by others including European projects. HAPS flying at ~20 km altitude can act like "tower in the sky," covering a ~100 km diameter area with broadband. They can be quickly deployed to provide coverage or capacity in rural areas without infrastructure. An advantage is low latency (since the platform is much closer than a satellite). The EU and ESA are looking at HAPS for bridging coverage gaps. In the figure above, an airship (SCP: HAP) is depicted providing coverage to rural terrain [5] . Challenges remain in keeping such platforms aloft long-term and carrying heavy telecom equipment, but advancements (e.g., solar-powered fixed-wing HAPS that can fly for months, like Airbus Zephyr) are promising. If solved, HAPS could directly beam LTE/5G or Wi-Fi to rural users below.
- **Next-Gen Satellite Broadband**: For the most hard-to-reach rural spots, LEO satellite broadband (Starlink, OneWeb, or EU's upcoming IRIS² constellation) is a practical approach. As Starlink has shown, performance can rival DSL or better, with now average latencies around 30-40 ms and 100+ Mbps throughput. The cost per user terminal is a concern, but that may fall over time or be subsidized. A potential approach is **community Starlink terminals** – one dish in a village distributing via Wi-Fi to multiple homes, to amortize cost (though current terms of service discourage sharing, it's technically possible). Moreover, integration of satellite into 5G (NTN) means in a few years, standard 5G phones might directly use satellites for data/voice [17].

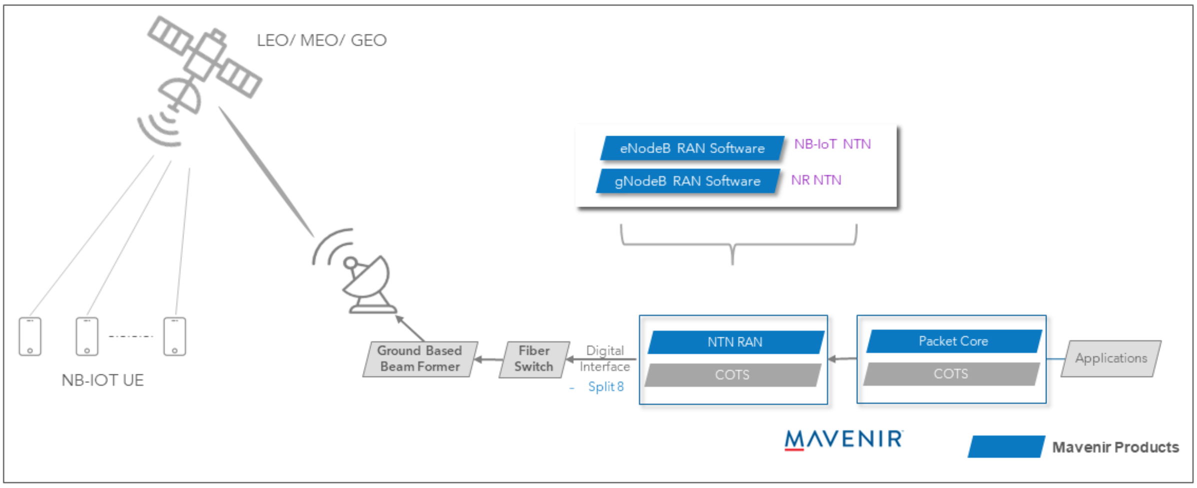

Figure 3: Integration of satellite into 5G (NTN) [17].

This would automatically solve some coverage issues without separate terminal.

