SatMerge WP2: Requirements Capture and Challenges Identification.

Stakeholder Interview outcomes.

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1. Overview

The SatMerge project has been conducted by the Satellite Applications Catapult (SAC) to support National Gas (NG) in exploring how hybrid satellite-cellular terminals, can better support operational staff working across remote and safety-critical environments.

This report summarises the first phase of Work Package 2 (WP2), which focuses on capturing user requirements and understanding real-world challenges associated with connectivity across National Gas operations.

This phase concentrated on qualitative discovery: building an initial picture of how field and site-based staff currently use communication and connectivity tools, the contexts in which they operate, and the pain points and opportunities in order to support the selection, integration or design of future solutions.

1.1. Objectives of User interviews

The primary objectives of this first phase were to:

- Conduct stakeholder interviews in order to develop an initial understanding of day-to-day operational contexts to scope the levels of connectivity required, particularly in and around remote and secure gas infrastructure, and how operations are performed in the network by staff - E.g., Inspections on the move, static repairs/monitoring, etc.
- Identify early user requirements, challenges and risks related to the current connectivity arrangements and tools used by National Gas staff.
- Define key elements influencing the working conditions of National gas staff including:
    - Operational environment conditions
    - Environmental factors affecting connectivity
    - Connectivity applications, power, latency and bandwidth requirements
    - Communication requirements for document sharing, voice or video calls or other working communication requirements
    - Specific use case identification and operations considerations for each
- Surface key use cases to be explored in greater depth in subsequent stages of WP2 and the wider SatMerge project.

These objectives form the foundation for later analytical, design and validation activities, ensuring that any proposed connectivity solution is grounded in real operational needs.

1.2 Scope and Approach

The activities focused on in-depth stakeholder interviews with National Gas personnel who have direct experience of using connectivity tools in the field and at key infrastructure sites.

During this phase:

- Three remote interviews (Roughly 60 minutes in length) were conducted via Microsoft Teams by the SAC team, with one Operations Engineer in the West region, one IT and Operations Engineer in the West region, and finally one Operative. Their roles and activities were discussed to clarify their current practices, systems and tools, and any existing challenges or pain points.
- An additional planned interview with one Operations Engineer was planned but could unfortunately not be scheduled.
- Interviewees were asked to describe what a typical day looks like in their role, regular scenarios require remote connectivity, tools they rely on, current challenges and workarounds they face, and their vision of an ideal future-proof solution.

To accommodate the tight timelines and limited availability of National Gas staff the work was deliberately exploratory, focusing on depth of insight rather than breadth of coverage.

2. Research findings

The following sections outline the key findings of the three user interviews conducted by the SAC team.

2.1. Confirmed use cases

During the discussions with the interviewees, the following connectivity difficulties were raised.

Compressor station operations (fixed but remote sites)

- Day-to-day work is largely at remote compressor stations with a control room and office where corporate Wi-Fi is available, but mobile signal around the wider plant and car park is poor or unavailable.
- Intrinsically safe iPads and other tools are used around site but often struggle to maintain data connections once staff leave the main building.

AGIs (above-ground installations) and unmanned cabins

- AGIs are smaller, unmanned sites with cabins and flow-related equipment, typically without control rooms, often lacking connectivity infrastructures leading to poor connectivity.

Pipeline inspection / line-walking and third-party supervision

- Dedicated line-walking teams and operatives cover long distances on foot to inspect pipelines, test posts and third-party works, often over many kilometres per day.
- These roles rely on CP Logger, DWM and mapping tools, and are more sensitive to gaps in coverage than site-based staff.

Van-centred connectivity for operations

- "Always connected" vans with EE roof-mounted antennas and routers have been rolled out to ~150 vehicles, creating a Wi-Fi hotspot in an estimated 150 metre radius around the van for up to two hours after the engine is turned off.

Temporary project / construction sites (NG Services)

- National Gas Services and project teams sometimes need temporary site-wide connectivity for 30–50 people on remote projects; historic Vodafone "yellow briefcase" portable networks met this need but were perceived as too heavy and bulky for day-to-day operations use.

Of these use cases, pipeline inspection, followed by AGI inspection appeared to have the highest requirement for nomadic connectivity systems, owing to the lack of infrastructure available to the Engineers and Operatives when conducting inspections, and the risks of potential data loss requiring duplication of work to be completed, or onerous additional hours being spent to input data post collection. The following sections outline the issues that were raised.

2.2. Bandwidth / connectivity features

- Patchy cellular coverage at compressor stations and AGIs means calls and data connections often fail once staff step outside the office/control room Wi-Fi, forcing repeated trips indoors or to specific “signal spots”.
- Line-walking and third-party supervision have roughly “80%” connectivity coverage, but the remaining 20% requires workarounds such as driving away to download or load drawings/schematics or make calls, and then returning to site.
- Van hotspots supplied by EE have improved connectivity within a fixed range (roughly 150m) but have limited range when Operatives are expected to walk kilometres away from their van. There are data-caps (8–50 GB/month per van) on these services, though these haven’t been flagged as a major issue.
- Future ambitions such as video-based inspections with AI analysis will significantly increase bandwidth and storage demands compared to current text/photo capture.
- Safety was raised as a significant concern for operatives when inspecting remote pipelines. In cases where multiple Operatives are inspecting a line over multiple kilometres, a cooper wire is laid over the distance of the line, and a single operative would collect/ re-roll the wire following inspection. This would be a lone working scenario, and in the event of an accident or injury, the fellow Operatives may not be aware of the incident until they have noticed that their colleague has not returned within the expected time frame. This raises a significant concern for staff safety that could be resolved by more regular connectivity and communication capabilities.

2.3. Reliability and data capture

- Several tools (e.g. inspection apps and DWM) are not robust offline and can lose data if connectivity drops or if users pause and resume work orders; this can mean repeating up to an hour of work.
- A previous bug between DWM and CP Logger caused corrosion readings to disappear when users switched between work orders, requiring re-measurement of up to 20 readings per job.
- Because of these experiences, some staff prefer paper-based inspections that can later be transcribed, seeing them as more reliable than partially connected digital systems.

2.4. Environmental factors for use

- Compressor stations and AGIs are remote, security-sensitive and often exposed sites, with work taking place both outside and inside compressor cabins and other plant buildings.
- Many tasks occur in hazardous zones (1, 2) where explosive atmospheres are possible; devices used in Zone 1 must be certified and housed in protective cases.

- Line-walking involves long distances on foot, varied terrain and weather, which makes carrying additional heavy or fragile equipment particularly burdensome.

2.5. Size / weight and physical ergonomics

- Zone-1 compliant iPads in explosion-proof cases can weigh around 1 kg per device, adding to the load engineers carry.
- Historical Vodafone “yellow briefcase” portable networks were rejected by operations as too bulky and heavy, even though they were valued for site-wide connectivity by project teams.
- Previous Trimble GPS units were also considered over-complicated and unreliable, contributing to a preference for lighter, simpler phone- or tablet-based workflows.

2.6. Duration of use and charging opportunities

- Van-mounted routers stay active for roughly two hours after the engine is switched off, limiting how long they can support static work away from roads or car parks.
- Line-walking and LS buds/third-party supervision can involve full-day outdoor work, with a practical expectation that iPads, phones and any portable terminal will last the whole shift without the need for mid-day charging.
- Some Cathodic Protection monitoring hardware is moving to multi-year battery life telemetry, suggesting a preference for low-touch, low-maintenance power solutions where possible.

2.7. Organisational requirements and change

- Rolling out new technology across a national operational workforce is challenging because regions have different ways of working, despite common systems; gaining adoption requires careful change management, not just technical deployment.
- It was suggested that there has been a history of systems being introduced before data capture and offline behaviours were fully designed, which has eroded trust among technicians.

2.8. User-experience requirements

- Users want simple, reliable workflows that don’t lose data, with the ability to complete work at the point-of-work rather than bulk-entering later. In some cases, where larger collections of readings are required, it was suggested that it would be preferable for options to be available to save and back up data on site, with the ability to edit the data, or publish for review at a later time.
- There is interest in large, glove-friendly controls and speech-to-text input for any new mobile app or terminal interface. It is currently accepted that gloves can be removed to navigate issues at the moment, but this should be considered for future ease of use.

3. Implications for design requirements of the mobile hybrid terminal

Drawing these themes together, the interviews suggested the following emerging design requirements for the SatMerge terminal and service:

Hybrid, site-wide and portable connectivity [Functional / bandwidth]

- The solution should support portable coverage for line-walking, which could also be utilised for inspections at AGIs and for third-party supervision, e.g. via a van-mounted unit and/or a lightweight carriable unit.

Hazardous-area and environmental robustness [Environmental / organisational]

- Hardware ideally should be compatible with Zone-1 and Zone-2 environments, either via certified devices or safe separation between hazardous areas and the radio equipment, and must tolerate outdoor conditions (weather, dirt, long distances walked).

Ergonomics: minimise weight and carrying burden [User / size & weight]

- Any portable element should be lighter and less cumbersome previously implamented briefcase solutions or heavy Zone-1 cases, with options for vehicle mounting, body-worn carrying and simple stands/fixtures on site.

Power and charging strategy [Duration of use / charging]

- The terminal should be designed for full-shift autonomy where possible, with charging from vehicles and site power, and clear indication of remaining runtime; low-touch power options (e.g. long-life batteries for some use cases) are desirable.

User-centred interface design [User requirements]

- Interfaces would benefit from but are not obligated to prioritise clarity, speed, and error-proofing: big buttons usable with PPE, potential speech-to-text, simple forms, and condensed views of key readings and defects.

Support for future media-rich workflows [Functional / bandwidth]

- Architecture should anticipate photo and video capture, both for data upload and real time video calls and communication.

4. Gaps and further research questions

Following the research described above, the following areas of inquiry would benefit from further exploration.

- Quantify how often and where the 20% "no connectivity" scenarios occur for line-walking and AGI work to prioritise coverage.
- Clarify typical shift lengths, kit carried and charging patterns (home/van/site) for different roles to refine power and ergonomics requirements.
- Explore organisational constraints around introducing satellite equipment on vans and sites (e.g. leasing models with EE, safety rules, data governance).

5. Reflections and conclusions

Overall, the interviews confirm that connectivity is already a critical enabler of safe and efficient operations for National Gas staff working at compressor stations, AGIs and along the pipeline network. However, the current mix of cellular coverage, van-based Wi-Fi and partially offline digital tools leaves important gaps that are felt most acutely in the field – particularly during pipeline inspections and remote, lone-working scenarios.

The findings highlight that while many core systems (Maximo, DWM, CP Logger, Hadi, GIS tools) are in place, their effectiveness is constrained by connectivity variability, limited offline robustness and historic integration issues. This has led some staff to favour paper-based methods, even when they recognise the potential value of digital workflows, because these are perceived as more reliable under current conditions.

From a user perspective, the most pressing issues are not solely about "more bandwidth", but about trusted, dependable workflows: being confident that work done in the field will be captured once, stored safely, and available to colleagues without rework.

At the same time, the interviews show that any SatMerge solution should be viable within National Gas' operational and organisational constraints: hazardous area classifications, mixed device estate, regional ways of working and existing commercial arrangements for connectivity.

In summary, the interviews have validated the relevance of the SatMerge concept and provided a clear, user-informed starting point for designing a mobile hybrid terminal and associated service. It has also surfaced specific pain points and risks that can be directly addressed in subsequent phases.

6. Recommendations and next steps

Based on the findings and gaps identified, the following recommendations are proposed for the next stages of WP2 and the wider SatMerge project:

6.1. Deepen understanding of priority use cases

Undertake focused research on pipeline inspection and AGI scenarios – possibly including additional interviews with line-walking engineers and operatives who regularly work on the most remote parts of the network. This will help quantify the frequency, location and impact of the "20% no connectivity" situations and refine requirements for coverage and offline behaviour.

Capture richer detail on shift patterns, kit loads and charging behaviour across different roles (operations engineers, IT/ops hybrid roles, operatives). This will support more precise ergonomics and power-budget assumptions for any mobile hybrid terminal design.

6.2. Test and refine the emerging design requirements

Validate and prioritise requirements with a broader stakeholder group (including representatives from HSE, digital/IT, regional managers and union/worker representatives where appropriate). This should include a structured review of the "must have / should have / nice to have" requirements identified in within this report and , to confirm which constraints are truly non-negotiable. This could be achieved via online or in person workshop/ roundtable session, or via a survey or shared feedback document.

Explore options for integrating SatMerge connectivity with van-based and personal devices, considering how a mobile hybrid terminal could complement or enhance the existing EE van hotspot model rather than duplicate it.

6.3. Assess feasibility and organisational fit

Work with National Gas governance, safety and procurement teams to clarify constraints around introducing satellite connectivity on operational vehicles and sites, including leasing models, data governance and hazardous area compliance. This will help define the realistic design space for the SatMerge solution.

Identify potential pilot sites and user cohorts (e.g. a line-walking team in a region with known connectivity gaps and one or two AGIs) where a future SatMerge prototype could be trialled. Early thinking on pilot design will ensure that subsequent technical work remains grounded in measurable outcomes.

D3.1 – State of the Art Review and Assessment

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Terms, Definitions, and Abbreviated Terms

Abbreviated Terms

Abbreviation	Meaning
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
GEO	Geostationary Earth Orbit
TN	Terrestrial Network
NTN	Non-Terrestrial Network
D2D	Direct to Device
5G-NR	5G New Radio
HAPS	High Altitude Platform Station
HTS	High Throughput Satellite
SATCOM	Satellite Communications
COTM	Communication-On-The-Move
VSAT	Very Small Aperture Terminal
IoT	Internet of Things
BGAN	Broadband Global Area Network
5G	Fifth Generation Mobile Network
EOW	Eutelsat One Web

Executive Summary

This document has been prepared as part of the SATMERGE project to provide a State of the Art (SoA) review of communication technologies relevant to remote connectivity. The purpose of this document is to identify and assess existing connectivity solutions that can support nomadic operational scenarios, where communication infrastructure must be portable and capable of operating in remote or infrastructure-limited environments.

The objective is to review current connectivity approaches and evaluate relevant technologies, including non-terrestrial networks, terrestrial mobile networks, and hybrid architectures, that may enable reliable communications for such deployments.

The document is structured as follows. Section 1 summarises current connectivity approaches and operational requirements. Section 2 presents the state of the art of communication systems and relevant technologies. Section 3 reviews portable standalone connectivity solutions developed in related sectors. Finally, Section 4 provides conclusions and outlines potential next steps.

1. Existing connectivity solutions for National gas

1.1 Legacy/ current approaches and their operational limitations summary

Current National Gas field operations, including pipeline inspection (line-walking), AGI visits, and compressor station activities, rely on a combination of connectivity solutions to enable communication and data access in remote and semi-remote environments. These approaches have evolved to address gaps in terrestrial network coverage; however, they remain constrained in their ability to fully support pipeline and AGI work use cases which relies on nomadic connectivity.

Insights gathered from stakeholder interviews conducted during the WP2 *Requirements Capture* activity, compiled in *D2.1 Stakeholders Interviews Report,* indicate that two primary connectivity approaches are currently used in operations:

Van-centred connectivity (EE vehicle hotspots).

Approximately 150 operational vans are equipped with cellular antennas and routers for boosting cellular connectivity reception, while creating a Wi-Fi hotspot with a coverage radius of roughly 150 m. These systems remain active for about two hours after the engine is switched off. This approach is useful for short tasks near the vehicle. In those operational environments where roads are not available closer to the pipeline, engineers must go on foot for up to several kilometres away from the van to perform pipeline inspection. Cellular connectivity availability is estimated at around 80% of the operation time, with the remaining 20% requiring workarounds, such as leaving the worksite to download drawings or make calls, returning to the operation area after that.

Few limitations were observed as follow:

Table 1: Van-centred connectivity limitations summarised from D2.1

Limitation	Description / Impact
Limited coverage radius	Connectivity is restricted to ~150 m from the van, making it unsuitable for pipeline inspection tasks where engineers may walk several kilometres away.
Dependency on VAN proximity	Engineers must remain near the van to stay connected, which is impractical in inaccessible areas and need to come back to the VAN proximity for connectivity to perform critical tasks such as downloads/uploads etc
Partial operational coverage	Connectivity is available for ~80% of operational time, but ~20% requires workarounds such as leaving site to download/upload data, make calls etc leading to extra time (up to 3 hrs) spent in the field operations
Lack of continuous connectivity on the move	Current solutions do not support seamless connectivity during line-walking, resulting in interruptions to workflows and reduced productivity.

Portable site connectivity units (Vodafone “yellow briefcase”).

Temporary portable network kits like Vodafone kit as shown in Figure 1 were identified by the National Gas team and used during field trials to provide site-wide connectivity for approximately 30–50

personnel during project work at remote locations. These units operate using cellular technologies (LTE/UMTS/HSDPA, up to ~150 Mbps) and create a local Wi-Fi access point for users.
While effective in establishing connectivity within a defined area, their performance remains dependent on the availability and quality of the underlying cellular network. In remote pipeline environments, where cellular coverage is often limited or inconsistent, this results in variable connectivity in terms of reliability, continuity, and achievable data rates.

In nomadic scenarios such as pipeline inspection and line-walking, where engineers move over several kilometres, this dependency can lead to service interruptions and require users to relocate to regain connectivity. Additionally, although the unit weighs approximately 3.8 kg, the need to carry this alongside existing inspection equipment over extended distances can impact usability during prolonged operations.

Consequently, such solutions are better suited to temporary or semi-static deployments rather than continuous, on-the-move field operations.

PORTABLE OUTDOOR
For remote, outdoor locations
LTE/GSM/UTMS/HSDPA 150/50Mb/s
30,000 mAh Lithium-Ion battery, AC or 9-28V charging options
802.11 b/g/n/ac, Dual Band, 300/900Mb/s
16GB
1x LAN port, 1x USB 2.0
Yes
3.8kg
280mm x 220mm x 170mm

Figure 1: Vodafone portable kit

Overall, both approaches highlight a gap between vehicle-based connectivity with limited mobility and portable solutions that are too large and cumbersome for regular field deployment.

1.2 Connectivity related requirements

Within this study, the primary operational context is a nomadic use case. In this scenario, connectivity systems must be portable, quickly deployable, and capable of operating independently of permanent infrastructure, while supporting engineers who move between sites or conduct inspections over large geographic areas. Unlike fixed or vehicle-mounted systems, nomadic solutions must balance portability, power autonomy, and ease of setup with sufficient performance to support operational applications such as data access, communication, and reporting.

A set of connectivity related requirements for this use case were extracted from the interviews and compiled in *D2.2 - Connectivity Requirements*. These requirements have driven the research of technology solutions, and the suitability of the solutions will be assessed during trade off analysis at later phase based on them.

2. State of the Art on Communication systems and solutions

This section reviews the current State of the Art (SoA) in communication systems and connectivity solutions that could support National Gas' operational field activities. The focus is on technologies capable of providing reliable connectivity in remote or infrastructure-limited environments, where traditional terrestrial networks may be unavailable or show a degraded performance.

The analysis is structured around the key components of communication systems, including non-terrestrial networks (satellite connectivity), terrestrial cellular technologies, and portable user terminals that enable field deployment. Particular attention is given to solutions that can support mobile or rapidly deployable connectivity, rather than fixed installations.

The following subsections therefore examine relevant technologies and systems with respect to their suitability for nomadic field operations, considering factors such as coverage, throughput, portability, power requirements, and deployment complexity. Where available in public domain, indicative cost of the terminals and subscription are included, based on information obtained at the time of writing this document. These could vary in future and are subjected to commercial agreements that can be reached.

2.1 Non-terrestrial Networks

2.1.1 Introduction to NTNs

Non-Terrestrial Networks (NTNs) refer to communication systems in which part or all the transmission path is supported by space-based or aerial platforms, rather than terrestrial infrastructure exclusively. In practice, this includes telecommunications satellite systems operating at different orbits – e.g., Low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geostationary Orbit (GEO) [1].

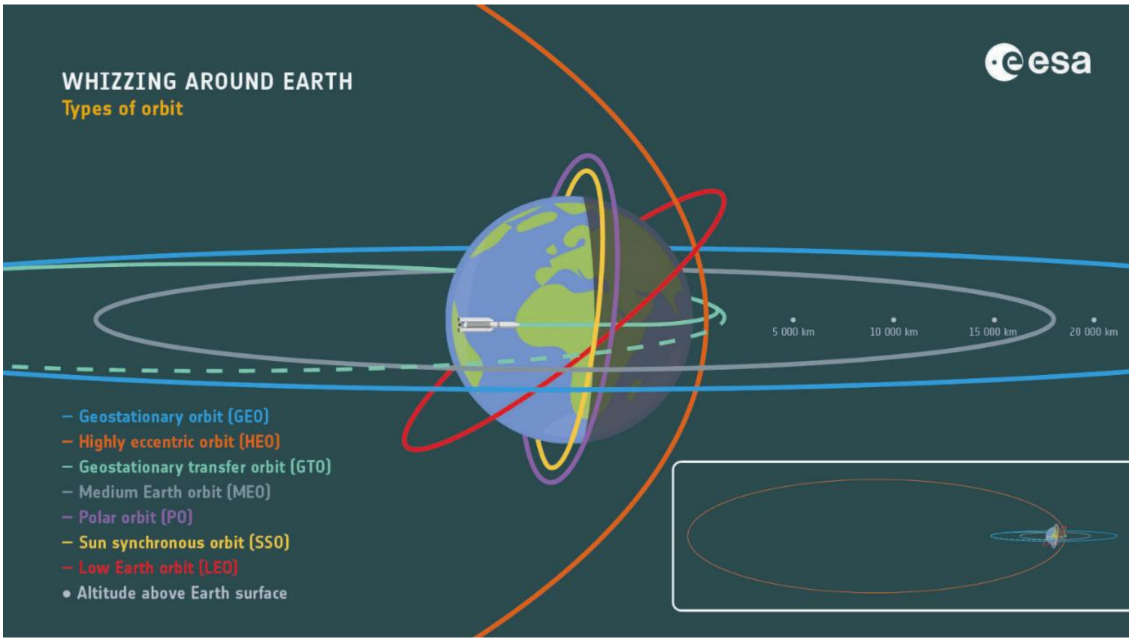

Figure 2. Satellite Orbits - Source: ESA

Additionally, emerging high-altitude platform systems (HAPS) such as stratospheric balloons or planes are also part of NTNs.

A visual breakdown of the different altitudes for each platform is shown in Figure 3. The higher the altitude, the greater the coverage that they provide – See Figure 4 for visual reference of the coverage.

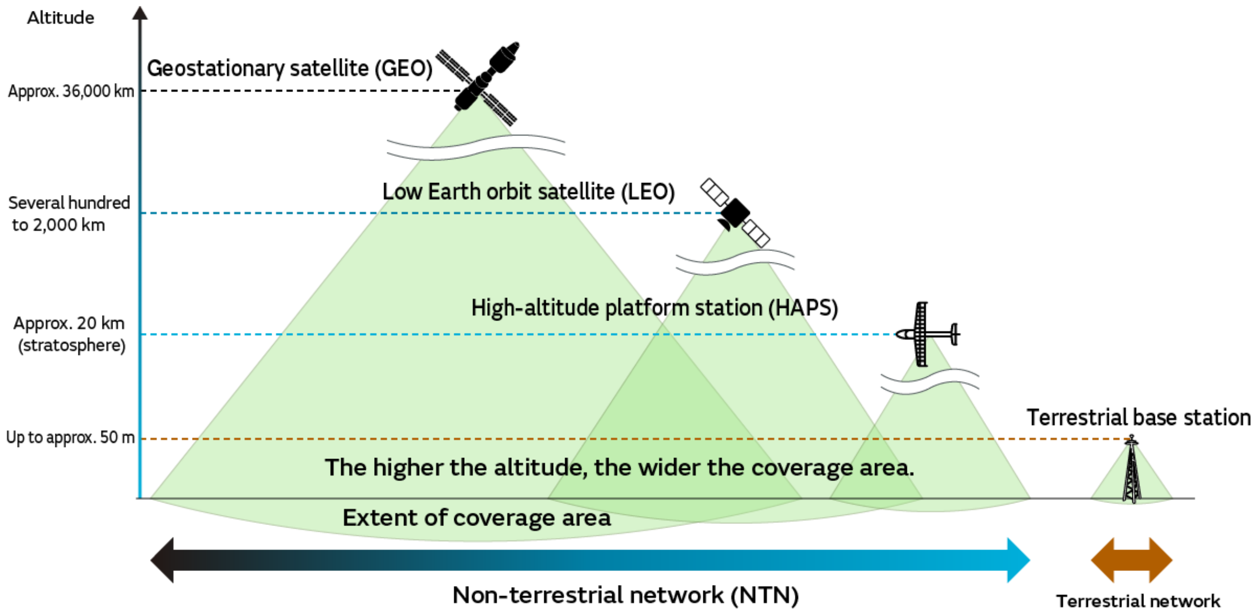

Figure 3. Altitude and Coverage Area of NTN platforms

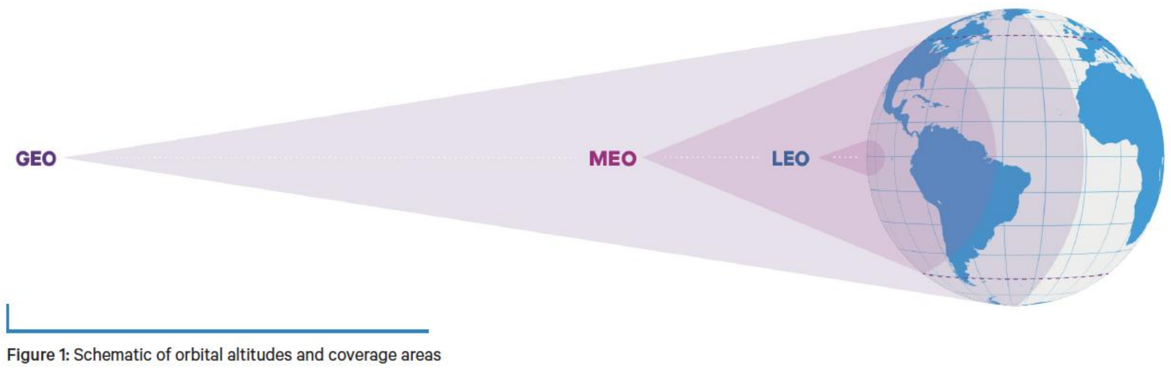

Figure 4. GEO, MEO and LEO coverage reference

Even in the case of LEO satellites, which operate very close to the Earth, when compared to terrestrial cellular networks, NTNs provide wide-area coverage, and is independent of ground-based infrastructure, making them particularly relevant for remote, rural, offshore, and infrastructure-limited environments. For National Gas' pipeline inspection and maintenance operations use cases, sometimes undertaken in such remote geographical locations, NTNs offer a complementary connectivity method to ensure that the maintenance and inspection teams can continue operating even if cellular coverage is intermittent or absent.

2.1.2 NTN Architecture Basics

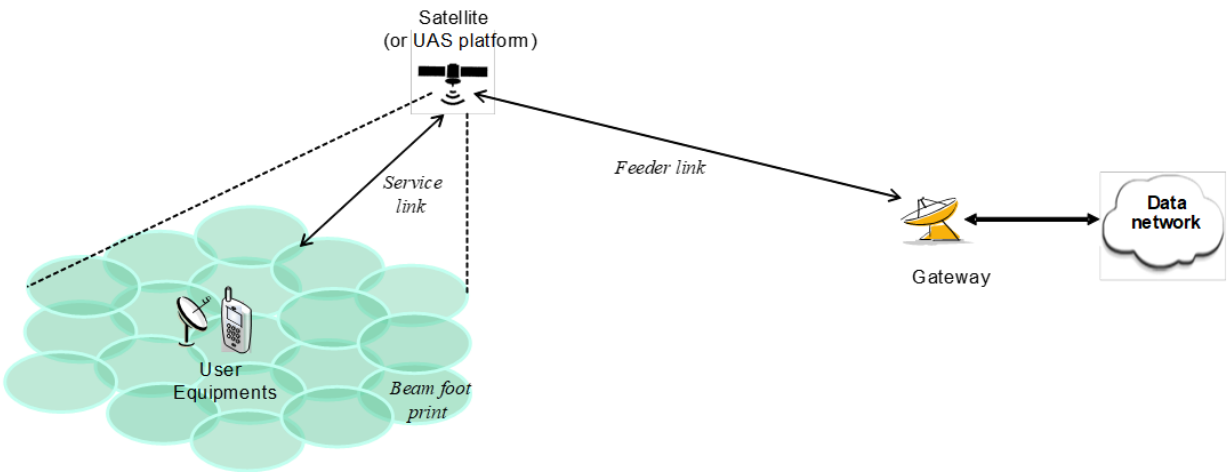

Figure 5. Non-terrestrial network diagram – Source: 3GPP TR 38.821

A basic satellite network architecture is shown in Figure 5. It represents how the traffic is carried between end devices and external networks via a satellite system. The user equipment is located in the geographical area illuminated by the satellite – the satellite beam footprint. Within that area, the users can transmit and receive information to and from the satellite. The area has a determined size and shape based on the characteristics of the telecommunications satellite. The link between the user terminals and the satellite is called User Link or Service Link. On the other end, the satellite is connected down to the Ground Station/Gateway via the Feeder Link. The Gateway is the interface between the satellite network and terrestrial networks, such as internet, other terrestrial operators core networks or, more generic, any other data network. In this scenario, the satellite acts as a bent pipe, as a relay. It receives information from the user and, after performing some filtering, frequency conversion and amplification, it relays the signal to the Gateway via the Feeder Link. The Gateway receives it and forwards the traffic to the data network.

Three layers can be identified in the diagram of Figure 5, and applies to any NTN networks:

Table 2: NTN layers

Layer	Description
Space Segment	The orbital layer providing connectivity independent of terrestrial infrastructure. It can include LEO, MEO, and/or GEO satellites and constellations, each offering complementary capabilities (low latency, regional balance, or wide-area coverage).
Ground Segment	Network of geographically distributed Gateway Earth Stations and control centres. Provides feeder links between satellites and terrestrial backbone networks, enabling IP routing, service management, monitoring, and internet interconnection.
User Segment	End-user access equipment including antenna, satellite modem, power system, and local networking interface. Form factors range from fixed installations to portable, vehicle-mounted, or manpack terminals. This layer primarily determines portability, power consumption, and field usability.

The satellites that follow the diagram from Figure 5, work simply as a bent pipe, receiving and forwarding the traffic. They are also known as transparent payload satellites, as the waveform, the signal repeated by the satellite, is unchanged from the originated in the user terminal.

Alternatively, the satellite can demodulate/decode the signal, process the packets or frames, make switching or routing decisions and regenerate the signal, re-modulating it/re-coding the signal again. In this case, the satellite is a node in the network, not a mere repeater. That is known as regenerative payload and its basic architecture can be seen in Figure 6.

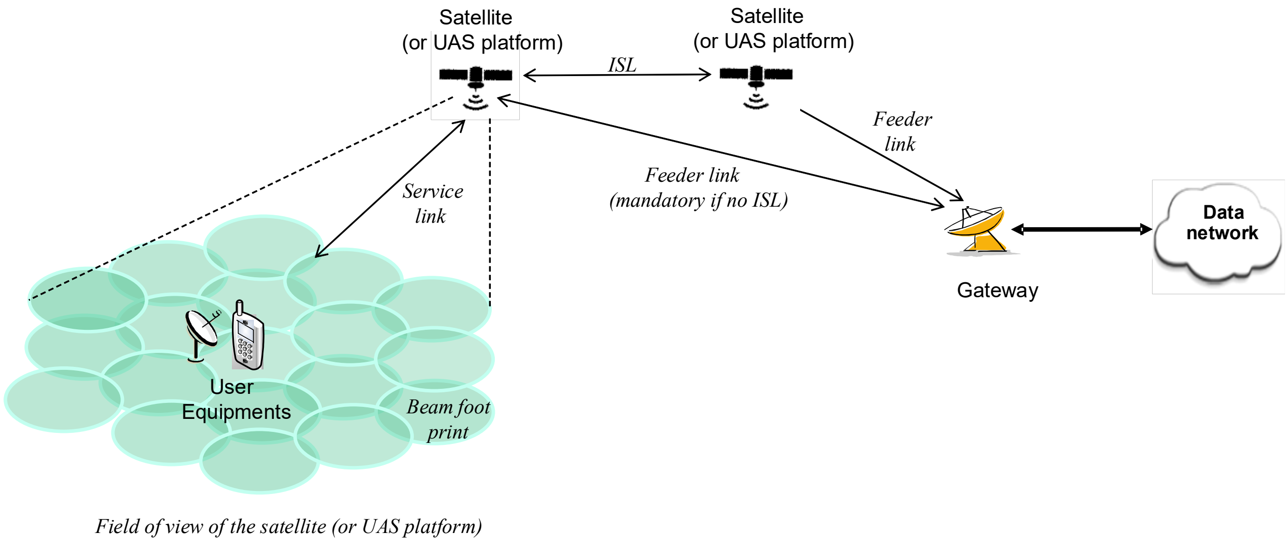

Figure 6. Non-Terrestrial network typical scenario based on regenerative payload - Source: 3GPP TR 38.821

Regenerative payloads improve the user experience, as well as potentially, enable a more autonomous routing and inter-satellite link utilisation – e.g., sending information from one satellite to another based on route optimisation algorithms, ground station visibility or traffic prioritisation policies. Those inter-satellite links are essential for Mult-orbit scenarios, discussed in the next section. Regenerative satellites are also key for integrating TN and NTN and is discussed more in-depth in Section *Direct to device commercial solutions (Emerging)*.