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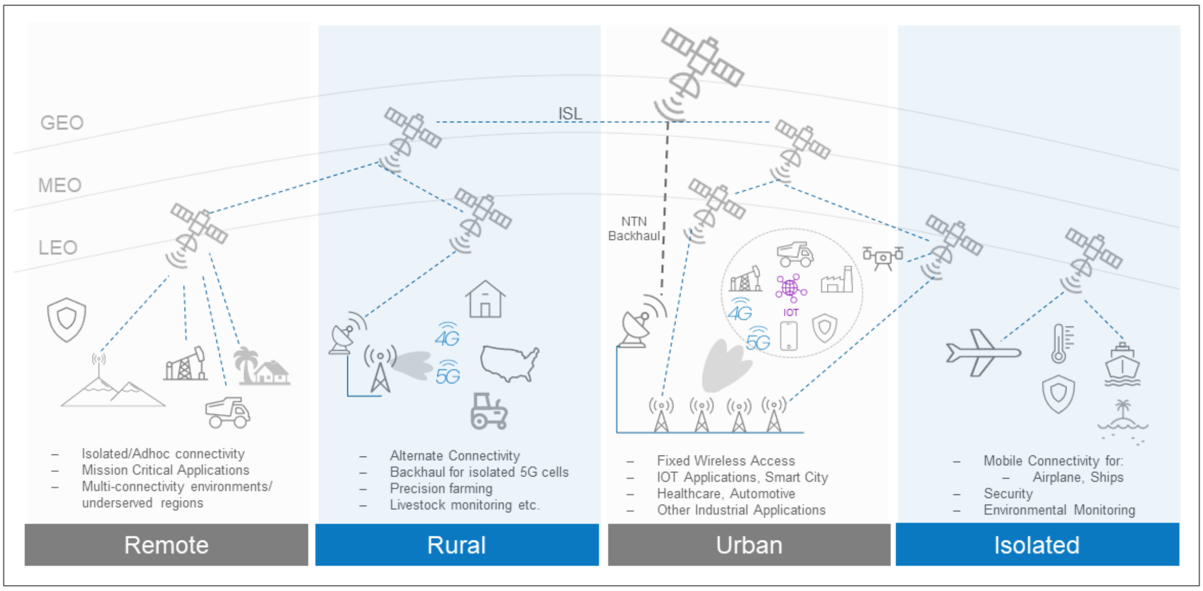

Figure 4: Satellite Use cases diagram

- **Edge Caching and Content Delivery**: To improve the effective experience on constrained rural links, deploying caches or content delivery network (CDN) nodes closer to rural users can help. For example, having popular YouTube or educational content cached at a telco exchange in a region so that each video doesn't have to traverse the core network. This doesn't increase last-mile bandwidth, but it optimizes usage. Similarly, local data centers in rural counties for government or health services can make those services faster to reach.
- **User-centric solutions (receiver improvements)**: Sometimes, the gap can be narrowed by improving user equipment. For instance, using higher-gain external antennas on houses for LTE can turn an unusable 1-bar signal into a decent 3-bar signal, improving speeds. Initiatives to distribute such gear or set up community towers that rebroadcast cellular signals (with operator permission) can extend coverage. In technical terms, this includes **repeaters** or **relays** for cellular signals in valleys.

6.1.2 Remote connectivity solutions

Remote connectivity solutions often overlap with rural ones (since remote places are an extreme case of rural), but some are unique due to the absence of any infrastructure. Key approaches include:

- **LEO Satellite Constellations**: As already touched on, for remote areas (like a lone farmstead, a ship at sea, or a mountain refuge), LEO satellites are currently the most promising approach to provide high-data-rate connectivity quickly. Expanding user access to these and ensuring global coverage will incrementally eliminate blank spots. The EU's planned IRIS² (Infrastructure for Resilience, Interconnection and Security by Satellite) by 2024+ aims to offer government and commercial SatCom that could be leveraged for remote regions in Europe, emphasising resilience. These constellations, equipped with hundreds of satellites, will feature beam-hopping

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and networking capabilities to concentrate capacity where needed and facilitate direct links between satellites, potentially reducing latency further and providing backhaul in otherwise unreachable areas.