2.1.3 LEO based Industrial solutions/commercial solutions

This section provides an overview of commercially available LEO based connectivity solutions for industrial and enterprise applications. LEO satellite systems operate at altitudes of approximately 500–2,000 km and consist of constellations of satellites that work together to provide continuous coverage. Compared to Geostationary Earth Orbit (GEO) systems, LEO architectures offer significantly lower latency and improved performance for time-sensitive applications.
Modern LEO systems utilise electronically steered antennas and advanced network management techniques to maintain connectivity as satellites move relative to the Earth. This enables reliable broadband connectivity, higher data throughput, and improved support for mobile and on-the-move use cases. The solutions presented in this section are limited to those currently accessible or deployable within the UK and represent a subset of commercially available systems relevant to the use cases identified in this study. Key providers offering coverage in the UK include Starlink, Eutelsat OneWeb, and emerging service providers.

Starlink

Starlink provides LEO satellite connectivity designed to deliver broadband internet access with relatively low latency and global coverage. For nomadic applications, the service can be typically used as a primary connectivity layer, enabling communications independent of terrestrial infrastructure and supporting rapid deployment in remote or temporary locations [1].

Figure 7: a) Starlink constellation b) Coverage over Uk

Table 3: Starlink Service characteristics

Characteristic	Typical values / description
Orbit	LEO, approximately 500–600 km altitude
Constellation size	Thousands of satellites in multiple orbital planes
Coverage	Near-global land coverage, subject to national regulatory approval
Service type	Broadband IP connectivity
Round-trip latency	Typically ~30–60 ms; can exceed 100 ms under congestion
Downlink data rate	Typically ~50–200 Mbps, location dependent
Uplink data rate	Typically ~10–30 Mbps, location dependent
Session continuity	Continuous connectivity provided within coverage areas
Typical use profile	General-purpose data, voice, and video services

Starlink User Terminals

Starlink terminals use Active Electronically Scanned Array (AESA) technology to track satellites.

Early terminal designs, such as the first-generation circular dish (Gen1, introduced in 2020) and second-generation rectangular actuated dish (Gen2, introduced in 2021–2022), incorporated motors to support initial “coarse” alignment to a fixed position. However, all real-time satellite tracking is performed electronically, enabling rapid switching between satellites without continuous physical movement of the dish. More recent terminal designs, including the stationary rectangular Gen3/V4 models (introduced from 2023 onwards), reduce or eliminate mechanical components, improving reliability and efficiency. The section below lists the various terminal types and their performance, cost parameters.

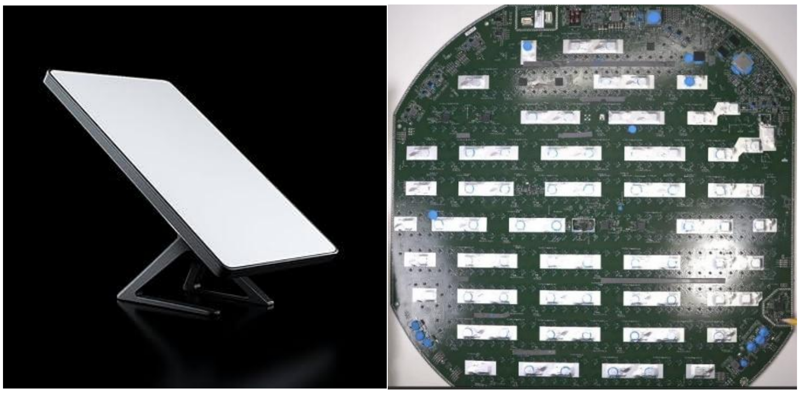

Figure 8: Starlink user terminal

Standard Fixed User Terminal

Fixed Starlink terminals are intended for stationary deployment at a single location over an extended period. These terminals prioritise stable performance and link reliability over portability and are typically installed at sites where relocation is infrequent or planned well in advance. Their deploy-and-operate model is best suited to fixed-site connectivity scenarios, including remote or harsh environments where a terminal can remain installed and provide continuous service. Although these terminals might not be suitable for on the move pipeline inspection but can be suitable for compressor sites or AGI (Above Ground Installation) sites.

Table 4: Starlink fixed terminals characteristics [2]

Name	Terminal Type	Top level Specifications	Indicative hardware cost	Link to product/datasheets
Standard Terminal	Stationary	Data rate: 100 Mbps to 200 Mbps	£300–£500 Subscription cost: £35 for 100 Mbps £55 for 200 Mbps £75 for Max	Starlink Standard
		Power: 75-100W		
		Size and weight: 594 x 383 x 39.7 mm (H x W x D) 2.9 kg (only terminal) 3.2 kg with Kickstand 3.8 kg with kickstand and 15 m cable		

Note: The prices are taken from the Starlink` s website on 10.03.2026

Portable Starlink terminals

Portable Starlink terminals are designed for frequent relocation and deployment across multiple locations, supporting users who move between sites as part of their daily activities. These systems prioritise lightweight design, portability, and rapid setup, enabling connectivity to be established quickly by non-specialist personnel.

Unlike fixed installations, portable terminals are intended to travel with the user and be redeployed whenever connectivity is required, while remaining stationary during operation. This makes them well suited to short-duration worksites, inspections, maintenance activities, and other field operations where connectivity must be quickly established and then packed away when work is complete. In the case of Starlink Mini, there are vehicle roof mount kits with quick release mechanisms that allow the user to install the kit safely in the roof (e.g., while on the move) and quickly detach it when needed.

Figure 9: Starlink Mini b) Starlink Flat panel

Table 5: Starlink portable terminal options and characteristics [2]

Name	Terminal type	Top level Specifications	Indicative hardware cost	Link to product sheet
Mini	Portable	Data rate: Download: 100 – 200 Mbps Power: 25-40W Size and weight: 298 x 259 x 38.5 mm (H x W x D) 1.1 kg (only terminal) 1.16 kg with Kickstand 1.53 kg with kickstand and 15 m cable	£179-£299 Subscription cost: Roam 50 GB: £50 Unlimited: £96	Starlink Mini

Performance (Gen 3) / Flat panel Terminal	One the move (Vehicular)	Data rate: Up to 400+ Mbps Power: 70-100 W Size and weight: 696x396x40 mm (HxWxD) 2.2 Kg	£2,000–£3,000 Subscription cost: Local Priority 50 GB: £39 Local Priority 500 GB: £99 Local Priority 1 TB: £174 Local Priority 2TB GB: £324	[Starlink Performance (GEN 3)]

Eutelsat OneWeb

Eutelsat OneWeb (EOW) provides broadband satellite connectivity using a LEO constellation, with a focus on enterprise, government, and critical infrastructure users. Unlike consumer-oriented services, EOW connectivity is typically delivered through managed service providers and is designed for controlled, professional deployments rather than mass-market use [3].

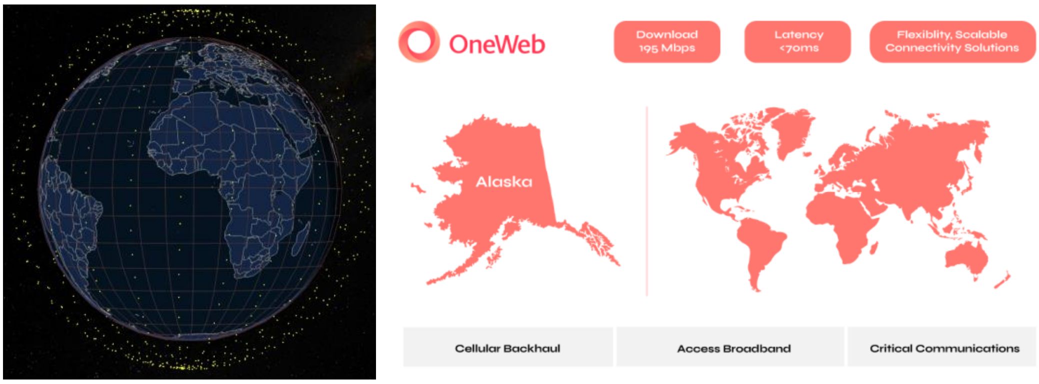

Figure 10: a) EOW constellation b) Coverage over Uk

Table 6: EOW Service Characteristics

Characteristic	Typical values / description
Orbit	LEO, approximately 1,200 km altitude
Constellation size	1200 satellites in polar and inclined orbits
Coverage	Global coverage, including high-latitude regions, strong UK coverage
Service type	Managed broadband IP connectivity
Round-trip latency	Typically ~50–80 ms

Downlink data rate	Typically ~50–195 Mbps (service-profile dependent)
Uplink data rate	Typically ~10–50 Mbps
Typical use profile	General-purpose data, voice, and video services

EOW User Terminals

For the EOW network, land mobility connectivity is mainly provided through user terminals developed by manufacturers such as Intellian Technologies. These terminals use electronically steered flat-panel antennas that track LEO satellites without mechanical movement, enabling broadband connectivity in remote locations.

The Intellian OW-series terminals (e.g., OW10HV) are designed for portable, fixed, or vehicle-mounted deployment, supporting field operations and temporary connectivity where terrestrial infrastructure is unavailable. Other terminals like the new OW7MP are focused on portability and are ruggedised military grade, offering throughputs of 57/10Mbps (downlink/uplink) and up to 5h of operation.

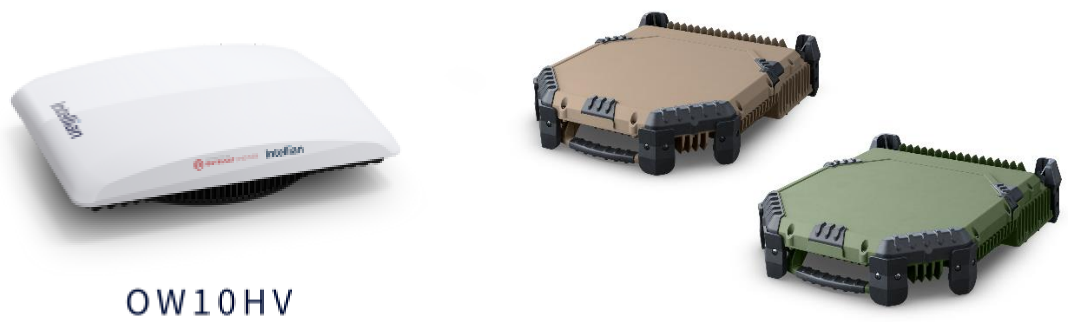

Figure 11: Compact Flat Panel for Land Mobility (left), OW7MP Manpack portable terminal (right)

Table 7: EOW Terminal options and characteristics [4]

Name	Terminal Type	Top level Specifications	Indicative hardware cost	Link to product sheet
OW10HV Compact Flat Panel for Land	On the move/Portable	Peak Downlink Data Rate: 75 Mbps Peak Uplink Data Rate: 14 Mbps Power: 150W average Size and weight: Outdoor unit - 56 x 45 x 12 cm Internal unit (modem): 21 x 17 x 8 cm	£8000 Subscription cost: depending on service	OW10HV

		Weight: 12.2kg		
OW7MP Manpack	On the move / portable (manpack)	Peak downlink up to 10 Mbps, Peak uplink up to 3 Mbps (service-dependent) Power: ~60–100 W typical Size: 45 × 35 × 10 cm Weight: ~9–10 kg total kit with battery and accessories	~£20,000–£25,000 (depending on configuration and modem options) Subscription cost: depends on service	[OW7MP]

Amazon LEO/Kuiper (Emerging, launch in Q1 2026)

Amazon's LEO system follows a modern satellite network architecture, based on a dense constellation of Low Earth Orbit satellites working together to provide continuous coverage. It uses Ka-band frequencies (high-frequency spectrum suitable for high data rates), spot beam technology (focused coverage areas to increase capacity), and optical inter-satellite links (laser links between satellites) to enable low-latency, high-capacity broadband connectivity. These features also support improved network resilience and dynamic traffic management across the system.[7].

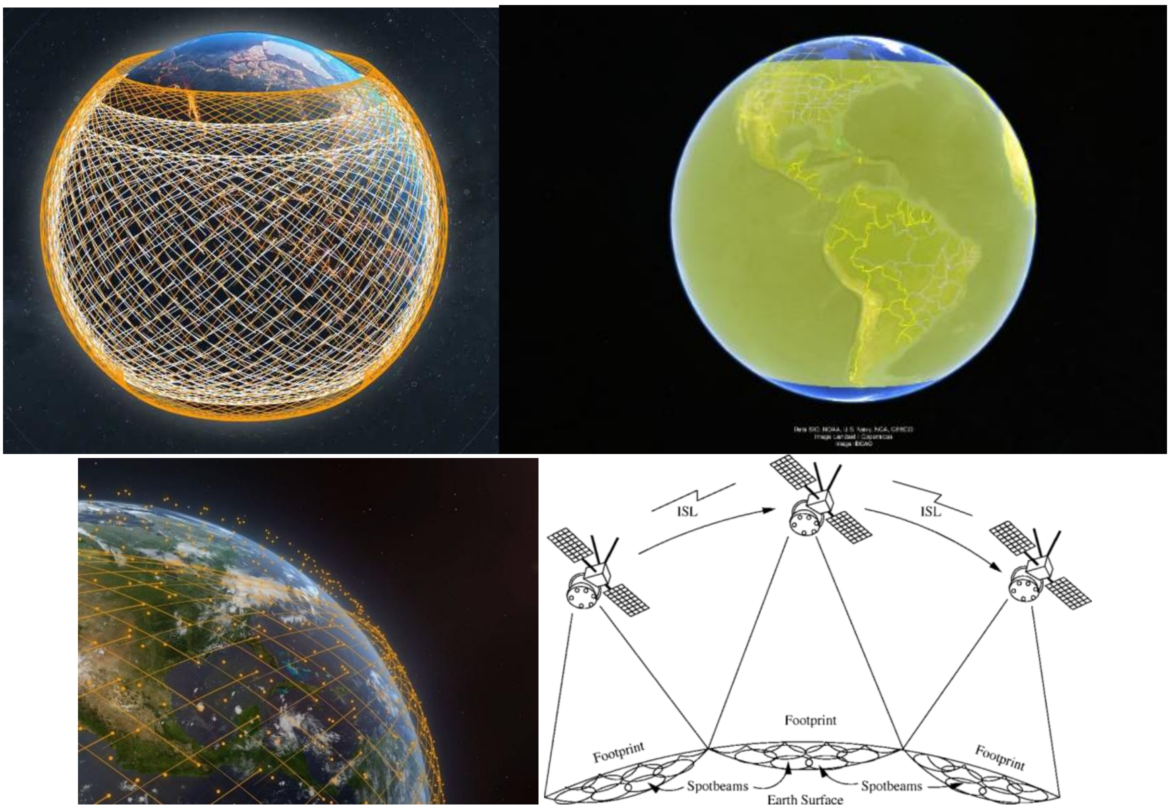

Figure 12: a) Amazon LEO constellation b) global coverage (without polar regions) c) cross links d) spot beam configuration

Table 8: Amazon Leo service characteristics

Characteristic	Typical values / description
Orbit	Low Earth Orbit (LEO), ~590–630 km altitude (multiple orbital shells)
Constellation size	Planned ~3,200+ satellites
Coverage	Global coverage (progressive rollout during deployment phase)
Service type	Broadband IP connectivity (consumer, enterprise, government tiers)
Round-trip latency	Expected low LEO latency
Downlink data rate	Broadband class (terminal/service dependent)
Uplink data rate	Broadband class (terminal/service dependent)

Amazon Leo User Terminals

Amazon Kuiper delivers broadband services through a range of electronically steered Ka-band user terminals designed for fixed and transportable deployment. The terminals utilise flat-panel phased-array antenna technology, eliminating mechanical steering and enabling rapid installation. The portfolio spans multiple performance tiers, balancing throughput, aperture size, and portability for remote and field-based applications [12] .

Figure 13: Amazon Leo user terminals

Table 9: Amazon Leo user terminal options and characteristics [10].

Name	Terminal Type	Top level Specifications	Indicative hardware cost	Link to product sheet
Leo Nano	Portable	Data rate: Download:100 Mbps Uplink: 20 Mbps	Not publicly available yet	Not publicly available yet
		Power: 25-40W		
		Size and weight: 18 × 18 × 2.5 cm, 1.1 kg		
Leo Pro	Outdoor flat-panel on the move broadband, suitable for RVs, vans, and commercial vehicles	Data rate: Peak Downlink 400 Mbps Peak Uplink 100 Mbps	Not publicly available yet	Not publicly available yet
		Power: 25-40W		
		Size: 28 × 28 × 3.3 cm Weight: 2.5 kg		

Iridium

Iridium operates a global LEO satellite constellation designed to provide reliable voice and data communications in remote and infrastructure-limited environments. Unlike broadband-focused LEO systems, Iridium's architecture is optimised for low-power, narrowband connectivity, enabling compact, handheld, and wearable terminals suitable for mobile users operating in challenging conditions. Its polar orbital configuration provides true global coverage, including oceans and high-latitude regions, making it particularly relevant for safety-critical and field-based applications.

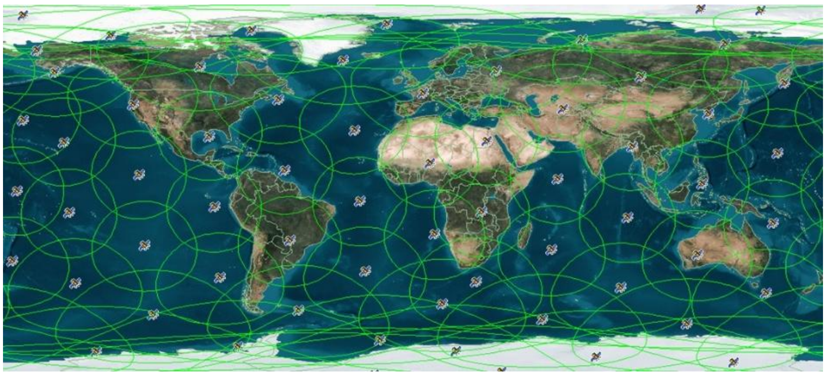

Figure 14: Iridium constellation coverage

Table 10: Iridium constellation service characteristics

Characteristic	Typical values / description
Orbit	LEO, ~780 km altitude
Constellation size	66 active satellites (+ on-orbit spares)
Orbital configuration	Polar orbital planes providing global coverage
Frequency bands	L-band (user links)
Coverage	Global, including polar regions and remote land areas
Service type	Managed voice, messaging, narrowband IP connectivity
Round-trip latency	Typically ~30–50 ms
Downlink data rate	Up to ~700 kbps (Certus tier dependent)
Uplink data rate	Comparable to downlink (service-tier dependent)
Dependency on terrestrial networks	Independent satellite connectivity; gateways used for internet interconnection

Iridium User Terminals

User connectivity on the Iridium network is enabled through a range of specialised devices designed for remote and mobile operations. These terminals typically prioritise global coverage, reliability, and low power operation, making them suitable for environments where terrestrial connectivity is unavailable.

Figure 15: Iridium user terminal and devices

Table 11: Iridium user terminal and devices characteristics

Name	Terminal Type	**Top level Specifications**	Indicative Hardware Cost	Link to product sheet
MissionLINK 700 (Certus 700 class)	Portable on the move broadband access	Latency (one-way): >200 ms Data rate: Up to 700 kbps Power: External DC supply Size & weight: Compact external antenna + modem unit: ~6 kg including antenna and Terminal Dimensions: 30.5 cm x 22.9 cm x 7.6 cm	Mid-tier cost £5,900 – £7,000 Service Subscriptions: 20 MB: ~£55–65 50 MB: ~£85–100 100 MB: ~£140 1–10 GB+: ~£900 – £4,300+	[Thales MissionLINK 700]

		Antenna dimensions: 35.6 cm diameter x 10.2 cm height		
Iridium Edge	Low-data IoT. Emergency messaging terminal	Latency (one-way): >200 ms	£360–£400 Subscription: £11.00- £11.80 per month	[Iridium Edge]()
		Data rate: Up to 350 bytes per message		
		Power: Low power consumption		
		Size & weight: Small-form IoT module		
Iridium Go! Exec	Low-data. Voice Calls. SOS terminal	Latency (one-way): >200 ms	From ~£65/month (5MB) to £390/month (250MB). Voice included.	[Iridium Go! Exec]()
		Data Rate:		
		Power: Battery life (standby): 24h; Operational: 6h		
		Size & weight: 203mm x 203mm x 25mm; 1200gr		

2.1.4 MEO based Commercial Solutions

MEO satellite systems provide high-throughput connectivity with lower latency than GEO systems, typically operating in Ka-band frequencies. Commercial MEO constellations such as O3b mPOWER developed by SES satellites are primarily designed for regional broadband connectivity for enterprise, maritime, and government users. Although current MEO coverage does not extend to the UK operational area considered in this study, available user terminals illustrate the design characteristics and capabilities of MEO mobility terminals. In the future, MEO constellations could be incorporated into broader multi-orbit networks which can make use of LEO, MEO and GEO satellites and constellations, providing resilient and guaranteed service to customers [21].

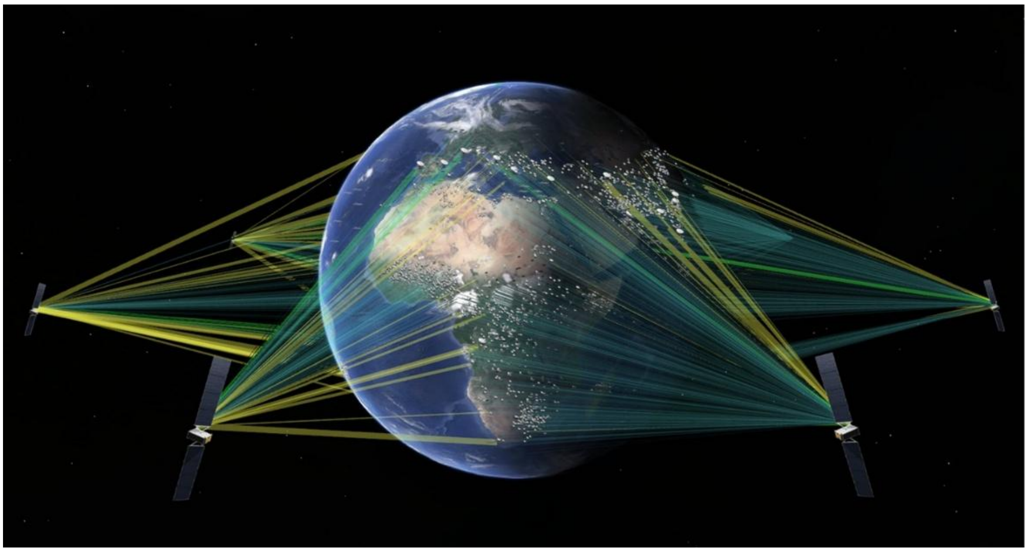

Figure 16: SES O3b mPOWER constellation

User Terminals

NANO SAT H, an ultra-small satellite terminal designed for communication-on-the-move (COTM) applications in remote environments. It is compatible with SES O3b mPOWER MEO constellation, featuring a compact, lightweight form factor with full 360° azimuth coverage and a wide elevation range, enabling rapid deployment and continuous connectivity for mobile users. The terminal supports Ka-band operation for MEO systems, is powered via external DC supply, and is intended for person-carried field deployment where size, weight, and setup speed are critical constraints.

Figure 17: NANO SAT H Terminal

Table 12 : NANO SAT H Terminal Characteristic

Parameter	Specification
Terminal type	Communication-on-the-Move (COTM)
Configuration	Portable, person-carried
Supported orbit	MEO
Frequency band	Ka-band
Transmit frequency	27.5 – 31.0 GHz
Receive frequency	19.2 – 21.2 GHz; 17.5 – 20.0 GHz
Antenna size	19.5 × 16 cm
Weight	~2.3 kg
Dimensions	~7.6 × 6.3 in
Interfaces	Ethernet, RS-232

2.1.5 GEO based Commercial solutions

Geostationary Earth Orbit (GEO) satellite systems provide established and widely deployed connectivity services for enterprise, maritime, aviation, and remote site applications. These systems operate across multiple frequency bands, including L-band, Ku-band, and Ka-band, each offering different trade-offs between coverage, capacity, and terminal requirements.

Lower frequency bands such as L-band offer highly reliable connectivity with small, portable terminals but are limited in data throughput. In contrast, higher frequency bands such as Ku-band and Ka-band enable significantly higher data rates and are commonly used in High-Throughput

Satellite (HTS) systems. Traditional GEO systems often relied on wide-beam (single beam) coverage, where a single large footprint served a broad geographic area, resulting in limited capacity per user. Modern HTS systems improve on this by utilising spot beam architectures , which divides coverage into multiple smaller beams as shown in Figure 18: Single beam vs spot beam architectureFigure 18. This enables frequency reuse across different beams, significantly increasing overall system capacity and data throughput compared to wide beam.

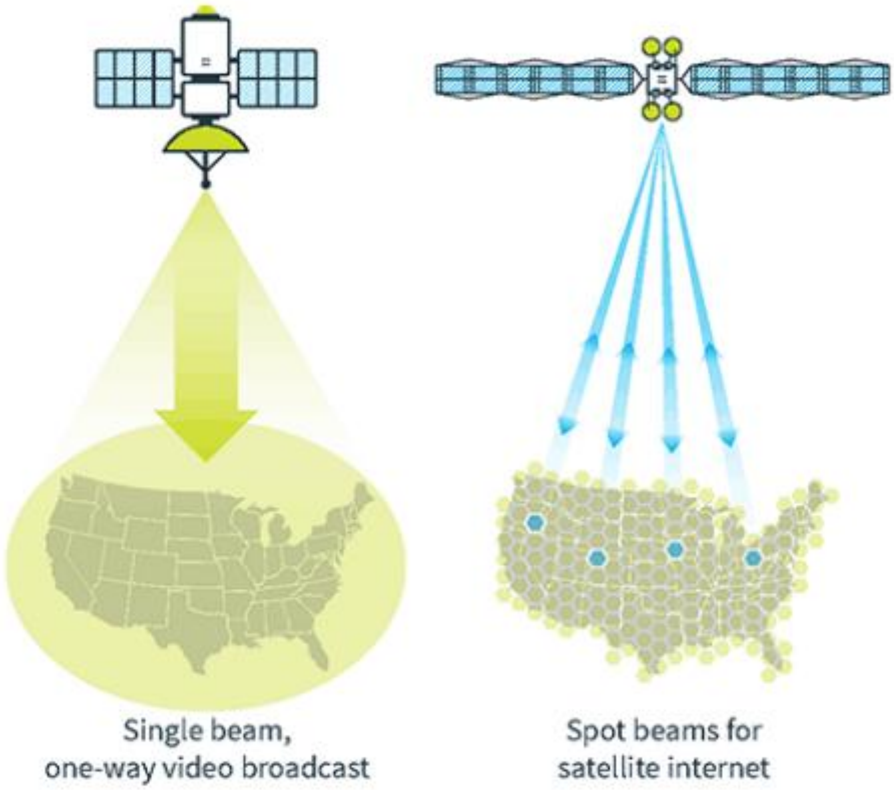

Figure 18: Single beam vs spot beam architecture

However, the use of higher frequency bands typically requires larger, more precisely aligned antennas, as well as increased power and pointing accuracy. As a result, terminals operating in Ku- and Ka-band are generally fixed, transportable, or vehicle-mounted, requiring stable installation and external power supply.

While these systems are well suited to remote facilities and temporary field sites, GEO-based terminal architectures, particularly those operating in higher frequency bands are less compatible with single-person, on-foot deployment due to constraints related to antenna size, portability, and system latency. [5].

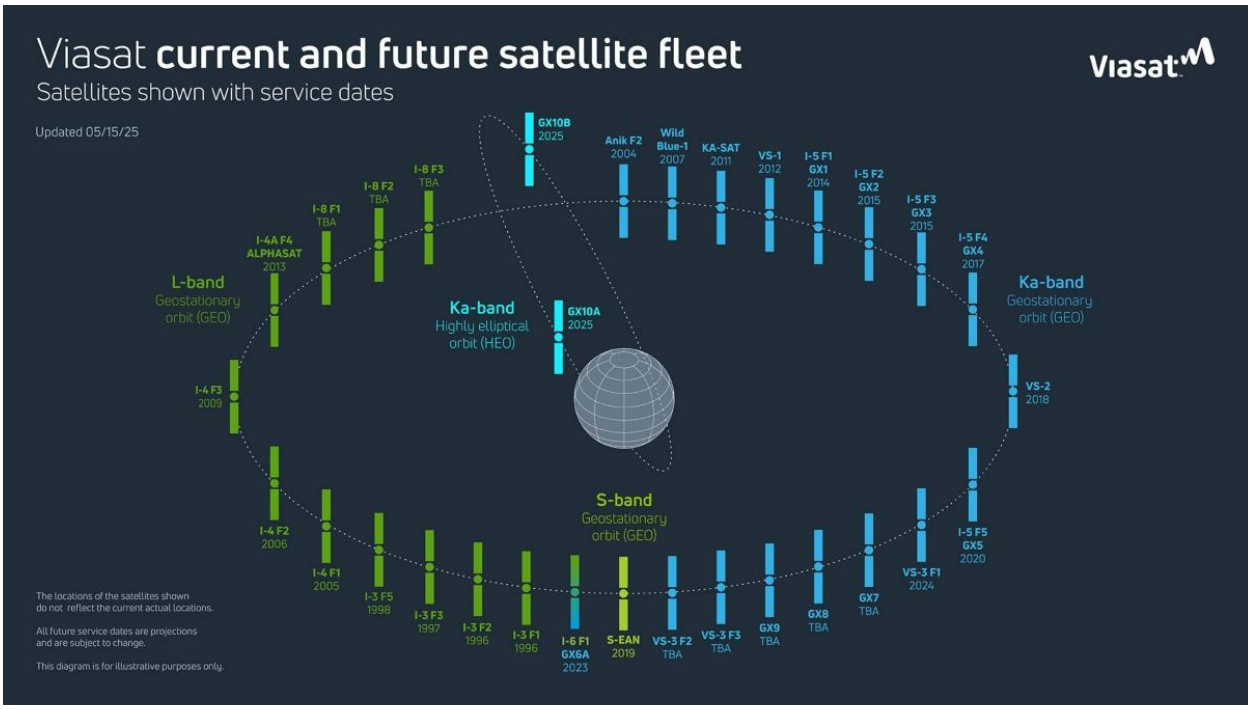

Figure 19: Viasat GEO fleet

Characteristic	Viasat (including Inmarsat services)
Orbit type	Geostationary approx. 36000 km
Frequency bands	L-band (legacy Inmarsat services), Ka-band (Global Xpress / Viasat HTS)
Coverage	Near-global coverage via multiple GEO satellites
Typical data rates	~0.4–0.6 Mbps (BGAN L-band portable terminals) up to ~10–50 Mbps (Ka-band HTS services)
Latency	~600–700 ms round-trip
Primary services	Broadband connectivity, maritime communications, aviation connectivity, government and enterprise networks

GEO user terminals

GEO terminals generally provide reliable managed connectivity, but portable systems typically deliver sub-Mbps data rates, while higher-throughput solutions require vehicle-mounted antennas and significantly higher hardware cost. Viasat provides high-throughput broadband services such as enterprise satellite internet and government connectivity solutions, typically delivered through fixed or transportable terminals. Inmarsat, now part of Viasat, offers several service families including Inmarsat BGAN for portable broadband connectivity, Inmarsat Fleet Xpress for maritime communications, and Inmarsat Global Xpress, a global Ka-band network providing high-capacity services for aviation, maritime, and government users. These services are generally designed for managed connectivity environments with dedicated terminals, rather than lightweight systems intended for continuous on-foot mobility.