- **D2D satellite connectivity**
- 5 G “direct-to-device” (D2D) satellite connectivity extends the 3GPP NR-NTN waveform so that unmodified smartphones can camp directly on a LEO or GEO payload, removing the need for VSAT dishes or rural base-stations. 3GPP Release 17 formalised the physical-layer adaptations (Doppler pre-compensation, extended timing advance, satellite ephemeris assistance) that make this possible [18]. while WRC-23 secured global S- and L-band allocations for mobile-satellite downlinks and there are some examples of POC. For sparsely populated interiors, maritime corridors and disaster zones, D2D satellite offers an instant lifeline and low-bit-rate IoT channel, delivering incremental coverage without terrestrial CAPEX.
- NTN–TN integration is particularly valuable in emergency response and rural scenarios where terrestrial infrastructure is limited or unavailable. A critical enabler of this architecture is the Integrated Access and Backhaul (IAB) framework, which allows a single NTN node to serve both as a user access point and a backhaul link to the core network, eliminating the need for extensive terrestrial infrastructure and enabling rapid deployment in disaster recovery zones and underserved areas. However, the deployment of mobile IAB (e.g., UAV) in NTN–TN systems imposes additional requirements, such as efficient relay selection, adaptive spectrum reuse, and mobility-aware routing, to address NTN-specific challenges including limited power, high mobility, intermittent link blockage, and complex propagation environments [19].
- One of the critical ICT gaps in rural and underserved areas is the lack of cost-effective and rapidly deployable backhaul infrastructure to support mobile broadband and edge services. Traditional terrestrial backhauling methods (e.g., fiber or microwave links) are often economically unfeasible or geographically impractical in such regions. This creates significant latency, reliability, and coverage issues in rural TN/NTN integration. UAV-based Integrated Access and Backhaul (IAB) emerges as a promising solution to bridge this gap, especially when
- integrated with O-RAN architectures. In addition, there are also some more gaps such as energy-efficient flight operation, real-time coordination between aerial and ground segments, and intelligent handover mechanisms in 3D environments. Moreover, current standardization efforts are still maturing in supporting autonomous UAV-based RAN deployments in NTN/TN scenarios.
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- **Geostationary HTS and VHTS**: Meanwhile, new generations of geostationary satellites (High Throughput Satellites, and Very High Throughput Satellites) like ViaSat-3, Eutelsat Konnect, have vastly increased capacity (through frequency reuse and spot beams) and can deliver 100+ Mbps per user too, though still with 600 ms latency. For some remote scenarios (like downloading large files or streaming buffered video), this is acceptable. These satellites can be used to serve community Wi-Fi hotspots – e.g., a remote village might get a VSAT dish that

feeds a local network. Ensuring these services are funded or subsidized where needed is a way to immediately connect remote communities.

- **High Altitude and Aerial Relays**: For providing temporary or on-demand connectivity in remote areas, disaster-struck areas, or large events in remote places, **UAV-based** can be deployed For example, a drone carrying satellite communication and hardware capable of receiving and relaying RF signals from ground UEs could leverage user communication. Another possibility is that a UAV can serve O-RU capabilities to UEs, providing coverage where there's limited access. The extension of coverage could be made, for example, with the previously mentioned satellite communication integrated with a 5G network or by other drones connected between themselves by a FANET, where at least one drone has 5G connectivity.
- **Resilience and Redundancy**: For remote critical sites (like a remote hospital or critical infrastructure), combining multiple systems is key. For example, equip the site with both a GEO VSAT and a Starlink terminal, perhaps also a point-to-point radio to a neighbour facility, etc., each activates if the other fails (smart routers can failover between links). That way, the extremely high availability requirement can be met. If one link is down due to weather condition or maintenance, another can take over the traffic.
- **Renewable Energy and Power**: One often overlooked aspect: powering telecom equipment in remote areas is a challenge. Solar panels, wind turbines, and better batteries now allow remote cell sites or relay stations to run without grid. For instance, a remote 5G microcell powered by solar could serve a cluster of homes. Ensuring solutions incorporate sustainable power is essential. The approach is to design low-power base stations (some are being built for IoT networks) that can run on solar. This could extend to remote IoT networks (like LoRaWAN gateways in mountains for environmental monitoring – those often run on solar already).
- **Policy – USO and Funds**: Governments might define a **Universal Service Obligation (USO)** that includes broadband (some countries have, at some minimum speed). This means even a single remote household might be entitled to a connection, compelling either the state or operators to provide it. Funding mechanisms like the USO fund or broadband funds can then cover the cost. For instance, if a fisherman on an isolated coast needs internet, a USO could fund a satellite terminal for him, treating it like a right similar to phone service. Such policy moves ensure no area is truly left unconnected due to cost.

7 Open-source projects and solutions

Open-source initiatives play an important role in advancing non-terrestrial networks (NTN) and their integration with 5G and 6G. Several European and international projects have released code, simulation tools, and testbeds that are publicly available for research and experimentation. These efforts provide a foundation for future NTN developments and ensure transparency and collaboration across academia and industry. Here is the list of the related projects that have been considered in the MECON project.

Key Projects:

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- **H20205 G!Drones**
  Focus: 5G for UAVs; open-source testbeds, mobility management.
- **ESA SATis5**
  Focus: Satellite-5G integration; multi-orbit satellite testbeds, open code for satellite backhaul.
- **3GPP Release 17 NTN Standardization**
  Focus: Protocols and architecture for satellite IoT, NB-IoT NTN, and NR NTN.
- **H2020 SANSA**
  Focus: Hybrid terrestrial/satellite networks, radio resource management, software modules.
- **OAI (OpenAirInterface) NTN extensions**
  Focus: Open-source RAN/core, early NTN support (simulators, emulation).
- **ESA ARTES projects (e.g., SATNEX IV)**
  Focus: Technical enablers for next-gen satcom, with various code contributions.
- **6G Flagship (Finland)**
  Focus: Vision and frameworks for 6G including NTN integration, simulation tools.