Figure 20: a) Cobham Explorer b) Huges

Table 13: GEO terminals options and characteristics

Terminal	Operator / Network	Terminal Type	Top level Specifications	Typical Hardware Cost*	Link to datasheet
Cobham Explorer terminals (510 and 710)	Inmarsat (BGAN)	Portable terminals	Data rates: 32 – 650 kbps (service dependent) Power: ~100 W typical during transmission Weight range: ~1.4 kg – 3.2 kg Size range: ~20 × 20 × 4 cm to ~28 × 33 × 5 cm	~£6,500 -7500	Cobham 510 Cobham 710
Hughes 9211-HDR	Inmarsat (BGAN)	Portable terminal	Data rate: >650 kbps HDR streaming Power: ~100 W typical during transmission Size: Compact directional antenna (~25 × 25 cm unit) Weight: ~4 kg terminal unit	~£4,500	Hughes HDR
Satcube Ku	Intelsat (FlexMove)	Portable terminal	Data rate: Minimum 4 Mbps full-duplex, up to ~20 Mbps via HTS satellites Power: ~130 W typical consumption	£12k–£20k	

			Size and weight: Terminal: 470 × 300 × 55 mm Weight: ~8 kg (without batteries)		

2.1.6 Multi-Orbit Networks (Emerging)

Multi-orbital satellite constellations integrate GEO and LEO systems into a single, coordinated communications architecture. Rather than relying on a single orbital regime, this approach exploits the complementary performance characteristics of different orbits to deliver resilient, adaptable connectivity. In a multi-orbital architecture, traffic can be dynamically routed across orbital layers based on service requirements such as latency, availability, and capacity. This enables:

- Latency-sensitive services to preferentially use low-orbit links
- High availability backhaul to utilise higher orbits
- Seamless continuity during congestion, outages, or degradation in any single layer

From a resilience perspective, orbital diversity reduces systemic risk by avoiding dependence on a single altitude, constellation, or failure mode

Figure 21: Multi-orbit connectivity

Multi-orbit connectivity is currently delivered through managed service frameworks rather than standalone satellite contracts. Operators such as SES, Eutelsat (with acquisition of OneWeb), Intelsat, and Viasat provide integrated GEO, MEO, and/or LEO capacity, often bundled with enterprise-grade service agreements.

From the user segment infrastructure perspective, multi-orbit capability is realised through advanced terminals capable of interfacing with more than one satellite constellation. One such example of terminal. One example is the Hydra-2, developed by All.Space, which is designed to support simultaneous connectivity with multiple satellite networks in LEO, MEO and GEO through electronically steered antennas. Such terminals enable flexible, resilient communications by allowing the user segment to switch or combine links across different orbital systems. However, lightweight and highly portable terminals supporting true multi-orbit capability have not yet been widely developed

Figure 22: Hydra 2 terminal

Table 14: Hydra 2 specifications

Name	Terminal Type	Top level Specifications	Indicative hardware cost	Link to product/datasheets
HYDRA 2 (ALL.SPACE)	Vehicle-mounted/ fixed	Data rate: Up to ~100–200+ Mbps Power: ~150–300 W (typical operational range depending on active links) Size and weight: 86 cm Diameter x 18 cm Height ~77 kg (antenna unit, modem)	Enterprise (typically £10,000s+ depending on configuration and integration)	Hydra 2

2.2 Terrestrial networks

Terrestrial networks (TN) are part of our day-today. Ranging from short range networks such as Bluetooth or Wi-Fi to Wide Area Networks (WANs) like 3G, 4G and now 5G cellular networks, TN are fundamental to enable communication between individuals and local or remote systems.

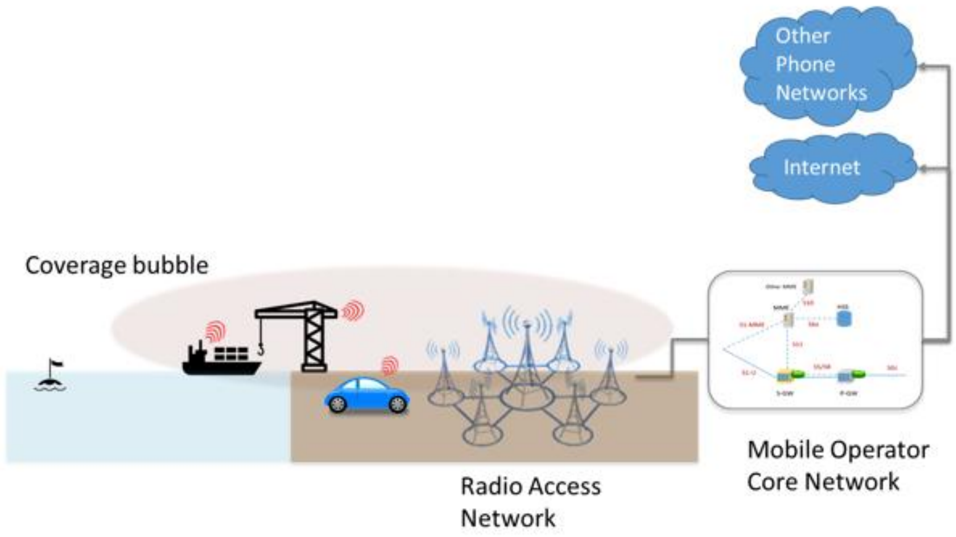

Figure 23. Terrestrial Network

There are 3 main components in a Terrestrial Network.

- User Equipment (UE): UE is simply a device used by the end-users such as smartphones, tablets, routers etc.
- Radio Access Network (RAN): RAN is the part of the network that connects your device to the operator`s core network using radio signals. It also manages connections and handovers, controlling radio resources etc.
- Core Network: The core is the brain of the network. It routes your data to the internet or other networks, authenticates users, manage sessions etc.

This section focuses on cellular networks, which are used as primary solution for a wide range of use cases, such as the ones that the current project target. Cellular networks are extended across the territory and although not ubiquitous, they are the most cost-effective solution where available. There exist gaps in coverage depending on the orography of the terrain and the density of base stations, as will be discussed within this section.

2.2.1 5G

5G (Fifth Generation) is the latest generation of mobile network technology, designed to significantly improve speed, latency, reliability, and connectivity density compared to previous generations such as 3G and 4G LTE. While earlier generations primarily focused on faster mobile internet, 5G expands the role of cellular networks to support massive device connectivity, real-time applications, and advanced digital services.

The three service categories of 5G are:

- Enhanced Mobile Broadband (eMBB):
    - eMBB focuses on delivering extremely high data speeds and large bandwidth for consumer applications.
- Ultra-Reliable Low Latency Communications (URLLC):
    - URLLC provides extremely low latency and high reliability, which is critical for mission-critical applications.
- Massive Machine Type Communications (mMTC):
    - mMTC enables large-scale connectivity for IoT devices.

To access 5G networks, users need compatible hardware such as 5G smart phones, 5G modems/chipsets, 5G Routers etc. Example of major modem/chipset manufacturers are Qualcomm, MediaTek, Samsung, Huawei, etc.

The market for 5G routers (Customer Premises Equipment or CPE) has split into three distinct categories: Premium Mobile, Home/Mesh, and Industrial/Enterprise. These manufacturers buy the chipsets we discussed mostly from Qualcomm and MediaTek and build high-performance networking hardware around them.

Main players in this 5G Router sector are Netgear, TP-Link, Huawei, Peplink, ZTE, etc. There are many different models they provide to the market, but some of the routers are listed in the table below:

Table 15: Summary Table: 5G Router Comparison

Manufacturer	Core User	Model	Estimated Price
Netgear	Pro-Travelers	Netgear Nighthawk M7 Pro [14]	£900 – £990
Peplink	Industrial / Maritime	Peplink MAX BR1 Pro 5G [15]	£900 – £1,000
TP-Link	Home Mesh Users	TP-Link Deco BE65 5G [16]	£500 - £600
Huawei	Global Standard	Huawei 5G CPE Pro [17]	£450 – £499
ZTE	Budget / Reliable	ZTE G5 Ultra [18]	£239 – £349

However, despite advancements in telecommunications technology, the 5G coverage across the UK remains patchy and unevenly distributed as shown in Figure 24.

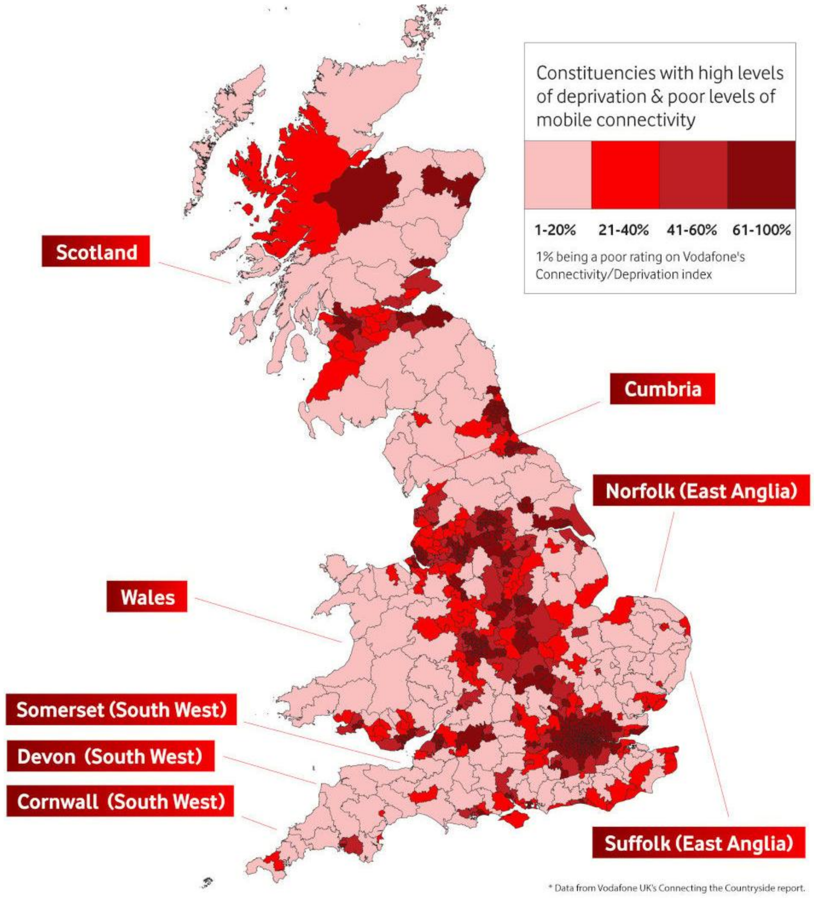

Figure 24: 5G coverage map UK [13]

While major urban centres generally enjoy reliable connectivity, rural areas often suffer from spotty coverage or even complete dead zones. However, in many cases the population density (directly related to the number of potential new customers) and the costs of installation of additional base stations to provide cellular coverage in those areas do not justify the investment by telcos for expanding their infrastructure.

To address this challenge, the regulatory bodies (Ofcom in the UK), standardisation organisations (3GPP) and telecommunications operators have identified NTN as key technology for complementing TN and providing ubiquitous coverage. That approach is called hybrid TN/NTN solutions or networks.

2.3 Hybrid Terrestrial and Non terrestrial solution

In modern architectures, NTNs are no longer standalone systems but are increasingly being integrated into hybrid communication frameworks combining satellite and terrestrial links to achieve ubiquitous connectivity solutions. Except for very specific scenarios (e.g., Military), normally a terrestrial/satellite-only solutions are not the most cost-efficient solutions. Deploying physical infrastructure (e.g., base stations) across the whole territory is unrealistic due to high costs and heterogeneous population distribution, creating connectivity dead spots. Similarly, due to a more limited capacity and higher cost, satellite-only solutions are not always the most cost-effective solutions for covering those areas with connectivity challenges. The combination of both communication technologies in hybrid solutions, normally provide the best cost/benefit balance. Added to failover capability (switching to satellite networks when e.g., cellular networks are not available), the availability of multiple bearers also enable a smart management of traffic across each one, traffic prioritisation or bonding. Those features enabled by the combination of terrestrial and non-terrestrial networks provide a seamless, enhanced user experience.

Until just few years ago, satellite communications and terrestrial communications have developed in parallel. Satellite networks have deployed their own protocol stack. If the satellite terminal manufacturer didn't incorporate TN failover capability into their products, automatically switching from terrestrial to satellite networks when terrestrial networks were unavailable, additional hardware and software (e.g., routers, 5G modems, etc) was required for bridging both TN and NTN in hybrid solutions.

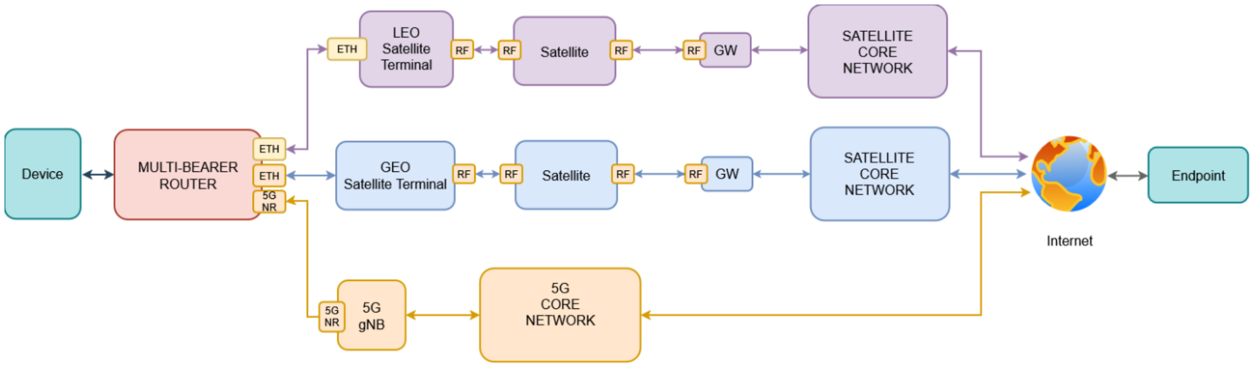

Figure 25. Generic hybrid solution using multi-bearer router, 5G and satellite LEO/GEO networks

2.3.1 Industrial solutions/commercial solutions for network management

The delivery of hybrid architectures requires network orchestration vendors, security layers, and systems integrators capable of managing multi-link connectivity across fibre, terrestrial, and satellite domains. There exist commercial solutions created for this purpose, also adding security layers such as VPN.

This subsection addresses some of the most used ones based on their suitability for the nomadic worker use case that this project addresses. Two reference architectures recur across the different vendors and are analysed:

- The first architecture is based on edge gateway models and normally is implemented as hardware, in the shape of a portable router which presents an access network (e.g., Wi-Fi or LAN Ethernet) and attaches to multiple Wide Access Networks (WANs), such as 5G, Satellite or even another Wi-Fi AP. On top of those, these solutions normally build tunnels to the remote endpoint, which can be of data centres, cloud platforms or servers, securing the connection between e.g., the office and the remote system.
- The second architecture is software based. A laptop or phone bonds available interfaces using a software application and connects to a cloud/remote software terminator that reassembles the traffic, forwarding it to the broader internet or corporate network.

Hardware-based Solutions

Intelligent routers such as Peplink's Pepwaves, Ericsson's Cradlepoint or Teltonika's routers are available commercially, offering common elements to achieve resilient, secure, multi-bearer networks.

They normally share a set of functionalities, combine multiple terrestrial modems (e.g., 4G/5G), embedded in the device, with multiple WAN ports that allow the connection via Ethernet of additional bearers such as external routers or satellite terminals. Failover capability is then implemented, prioritising the WANs – e.g., based on cost per MB, and failing over secondary bearers in case the primary is no longer available. They also offer tunnel-based bonding overlay, combining the bandwidth available to expand the capacity while also creating VPNs for securing the traffic, which is then split across each link and reassembled at the remote concentrator. That traffic can be steered based on certain policies, such as latency sensitivity, packet loss target, etc.

Despite sharing common features, each commercial solution has its distinctive and unique characteristics:

- Pepwave implements their own VPN solution called SpeedFusion, which enables advanced bonding and QoS policies, supporting packet level duplication for enhanced reliability. Also, Peplink has partnered with Starlink and supports the management of the Starlink terminals from their solutions. There are multiple Pepwave models, most of them focused on mobility applications (e.g., MAX BR Series [23]) while others are targeting enterprise, in-office deployments (e.g., Balance devices). The prices vary between models. For this project the MAX BR Series are of interest due to size, weight and power consumption, and their price point goes from £600 in the case of MAX BR1 Mini 5G [24] to above £900 for the MAX BR1 Pro 5G. Others like MAX BR2 Pro 5G are more capable with additional LAN and WAN ports and their price goes above £2000.

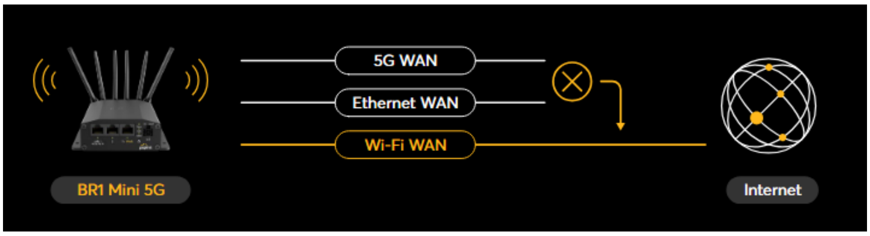

Figure 26. Peplink BR1 Mini 5G - Failover capability diagram - Source: Peplink

- Cradlepoint routers offer strong enterprise-grade routing, strong security, and a cellular-first architecture, more focused on 5G and private networks and not so much in NTNs. R980, R1900 and R2400 routers are example of devices suitable for this project. Their price point ranges between £1300 and above £2000.
- Teltonika offer a more cost-efficient and flexible industrial-grade routers, supporting multi-SIM and VPNs and offering custom Linux-based configurations, which makes their routers more open and offer a better flexibility for integrating their products with other software and hardware solutions. Models like RTUX50 or RTUC50 range from £500 to £800.

This is a limited selection of products and manufacturers. In addition to the three hardware-based solutions analysed, there are other solutions in the market from Cisco (Meraki), Semtech, Ubiquiti and MikroTik, each with their own distinctive characteristics.

A table summarising the models discussed in this section, alongside to reference prices and power requirements is shown below.

Table 16. Example of intelligent router solutions

Vendor	Router model	Approx price	WAN ports	Multi-bearer capability	Power consumption
Teltonika	RUTX50	~£500	1 configurable WAN (5× GbE total)	5G + Ethernet WAN + Wi-Fi WAN, dual-SIM failover	Idle <4 W Max <18 W
Teltonika	RUTC50	~£650–£800	1 WAN + 4 LAN	5G + Ethernet WAN + Wi-Fi WAN	Idle <4.5 W Max <13.5 W
Peplink	MAX BR1 Mini 5G	~£600	1 WAN + 1 LAN	5G + Ethernet WAN + SpeedFusion bonding	~13–18 W
Peplink	MAX BR1 Pro 5G	~£900–£1000	1 WAN + 2 LAN	5G + Ethernet WAN + SpeedFusion SD-WAN bonding	8W (nominal), 19W (max.)
Peplink	MAX BR2 Pro 5G	~£1500–£2200	2× Ethernet WAN + 4× LAN + USB WAN	Dual 5G modems + Ethernet WAN + Wi-Fi WAN + USB WAN	~12 W nominal, ~30 W max
Cradlepoint	R980	~£1300–£1700	2 GbE	5G + Ethernet WAN + SD-WAN	~15 W
Cradlepoint	R1900	~£1500–£2000	4 GbE	5G + Ethernet WAN + SD-WAN	~15–20 W

There are common functionalities that all these products share while also offering distinctive features. Teltonika offers lowest price and power consumption; suitable for industrial IoT deployments. Peplink offers the strongest multi-bearer bonding capability, especially with SpeedFusion. Finally, Cradlepoint is more focused on enterprise cellular routers.

Software-based Solutions

An alternative approach to the hardware-based solutions analysed in the previous section are the software-based solutions. They can run on endpoints and generic servers, enabling multi-bearer management without requiring a vendor-specific router appliance. Sometimes the vendors also offer hardware for simplifying the deployment to the customers. Examples of these are Livewire Digital Razorlink or Speedify (among others).

These solutions normally offer a set of common features, such as packet-level scheduling, aggregation or bonding, real-time link optimisation e.g., based on latency or packet loss metrics, and seamless link transition to avoid session drops. They normally have packet-level control and offer specific QoS and routing policies per applications or protocols.

As happens with hardware-based solutions, each vendor offers distinctive characteristics with their products.

- In Razorlink, Livewire implements their own proprietary protocol – Smart Networking Protocol (SNP), which offers packet-by-packet control. It is cross-platform and supports IP and non-IP underlays. It can manage multiple GEO, LEO and cellular links seamlessly. Their architecture approach is focused on hybrid TN/NTN solutions, abstracting the user from the different underlays. For that purpose, they offer also a cloud-managed "Hybrid Communications as a Service" (HCaaS) option, which removes the need for the user to set up a fixed endpoint for enabling the bonding feature, doing it in their cloud platform instead.

- Speedify offers an endpoint-based bonding service. It is a VPN running on user devices, which act as clients, while using cloud servers. It also offers dedicated servers for enterprise use. From an architecture perspective, the client creates a virtual network interface (TUN), encrypts packets, selects which connection to send each packet on, and sends them to a cloud servers where they are reassembled and forwarded. They also perform packet-level distribution across multiple connections, and support different bonding modes – e.g., prioritising speed, resiliency, etc. It is a solution focused mainly on user-centric bonding.

These are examples of software solutions available in the market that provide a suitable level of multi-bearer management for this project.

Direct to device commercial solutions (Emerging)

Standardisation bodies such as 3GPP work based on releases. Each release introduces a set of specifications that define mobile network technologies, enabling new features and maintaining backward compatibility. In 2022 3GPP published the Release 17, introducing baseline support for NTN in 5G networks, both for 5G New Radio (NR) and IoT applications, while Release 18's programme (2024) explicitly includes further integration of satellite access into 5G systems and continued work on IoT and mobility/service continuity topics. That integration translates into Direct-to-Device (D2D) services, allowing 5G devices such as phones or tablets to switch seamlessly between 5G terrestrial and 5G NTN depending on service availability, not requiring any additional hardware or modification on the device. The path followed when connected via NTN is similar to the one using terrestrial cellular networks, replacing the RAN (Radio Access Network) of the 5G base station (gNB) with the satellite network elements (Satellite and the Gateway). The rest of the elements of the architecture are the same, with the traffic continuing its path from the gNB towards the 5G Core Network (5G CN), which works as the central piece of the 5G network. The Core network is where the user is authenticated, located and its traffic is routed to other Data Networks (e.g., Internet) - See Figure 27.

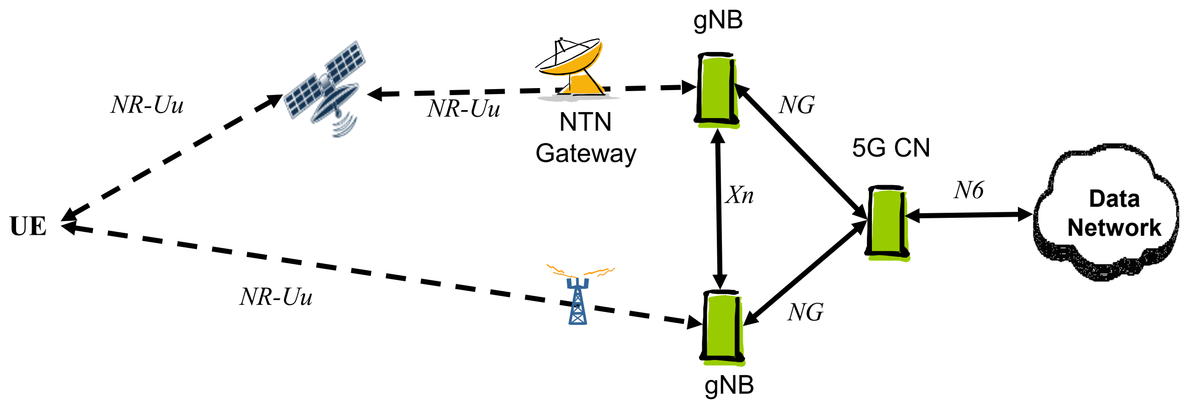

Figure 27. Multi-connectivity involving 5G NTN and 5G Terrestrial – Source: 3GPP TR 38.821

While D2D services are increasingly becoming commercially available, the commercial rollout has started with IoT services, which are out of the scope of this research. Broader 5G D2D services are currently on trial, and some operators are planning and/or deploying their constellations.

Examples of new services and initiatives are listed below:

- Virgin Media O2 launched the O2 Satellite service on 26 February 2026, powered by Starlink Direct to Cell, with a stated goal of expanding landmass coverage (reported as moving from 89% to 95%) and initially targeting selected applications and compatible devices. [25]

  The next generation of Starlink Mobile satellites (V2) aims to provide direct cellular connectivity from space, extending mobile coverage to areas without terrestrial networks. From the user perspective, the service is designed to work with standard LTE smartphones, without requiring specialised satellite terminals. Initially, the system will support SMS messaging, with later phases enabling voice and limited mobile data services up to 150 Mbps. The system is intended to operate in collaboration with Mobile Network Operators with announced partnerships including operators such as T-Mobile in the United States and Virgin Media O2 in the United Kingdom, allowing the satellites to utilise licensed cellular spectrum and extend existing mobile networks into remote areas. The service is intended mainly for basic connectivity and emergency communication in remote areas, acting as an extension of existing mobile networks [11].

- BT signed a global partnership with OneWeb in 2021, with early trials in BT labs and an expressed multi-orbit space strategy (LEO/GEO and, where appropriate, MEO), indicating a longer-term architecture view beyond single-constellation dependency. Talks with Starlink are also ongoing.

- VodafoneThree announced customer trials in summer 2026 for its satellite service using direct-to-device connectivity. Vodafone also highlighted a January 2025 satellite video call demonstration from rural Wales connected to AST SpaceMobile satellites. [26]

  AST SpaceMobile is developing a Low Earth Orbit LEO satellite constellation designed to provide direct cellular connectivity to standard mobile phones without requiring specialised satellite terminals. The system uses large satellites equipped with deployable phased-array antennas that act as cell towers in space, enabling communication directly with unmodified 4G and 5G smartphones using standard cellular spectrum [30].

The system is designed to operate in partnership with existing Mobile Network Operators (MNOs), integrating with terrestrial cellular networks and utilising the operators licensed spectrum. Through these partnerships, AST SpaceMobile aims to extend network coverage to remote, rural, and maritime regions where conventional ground-based infrastructure is limited or unavailable.

Table 17: AST SpaceMobile service characteristics

Characteristic	Typical values / description
Orbit	Low Earth Orbit (LEO), ~700–720 km altitude
Constellation size	Planned constellation of ~90–168 satellites
Orbital configuration	Inclined orbital planes for global coverage
Coverage	Planned global coverage including rural and maritime regions
Service type	Direct-to-device cellular connectivity
Latency	~30–50 ms typical LEO latency
Downlink data rate	Broadband mobile speeds (tens of Mbps target)
Uplink data rate	Comparable to downlink depending on service
Characteristic	Typical values / description (Estimated)
Peak download speed	Up to ~120 Mbps

3. Portable Standalone Connectivity Customised Solutions in Adjacent Sectors

The previous sections reviewed the main terrestrial, non-terrestrial, and hybrid communication technologies that can enable wide-area connectivity. However, beyond the communication infrastructure itself, practical deployment in nomadic and mobile operational scenarios also depends on the availability of integrated, portable connectivity systems that can host and operate these communication technologies.

The project within which this state-of-the-art research is framed focuses on hybrid connectivity solutions for nomadic use cases, particularly solutions that can operate both in in-vehicle environments and as portable systems used while walking or deployed temporarily in the field. While several satellite terminals and hybrid connectivity solutions exist, many of them are designed primarily for fixed installations or permanently mounted vehicle systems, which limits their suitability for highly portable operations.

For this reason, it is relevant to examine portable connectivity solutions developed in adjacent sectors, where similar requirements for mobility, robustness, and rapid deployment have led to the development of integrated portable communication kits. These solutions provide useful insights into system packaging, power integration, transportability, and field usability, which are critical aspects for the targeted nomadic connectivity scenarios.

3.1.1 Soft shell bags and Carry Systems

Compact LEO satellite broadband terminals can be integrated into lightweight soft-case carrying systems designed for remote and mobile deployment. These enclosures support person-portable operation, focusing on portability, quick transport, and fast setup. Usually made from weather-resistant fabrics, the internal layout distributes equipment across multiple compartments to improve ergonomics and maintain hands-free movement. Many designs permit the terminal to operate directly from the case, simplifying field deployment and minimising handling. Attachment points enable integration with backpacks or personal load-carrying gear.

Power is typically provided by external portable battery packs, enabling autonomous operation without dependence on vehicles or fixed infrastructure. Although this configuration demonstrates the practicality of single-operator portable broadband connectivity, most existing implementations target recreational or consumer scenarios and therefore do not address industrial requirements such as hazardous-area certification, continuous duty operation, or enterprise-grade security and network management.

An example of such portable connectivity implementation is presented below [20].

Table 18: Table 16: Softshell terminal backpack features

Feature	Details
Portability	~309 g lightweight Cordura case
Carry Method	MOLLE straps (attach to backpack, bike, vehicle)
Weather Protection	Weatherproof (rain, dust, mud)
Deployment	No unpacking; can connect while inside the bag
Power Handling	Space for Starlink Mini with power bank / cables
Integrated Mounts	MOLLE, handle/straps for flexible mounting

Figure 28: Softshell features and details

3.1.2 Hard Case-Based Kits

In addition to soft-case enclosures, hard case-based kits are also an option for enhancing the portability and ease the deployment of hybrid TN/NTN solutions in-field. These systems integrate satellite terminals (modem + antenna), router and networking equipment, optional additional connectors for antennas and batteries, enabling standalone operation in remote environments. These kits prioritise equipment protection and organisation, using impact-resistant enclosures with dedicated compartments for the different components.

Example of these types of products are Rescue42 SLC+[27], which integrates a Starlink satellite terminal, a battery pack, and Cradlepoint router inside a portable case, providing Wi-Fi connectivity and rapid deployment from vehicles or temporary sites.

Figure 29. Rescue42 SLC+ Hard Case kit

The advantages of hard-case kits are rapid deployment, robust environmental protection, modular equipment integration and compatibility with multiple power sources (e.g., mains, batteries, vehicle socket, etc). These kits are normally used in emergency response situations, business continuity as well as military and adventure. These are the use cases addressed by the SLC+, and due to their requirements, the weight and dimensions of this product (38 kg and 67.3 x 67.3 x 29.5 cm respectively) don't make it a good fit for this project. However, the concept can be implemented in a lighter and more compact way.

Few other hard-case-based kits provide enhanced durability and ease of handling during transport, with dimensions that can be tailored to meet specific size and weight requirements, improving suitability for extended on-foot carriage. Depending on the intended use, these parameters can vary, and a range of portable terminal kits are already available on the market, including compact solutions such as the SUBFIX waterproof hard case designed for Starlink Mini systems [19], which weighs approximately 3 kg and features precision-cut compartments for the dish and accessories.

Figure 30: Hard case with Starlink mini [19]

Customised designs can also incorporate additional characteristics, such as incorporating RF-transparent lids or radome panels, allowing the terminal antenna to operate without opening the case while maintaining environmental protection.

Figure 31. Examples of custom Drop-and-Go Starlink Mini Case [32]

4. Conclusion and next steps

This document has reviewed terrestrial, non-terrestrial, and hybrid connectivity technologies relevant to the identified operational scenarios for nomadic use case. The next step is to map these technologies against the connectivity requirements identified through stakeholder interviews and documented in the requirements specification spreadsheet. This spreadsheet focuses on key connectivity requirements, including performance and functionality, design considerations aspects. A trade-off analysis will be conducted by comparing the technical specifications of the solutions identified in the State of the Art with the defined requirements, enabling the identification of the most suitable connectivity approaches for the targeted use cases.

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D4.1 - Trade off Analysis

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Terms, Definitions, and Abbreviated Terms

Terms Specific to Present Standard

Term	Definition
Nomadic Deployment	A deployment scenario where users are mobile (e.g., walking along pipelines) and require portable, lightweight connectivity solutions.
Vehicle-Based Deployment	A deployment scenario where connectivity equipment is installed in or powered by a vehicle (e.g., VAN), enabling in-vehicle operation.
LEO Terminal	A user terminal designed to connect to Low Earth Orbit satellite constellations, providing broadband connectivity in remote areas.
Trade-Off Analysis	A systematic evaluation process used to compare technologies against defined requirements and identify optimal solutions based on competing factors.