OpenAirInterface (OAI) is an open-source software-defined radio (SDR) implementation of 4G and 5G, providing both RAN (gNB, UE) and Core Network components. It is maintained as a community-driven project with public repositories and continuous integration infrastructure. Recent ESA-supported projects, such as 5G-GOA (GEO satellite) and 5G-LEO (LEO satellite), have extended OAI to support 3GPP Release 17 NTN features. These developments include adaptations for satellite links, emulation environments, and protocol modifications to address delay, Doppler, and mobility challenges.

The NTN adaptations developed under these projects are in the process of being merged upstream into OAI's main development branch. This ensures long-term maintenance, community access, and alignment with ongoing standardization efforts.

8 Conclusions and Next Steps

8.1 Summary of Key Findings

In this deliverable, we have conducted a comprehensive analysis of the existing ICT infrastructure for rural, remote, and aerial connectivity in the EU context, identified critical gaps, and outlined potential approaches to bridge those gaps. Our findings highlight that while progress has been made (e.g., rural broadband coverage steadily improving, and new satellite systems coming online), substantial challenges remain to achieve truly ubiquitous, high-quality connectivity.

Key conclusions include:

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- The **rural digital divide** persists in terms of both availability and quality of broadband. Many rural areas lack access to very high-speed networks, leaving communities at a disadvantage socio-economically. However, a combination of fiber extension, 5G FWA, community network initiatives, and satellite services can complement each other to bring rural connectivity up to par. Strategic investments and collaborations (public-private, community-operator) are crucial to make this happen in a cost-effective way.
- **Remote areas** (sparsely inhabited or difficult terrain) are increasingly within reach of connectivity thanks to LEO satellite constellations and other innovations. By leveraging these, along with high-altitude platforms and mesh networking, even the most isolated locations can be connected. Ensuring resiliency (multiple links) and affordability for these solutions will be key to sustainable connectivity for remote users.
- For **aerial connectivity (UAVs)**, the emerging picture is optimistic: 4G/5G networks, with upcoming enhancements, can mostly serve drones, especially for low to medium altitudes. Satellite communications provides a complementary path for beyond-line-of-sight in areas without terrestrial coverage. Nonetheless, current networks have technical gaps in serving aerial users (interference, handovers, etc.), so a multi-faceted approach involving network upgrades, device capabilities, and potentially new airborne communications infrastructure is needed. This will enable safe and efficient integration of UAVs into commercial and civil uses (from delivery to environmental monitoring), unlocking their socio-economic benefits.
- **Socio-economic considerations** must guide technical solutions. It's not enough to deploy technology; it must be accessible, adopted, and maintained. Training, local engagement, and supportive policies (like subsidies, spectrum allocation, regulatory flexibility for experiments) are all part of the solution. For example, supporting local champions to operate community networks or mandating open access to rural infrastructure can magnify the impact of investments.
- The importance of **integration** was a recurring theme: integrating terrestrial and satellite networks (multi-connectivity), integrating edge computing with connectivity (to meet latency needs), and integrating drones into existing network management (so they are a known user category rather than an afterthought). Standards bodies and industry collaborations are making headway here, and EU research projects (like the one this deliverable is part of) have a pivotal role in piloting and validating these integrated approaches.

In conclusion, bridging the digital gaps in rural, remote, and aerial scenarios is a complex challenge, but one that is addressable with the right mix of technology and policy. Achieving Europe's vision of inclusive connectivity and enabling new aerial services will require continued innovation – from advanced network engineering (e.g., 5G/6G, NTN) to creative business models – and sustained commitment by stakeholders. The approaches outlined in this report serve as a roadmap for interventions in the short to medium term. Moving forward, demonstration projects and deployment trials (perhaps as part of subsequent Work Packages) should be conducted to assess these solutions in real-world conditions, refine their implementations, and develop best practices. By doing so, the EU can ensure that even the most far-flung village or highest-flying drone can become a full participant in the digital ecosystem, thereby fostering economic growth, social inclusion, and technological leadership.

8.2 Impact on Subsequent Work Packages

Indicate how the identified gaps and requirements will guide design, prototyping, or further studies in WP3, WP4, etc.

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