Abbreviated Terms

Abbreviation	Meaning
LEO	Low Earth Orbit
GEO	Geostationary Earth Orbit
NTN	Non-Terrestrial Network
TN	Terrestrial Network
D2D	Direct-to-Device
SoA	State of the Art
CON	Requirement Identifier (Constraint)

Executive Summary

This report evaluates connectivity solutions for the target use case of remote and nomadic operations, such as pipeline inspection, using a structured trade-off analysis of network technologies and terminal devices.

The analysis shows that while 5G provides high performance, it lacks coverage in remote areas, and GEO satellites suffer from high latency. LEO satellite systems offer a strong standalone solution, but a hybrid approach combining 5G and LEO delivers the best overall performance, coverage, and reliability.

At the terminal level, the Starlink Mini and Peplink MAX BR1 Mini 5G router were selected for their portability, cost, low power consumption, and ability to support seamless multi-network connectivity.

The recommended solution is a hybrid LEO/5G system using commercial off-the-shelf components, enabling reliable, low-latency connectivity with automatic failover between networks. Of the deployment options considered, a Peli case-based configuration is preferred due to its robustness, ease of use, and balanced portability.

Overall, the proposed solution provides an effective and practical balance between performance, cost, and ease of deployment, following a modular approach to support future technology advancements.

1. Introduction

This document presents the trade-off analysis conducted as part of the study to identify suitable connectivity solutions for remote and operational environments. The primary purpose of this analysis is to evaluate candidate technologies and determine the most appropriate solution based on defined operational and performance requirements. The analysis builds upon the findings of the *D3.1 - State of the Art Review and Assessment* document, which identified a range of potential network types, satellite systems, and supporting technologies relevant to the use case. This document focuses on further evaluating these technologies through a structured, requirements-driven approach to support solution selection.

The scope of this report includes technologies that are accessible and deployable within the UK, with consideration given to both satellite and satellite/cellular, hybrid connectivity solutions. The analysis considers different system levels, including network technologies, terminal solutions, and deployment configurations.

The study is centred around nomadic operational scenarios, where users are required to operate in remote or infrastructure-limited environments with a need for portable, reliable connectivity. These scenarios include activities such as field inspection and mobile operations, where constraints such as portability, power availability, and ease of deployment are critical.

Overall, the purpose of this report is to provide a comprehensive trade-off analysis leading to the selection of a practical, deployable connectivity solution, and to define its implementation and deployment characteristics.

2. Trade off Analysis Methodology

This section describes the methodology adopted to evaluate and select suitable technologies for the proposed solution. Technologies identified from the *D3.1 - State of the Art Review and Assessment* document are assessed against a defined set of operational and performance requirements. A requirements compliance-based approach is used, whereby each technology is evaluated in terms of its ability to satisfy individual requirements. The methodology has been implemented in following steps mentioned below:

- The trade-off analysis is performed using a requirements compliance-based approach, whereby each technology is evaluated against the defined set of requirements (CON-01 to CON-13) listed in in Section 3.

Fully meets / highly compliant	
Partially meets / partially compliant	
Does not meet / least compliant	

- The trade-off will be conducted in two stages:
  - **First stage** - It involves trade off analysis for different network types assessed in State of the Art Report. That will help to reduce the number of terminals to be assessed in the Second Stage, analysing only the terminals for the type of network suitable for the target use case, discarding non-suitable options.
  - **Second stage –** It will perform a trade-off analysis between the user terminals compatible with the most suitable network type identified in the First Stage.
- The assessment considers both:
  - **Non-Functional requirements**: performance-related aspects such as latency, throughput, data capacity, and coverage
  - **Functional requirements**: operational aspects such as portability, power consumption, deployment flexibility, and usability in field conditions
- Based on the compliance-based trade-off analysis, a combination of technologies is selected, forming the most suitable overall solution that balances key competing factors, including:
  - Performance vs portability
  - Power consumption vs operational duration
  - Cost vs capability
  - Coverage vs deployment complexity
- The selected combination of technologies is used to define the overall system architecture, including integration of network, terminal, and supporting components.
- Following this, further trade-off analysis is conducted at the deployment configuration level, comparing different integration approaches (e.g., Peli case-based and rucksack-based configurations) in terms of practicality, power, portability, and operational suitability.

3. Requirements summary

This section summarises the connectivity requirements used as the basis for the trade-off analysis. The requirements are derived from the *D2.2 - Connectivity Requirements* document and have been consolidated into a structured format to support systematic evaluation of candidate technologies.

The requirements are categorised into Non-Functional and Functional groups. Non-Functional requirements capture performance-related aspects such as connectivity range, bandwidth, latency, and coverage, which are used primarily for network-level evaluation. Functional requirements focus on operational constraints including portability, power, deployment flexibility, and usability, and are used for terminal-level evaluation.

This separation enables a staged assessment approach, where technologies are first evaluated based on their ability to meet core performance requirements, followed by a detailed evaluation of their practical suitability for deployment in pipeline inspection scenarios.

3.1 Non-Functional Requirements

Table 1: Non-Functional requirements

Req Type	Requirement ID	Requirement	Value
Connectivity Range	CON-01	The connectivity solution shall provide continuous connectivity to pipeline workers during inspection activities conducted on the move over several kilometres and extended durations.	4–5 km operation range; 5–6 hours continuous use
Data Usage	CON-05	The connectivity solution shall support the required monthly data usage for operational activities.	~50 GB per month per VAN
Data Types	CON-06	The connectivity solution shall support transmission of standard data types used in field operations.	Support of text, images, and any other standard IP-based data
Bandwidth	CON-10	The connectivity solution shall support applications requiring moderate to high bandwidth.	Comparable to household-level bandwidth usage
Latency / Real-Time	CON-11	The connectivity solution shall enable real-time or near real-time access to data on-site.	~50–100 ms latency (network dependent)
Scalability	CON-12	The connectivity solution shall be scalable to support future data-intensive applications.	Modular and upgradeable architecture supporting future expansion
Coverage	CON-13	The connectivity solution shall provide connectivity coverage across remote pipeline locations.	Coverage beyond terrestrial limits;

3.2 Functional Requirements

Table 2: Functional requirements

Req type	Requirement ID	Requirement	Value
Operational	CON-02	The connectivity solution shall support simultaneous connectivity for multiple users in both field and vehicle-based scenarios.	~1 user per vehicle; 2–3 users in field
Standalone Power	CON-03	The connectivity solution shall operate as a standalone unit with its own independent power source.	Battery-powered

Portability	CON-04	The connectivity solution shall be lightweight and portable for ease of use in field operations.	<80L rucksack weight Preferred form factor: Peli case based
Deployment Flexibility	CON-07	The connectivity solution shall be deployable both as a portable unit and integrated within vehicle-based systems.	Portable + vehicle integration;
Mobility Support	CON-08	The connectivity solution shall maintain active connectivity while users are moving during inspection activities.	Continuous operation while walking
Interface compatibility	CON-09	The connectivity solution shall be compatible with standard wireless communication interfaces.	Wi-Fi for tablets/devices

4. Trade off analysis – Networks

4.1 Networks Candidates summary

Based on the State of the Art (SoA) analysis, a range of candidate connectivity technologies have been identified that could potentially support the pipeline inspection use case. These technologies span both terrestrial and non-terrestrial communication systems, as well as hybrid approaches that combine multiple network types and are summarised in Table 3.

Terrestrial solutions, including public 4G/5G networks and private LTE/5G systems, provide high bandwidth and low latency but are limited by the network coverage in remote pipeline locations. Portable network kits offer localised connectivity but are constrained by range and mobility limitations.

Non-terrestrial network (NTN) solutions include geostationary (GEO) and low Earth orbit (LEO) satellite systems. GEO systems provide wide-area coverage and offer a Service Level Agreement, guaranteeing the contracted service. However, they suffer from high latency due to a longer Earth-satellite distance, making them less suitable for real-time applications. In contrast, LEO satellite systems offer lower latency and higher throughput, making them more suitable for broadband, internet-like connectivity in remote environments.

In addition, emerging direct-to-device (D2D) NTN solutions and services enable connectivity directly to handheld devices without the need for external or modified terminals. While these solutions provide significant advantages in terms of mobility and ease of deployment, they are currently limited in terms of service type (e.g., messages), bandwidth and data capacity.

Finally, hybrid terrestrial–non-terrestrial (TN-NTN) solutions combine the strengths of both network types, enabling seamless switching between terrestrial and satellite connectivity. These approaches offer the potential to provide both high performance and extended coverage, particularly in challenging operational environments.

Table 3: Network candidates summary

Technology	Description
5G (Public Cellular Networks)	Provide high bandwidth and low latency but are limited by coverage in remote pipeline locations.
LEO Satellite Systems (e.g., Starlink, OneWeb)	Provide high throughput and relatively low latency with wide-area coverage, making them suitable for remote connectivity, though they require user terminals.
GEO Satellite Systems	Offer near-global coverage but are constrained by high latency and are less suitable for real-time or interactive applications.
Direct-to-Device (D2D) NTN Solutions (Emerging)	Enable connectivity directly to handheld devices without external terminals, supporting high mobility. Currently emerging and limited in bandwidth and data capacity.
Hybrid TN-NTN Solutions	Combine terrestrial and satellite networks to provide enhanced coverage and performance through dynamic switching or integration.
Portable Network Kits (e.g., Vodafone portable units)	Provide localised connectivity for small teams but are limited in range, portability, and suitability for continuous movement.

4.2 Trade off analysis

A requirement-driven evaluation is performed to assess candidate connectivity technologies against key non-functional requirements identified for the pipeline inspection use case. Each requirement category, derived from the defined performance needs (CON-01 to CON-13), is used as an evaluation dimension to compare the capabilities of different technologies.

The assessment considers core network performance aspects including connectivity range, data capacity, bandwidth, latency, scalability, and coverage. Compliance is evaluated qualitatively to indicate the extent to which each technology satisfies the specified requirements.

Table 4: Trade off Analysis (Network level based on non-functional requirements)

Req Type	5G	LEO	GEO	Hybrid TN-NTN
Connectivity Range (CON-01)	Available except in remote/dead zones; depends on base stations (~1–10 km per cell).	Global coverage; constellation-based	Near-global coverage	Combination of satellite (global) and terrestrial (generally available except in remote locations)
Data Usage (CON-05)	>50 GB supported per month	>100 GB supported per month	~10–50 GB	High (combined terrestrial + satellite)
Data Types (CON-06)	Full IP support	Full IP support	Full IP support	Full IP support

Bandwidth (CON-10)	50–100+ Mbps	50–200 Mbps	10–50 Mbps	High (LEO-backed, 50–200 Mbps)
Latency / Real-Time (CON-11)	~10–50 ms	~20–50 ms	~600 ms	Low–medium (depends on active link)
Scalability (CON-12)	High (network dependent)	High	Limited	High
Coverage (CON-13)	Poor in remote areas	Excellent (rural/global)	Excellent	Excellent (multi-layer coverage)
Cost/MB	~£0.0001–£0.02	Network dependent: <£0.0005 (Starlink) ~£2 - £5 (Iridium)	~£2–£4+	~£0.005–£0.02

The comparison highlights that no single standalone technology fully satisfies all requirements. Terrestrial networks (4G/5G) provide strong performance but are constrained by limited coverage in remote areas. GEO satellite systems offer global coverage but are unsuitable due to high latency and lack of mobility support. Direct-to-device NTN solutions enable mobility and coverage but are limited in technology readiness and still emerging.

LEO satellite systems provide the most balanced standalone solution, offering high bandwidth, low latency, and wide-area coverage, although they are constrained by terminal portability and deployment considerations.

Hybrid TN-NTN solutions demonstrate the highest overall compliance by combining terrestrial and satellite capabilities, enabling both high performance and extended coverage. As such, they represent the most suitable approach for supporting the defined requirements, particularly for scenarios requiring both mobility and reliability in remote environments.

Based on the requirement-driven trade-off analysis, a subset of technologies is shortlisted for further evaluation. The selection is based on the ability of the technologies to meet the majority of functional requirements, particularly in terms of coverage, bandwidth, latency, and support for mobility.

Shortlisted Network candidates

- 5G Networks: Identified as the most cost-effective solution due to the reduced access cost, high bandwidth, low latency, and existing coverage.
- LEO Satellite Systems: Identified as the most suitable remote connectivity solution due to their ability to provide high bandwidth, relatively low latency (similar to terrestrial networks), and wide-area coverage in remote environments.
- Hybrid TN-NTN Solutions: considered the most robust approach, combining both 5G and LEO satellite systems for achieving both high performance and extended coverage, thereby addressing key limitations observed in individual technologies.

5. Trade off analysis - Terminals

5.1 Terminal candidate's summary

The subsequent section focuses on evaluating specific terminal solutions operating within these shortlisted network categories, considering factors such as portability, power requirements, deployment constraints, and suitability for nomadic and stationary use cases. The summary of both LEO based satcom terminal solution and hybrid TN/NTN router solution assessed in *D3.1 - State of the Art Review and Assessment* are provided in Table 5 and Table 6

Table 5 LEO terminals candidate technologies summary

Name	Terminal Type	Data Rate	Power	Size	Weight	Indicative Cost
Starlink Mini	Portable	Download: 100–200 Mbps	25–40 W	~298 × 259 × 38.5 mm	~1.1–1.5 kg	£179–£299 (HW); £50–£96/month
Starlink Performance (Gen 3)	Vehicular / flat panel	Download: up to 400+ Mbps	70–100 W	~696 × 396 × 40 mm	~2.2 kg	£2,000–£3,000
OneWeb OW10HV	Compact flat panel	Downlink: 75 Mbps; Uplink: 14 Mbps	~150 W	~560 × 450 × 120 mm (ODU)	~12.2 kg	~£8,000
OneWeb OW7MP (Manpack)	Portable (manpack)	Downlink: ~10 Mbps; Uplink: ~3 Mbps	~60–100 W	~450 × 350 × 100 mm	~9–10 kg	~£20,000–£25,000
Amazon LEO Nano	Portable (emerging)	Download: ~100 Mbps; Uplink: ~20 Mbps	25–40 W	~180 × 180 × 25 mm	~1.1 kg	Not publicly available
Amazon LEO Pro	Vehicular flat panel	Downlink: up to 400 Mbps; Uplink: up to 100 Mbps	25–40 W	~280 × 280 × 33 mm	~2.5 kg	Not publicly available

All evaluated routers in Table 6 include embedded 5G capability, enabling direct terrestrial connectivity without the need for external modems.

Table 6: Hybrid TN/NTN routers candidate technologies summary

Name	Terminal Type	Data Rate	Power	Size	Weight	Indicative Cost
Teltonika RUTX50	5G Router (Hybrid capable)	5G (up to ~3.3 Gbps); depends on backhaul	<18 W	~132 × 44 × 95 mm	~0.5 kg	~£500
Teltonika RUTC50	5G Router (Hybrid capable)	5G (up to ~3.3 Gbps); depends on backhaul	<13.5 W	~132 × 44 × 95 mm	~0.5 kg	~£650–£800

Peplink MAX BR1 Mini 5G	Compact hybrid router	5G + Ethernet WAN; depends on satellite backhaul	~13–18 W	~130 × 38 × 120 mm	~0.5 kg	~£600
Peplink MAX BR1 Pro 5G	Hybrid router (SD-WAN)	5G + SpeedFusion bonding	~8–19 W	~160 × 36 × 150 mm	~0.7 kg	~£900–£1000
Peplink MAX BR2 Pro 5G	Dual 5G hybrid router	Dual 5G + multi-WAN bonding	~12–30 W	~190 × 40 × 185 mm	~1.2 kg	~£1500–£2200
Cradlepoint R980	Enterprise hybrid router	5G + Ethernet + SD-WAN	~15 W	~210 × 40 × 140 mm	~1.0 kg	~£1300–£1700
Cradlepoint R1900	Vehicle-grade hybrid router	5G + SD-WAN	~15–20 W	~230 × 45 × 160 mm	~1.2 kg	~£1500–£2000

5.2 Trade off Analysis

Following the performance-based down-selection at the network level (Section 6), this section evaluates candidate terminal solutions based primarily on functional requirements. While the previous analysis focused on connectivity performance, this stage considers the practical constraints associated with real-world deployment, particularly for nomadic and remote operational scenarios.

The evaluation focuses on key functional requirements, including standalone power consumption (CON-03), portability (CON-04), deployment flexibility (CON-07), and mobility support (CON-08). In addition, selected non-functional aspects such as achievable data rate and multi-network capability are also considered where relevant, as they directly impact the usability and effectiveness of the solution in operational scenarios.

These factors are critical in determining whether a given terminal can be effectively deployed in field conditions, especially for use cases involving continuous movement, such as pipeline inspection and line-walking activities.

In addition to satellite terminals, hybrid routing devices are also assessed as complementary components. These devices enable integration of multiple network technologies (e.g., satellite and 4G/5G), enhancing overall system resilience through failover and bandwidth aggregation mechanisms.

The trade-off analysis is presented in tabular form in Table 7 and Table 8 , where each satcom terminal and hybrid device is qualitatively assessed against the defined requirements. The objective is to identify solutions that provide an optimal balance between operational feasibility and performance, while addressing the constraints imposed by mobility, power availability, and deployment environment.

Table 7: Satcom terminals trade off.

Terminal	Standalone Power (CON-03)	Portability (CON-04)	Mobility Support (CON-08)	Cost tier
Starlink Mini	25–40 W; battery possible but limited duration	~1.1–1.5 kg; portable	Suitable for continuous walking use	£ Low
Starlink Gen 3	70–100 W; external power required	~2.2 kg; not handheld	Supports in-motion use (vehicle); not suitable for walking	££ Moderate
OneWeb OW10HV	~150 W; high power demand	~12 kg; not portable	Not practical for quick swap and not portable. Fixed deployment	£££ High
OneWeb OW7MP	60–100 W; high for portable use	~9–10 kg; heavy manpack	Limited mobility; not suitable for continuous walking	£££ High
LEO Nano	25–40 W; battery feasible	~1.1 kg; highly portable	Potentially suitable; not validated (TRL limitation) – To consider in the future	Not available
LEO Pro	25–40 W	~2.5 kg	Supports in-motion use (vehicle); possible portability with custom design – To consider in the future.	Not available

Table 8: Hybrid TN/NTN router trade off.

Terminal	Avg Power	Portability (CON-04)	Deployment Flexibility (CON-07)	Multi-Network Capability (Critical)	Cost
Teltonika RUTX50	~11 W	~0.5 kg; highly portable	Supports vehicle integration + portable integration	Basic failover only; no bonding	£ Low
Teltonika RUTC50	~10 W	~0.5 kg; highly portable	Supports vehicle integration + portable integration	Basic failover	£ Low

Peplink MAX BR1 Mini 5G	~15 W	~0.5 kg; highly portable	Supports vehicle integration + portable integration	Advanced bonding + seamless failover	£ Low
Peplink MAX BR1 Pro 5G	~15 W	~0.7 kg	Supports vehicle integration + portable integration	Advanced SD-WAN + bonding	££ Moderate
Peplink MAX BR2 Pro 5G	~20 W	~1.2 kg	Supports vehicle integration + portable integration	Multi-link bonding	£££ High
Cradlepoint R980	~14 W	~1.0 kg	Enterprise-grade; supports vehicle + fixed deployment	SD-WAN; limited vs bonding	£££ High
Cradlepoint R1900	~17 W	~1.2 kg	Enterprise-grade; supports vehicle + fixed deployment	SD-WAN; limited vs bonding	£££ High

Based on the non-functional trade-off analysis, the **Starlink Mini terminal** is selected as the primary solution for portable and nomadic deployment scenarios. This selection is driven by its low weight (~1.1–1.5 kg), compact size (30 x 26 x 4 cm), moderate power consumption (25–40 W), and ability to support continuous operation during walking activities (CON-08), making it highly suitable for pipeline inspection use cases.

In addition, to enable multi-network integration and improving connectivity resilience, the **Peplink MAX series routers** are selected. These devices provide advanced multi-WAN capabilities, including seamless failover and bandwidth bonding, addressing the critical requirement for multi-network operation. They have cellular capability embedded, removing the need of external, additional cellular modems, and are also ruggedised for harsh environment operations, resisting shocks and vibrations.

Overall, this combination of satellite terminal and hybrid routing solution provides a balanced approach, meeting both portability and performance requirements while supporting flexible deployment across different operational scenarios.

6. Solution implementation

6.1 Selected COTs solution overview

Based on the two-stage trade-off analysis presented in Sections 4 and 5, a Hybrid LEO/5G based connectivity solution utilising commercial off the shelf hardware Starlink Mini and Peplink BR1 5G mini hybrid router has been selected as the preferred approach. The solution is designed to support both portable and semi-static deployment scenarios, enabling reliable connectivity for remote and nomadic operations.

Figure 1: a) Starlink mini terminal b) Peplink BR1 5G mini router.

The selected system provides wide-area coverage, low-latency communication, and sufficient throughput to meet the identified non-functional requirements, particularly in areas lacking terrestrial network infrastructure. In addition, the solution demonstrates strong alignment with functional requirements, including portability, manageable power consumption, and deployment flexibility.

Overall, this configuration offers a balanced trade-off between performance and operational practicality, making it well-suited for pipeline inspection and remote field activities. The detailed system architecture and component-level implementation are presented in the following sections.

6.2 System Architecture

6.2.1 Network Architecture

The network architecture can be divided into four main segments: the user segment, access segment, the backhaul segment, and the external service/network segment. Field users and operational devices (e.g., laptops, tablets, and mobile devices) connect to the system via Wi-Fi or Ethernet interfaces provided by the Peplink MAX BR1 Mini 5G router, which acts as the central networking node.

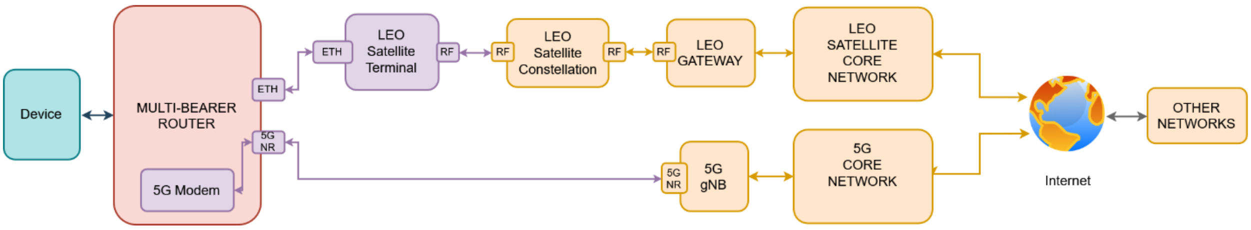

Figure 2: Network Architecture

Table 9: Network architecture components

Segment	Description	Components / Elements
User Device Segment	End-user equipment generating and consuming data within the system	Laptops, tablets, smartphones, inspection devices
Access Segment	Central networking node providing local connectivity and traffic management	Peplink MAX BR1 Mini 5G router
Backhaul Connectivity Segment	Wide-area connectivity enabling communication beyond the local network	Starlink Mini (LEO satellite) terminal, 5G NR cellular modem and 5G link
External Network and Service Segment	External infrastructure enabling data transport and service access	LEO satellite constellation, ground gateway, 5G core, Internet, cloud/enterprise services

The Peplink router aggregates user traffic and manages routing across multiple Wide Area Network interfaces. The primary connection is established via 5G interface through an integrated cellular modem, allowing terrestrial connectivity. The Starlink Mini terminal, connected through an Ethernet interface, enable satellite-based broadband connectivity, acting as secondary connection. Where cellular connectivity is available, traffic will be routed through the terrestrial 5G network and associated core infrastructure. In locations where cellular is not available, the BR1 will perform a swich from terrestrial to satellite. The users will keep connected to the same Wi-Fi access point while this transition happens and that network switch will be seamless for them. Data transmitted via the Starlink Mini is relayed through the LEO satellite constellation and corresponding ground gateway infrastructure, before reaching the public internet or enterprise-hosted services.

6.2.2 Power architecture

For designing the power architecture, a simple power budget analysis has been conducted.

From power perspective, both the Starlink Mini terminal and the Peplink router are designed for low to moderate power consumption, enabling deployment scenarios based on portable power sources such as battery packs or field power units. The Starlink Mini typically operates within the range of 25–40 W, while the Peplink router requires approximately 13–18 W, allowing the overall system to remain suitable for portable and nomadic deployment scenarios.

Table 10: System power budget

Component	Power (Typical)	4 Hours (Wh)	5 Hours (Wh)	Recommended Battery Allocation (+25% Margin)
Starlink Mini	30 W	120 Wh	150 Wh	150–190 Wh
Peplink MAX BR1 Mini 5G	15 W	60 Wh	75 Wh	75–95 Wh
Total System	**45 W**	**180 Wh**	**225 Wh**	**225–285 Wh (~250–300 Wh battery)**

Depending on the deployment configuration (backpack, Peli case), different power generation solutions can be adopted to balance portability, operational duration, and system flexibility.

Table 11: Battery configurations

Battery Configuration Type	Description	Advantages
Dual Battery	Separate batteries for satellite terminal and router	Improved power management, redundancy, flexibility
Vehicle-Powered	System powered from vehicle electrical supply (12 V / 24 V)	Long-duration or continuous operation

6.3 Deployment and possible configurations

From the user perspective, the deployment of the proposed system is designed to be simple and require minimal technical intervention. Based on the State of the Art (SoA) analysis, two physical integration approaches have been considered: a backpack-based configuration and a Peli case-based configuration. These configurations represent different form factors for integrating the system components and are not limited to specific operational modes, as both can support portable use as well as mechanical integration onto vehicles.

For deployment, the Starlink Mini terminal is mounted onto the selected platform (either backpack or Peli case) and positioned with a clear, unobstructed view of the sky to ensure optimal satellite connectivity. The terminal is powered using a portable power source, such as an integrated battery pack or external field power unit.

The Peplink MAX BR1 Mini 5G router is connected to the Starlink Mini via an Ethernet interface and powered using the same or a dedicated power source within the system. Once powered, the router automatically initializes and establishes the local network. User devices, including laptops, tablets, and smartphones, can then connect via Wi-Fi or Ethernet, using pre-configured network credentials.

No manual configuration is required during normal operation, as routing, failover, and network management functions are handled automatically by the router. The router utilises the integrated 5G connection as the primary link, with satellite connectivity acting as a secondary or backup link when cellular coverage is not available, ensuring improved connectivity resilience.

Overall, the deployment process is designed to be rapid, flexible, and user-friendly, enabling field personnel to establish reliable connectivity across a range of operational scenarios, including portable, vehicle-mounted, and semi-static deployments.

6.3.1 Peli Case-based configuration

The Peli Case-based configuration integrates all system components within a rugged, weather-resistant enclosure, providing a compact and robust solution for field deployment.

The case hosts all the equipment inside – satellite terminal, router and power during storage and transportation. This configuration is particularly suited for scenarios requiring stable, organised, and protected integration of components, where equipment protection, ease of handling, and extended operational duration are prioritised. In addition, the enclosure can be readily adapted for mounting onto vehicles (e.g., vans) with necessary power adapter, enabling flexible deployment across both portable and vehicle-based scenarios.

As shown in Figure 3, when deployed for operation, the Starlink Mini terminal is mounted externally on the lid of the Peli case to ensure unobstructed sky visibility, while internal compartments house the Peplink router, the battery system, and associated power management components.

Figure 3: Example of Peli case based deployment solution – Operational deployment.

A preliminary mass budget was developed for the Peli case-based configuration, including the Starlink Mini terminal, the Peplink MAX BR1 Mini 5G router, battery, and power distribution components. Based on the currently identified components, the total system mass is estimated at approximately 5 kg. The final integrated mass will increase slightly once the router power cable and any additional mounting accessories are confirmed.

Table 12: Indicative Mass budget for Peli case based config

Item	Notes	Mass
Enclosure (Amazon hard case, no foam)	Protective case without internal foam	2.00 kg
Starlink Mini	Primary satellite terminal	1.10 kg
Peplink MAX BR1 Mini 5G	Router for local connectivity	0.50 kg
Battery (Starlink Mini)	Dedicated router power supply	0.35 kg
Battery (Peplink)	External power station	0.96 kg
Cables & connectors	Combined power and data cabling	0.50 kg
Subtotal		5.41 kg

Overall system mass is approximately 5.4–6.0 kg, with an estimated cost of ~£1,000 (depending on suppliers), and an additional ~£50/month for Starlink data service. The upfront cost is driven by the Starlink Mini hardware, Peplink router, protective Peli case, and battery solutions, reflecting the need for reliable, portable, and self-sufficient field operation.

6.3.2 Backpack based configuration

The rucksack-based integration is considered as an alternative configuration derived from the defined form factor and portability requirements. However, based on the agreed system requirements and trade-off analysis, this configuration is regarded as a less preferable option compared to the Peli case-based solution.

A commercially available Starlink-compatible backpack solution has been reviewed as a reference implementation. Based on its form factor, such systems typically fall within a 40–60 L capacity range, confirming that the proposed requirement of a sub-80 L rucksack is feasible.

Given the compact size of the Peplink MAX BR1 Mini 5G router (~130 × 38 × 120 mm), integration in the rucksack is readily achievable without significant impact on internal volume. The router can be housed within a dedicated compartment alongside the battery and power distribution components, with appropriate consideration for thermal management and cable routing.

Figure 4: Backpack based configuration

Table 13: Mass budget backpack based config

Component	Notes	Mass
Savage UTV StarPack backpack	Dry weight, no Starlink or batteries included	5.13 kg
Starlink Mini terminal	External / integrated mount	1.10 kg
Peplink MAX BR1 Mini 5G	Router inside pack	0.50 kg
Cables & Connectors (combined)	Power + data cables	0.50 kg
Battery (for Starlink Mini)	Single battery pack	0.65 kg
Battery (for Peplink router)	External power station	0.96 kg
Total (both batteries included)		**8.84 kg**

Overall system mass is approximately 7.6–8.8 kg, with an estimated upfront cost of ~£1,300–£1,400, and an additional ~£50/month for Starlink data service. The higher cost is primarily driven by the specialised Starlink-compatible backpack (~£650), with integrated power system.

7. Conclusion and Final solution recommendation

The trade-off analysis and deployment assessment, led by the requirements shared by National Gas and based on current commercial terrestrial and non-terrestrial solutions, demonstrate that a hybrid connectivity approach combining 5G and LEO networks technology provides the most effective solution for supporting nomadic pipeline inspection use cases identified at the research phase of this project. Among the different LEO networks identified in this project, Starlink has been identified as the most suitable one for the target use cases due to its competitive cost per data usage, wide coverage, high data throughput, and proven availability in remote and rural areas Hybrid communications routers have been analysed in detail and Peplink MAX BR1 Mini 5G router has been selected as the most suitable option thanks to its reduced size, weight and power, as well as embedded 5G capability, reducing the requirements of additional hardware in the solution. This hybrid approach ensures that high-performance connectivity can be maintained across varying operational environments, including areas with limited or no terrestrial coverage.

From a system perspective, the proposed architecture enables seamless integration between the Starlink Mini terminal and the Peplink MAX BR1 Mini 5G router, allowing automatic management of connectivity links. The use of 5G as the primary link, complemented by satellite as a fallback, ensures an optimal balance between performance, cost, and coverage. This configuration supports real-time data access while maintaining resilience in remote scenarios.

Two physical implementation configurations were evaluated: a Peli case-based configuration and a backpack-based configuration. While both approaches are technically feasible and support the required operational scenarios, they differ in terms of practicality, robustness, and user suitability.

The Peli case-based configuration offers a structured and robust solution, with all components securely integrated within a protective enclosure. It provides enhanced equipment protection, improved cable management, and ease of handling during transport and deployment, aligning with operational requirements. The total system mass of approximately **5.4–6.0 kg** remains within acceptable portability limits while delivering a stable and reliable platform for both portable and vehicle-mounted use. The weight is largely driven by key requirements such as full-day battery-powered operation, which necessitates sufficiently large battery capacity. Additional contributions come from ruggedised housing, communication modules, and mounting hardware. From a cost perspective, this configuration has an estimated upfront cost of **~£1,000–£1,100**, with an additional ~£50/month for Starlink data service. The cost is primarily driven by the Starlink Mini hardware, Peplink router, battery system, and protective enclosure, reflecting the need for a reliable and self-sufficient field solution. This solution combines both terrestrial and non-terrestrial connectivity to ensure resilience in remote environments. If future requirements shift toward terrestrial-only operation, or if satellite terminals integrate terrestrial capabilities (e.g. 5G), both system weight and cost could be reduced due to fewer hardware components.

In contrast, the backpack-based configuration provides increased mobility but introduces limitations in terms of ergonomics, weight distribution, and equipment protection. With a total system mass approaching 8.8 kg when fully equipped, this configuration may impose a higher physical burden on users during extended field operations, particularly in nomadic scenarios involving long-distance walking.

Based on the overall assessment, **the Peli Case based configuration** is recommended as the preferred solution for the target use case of National Gas. It provides the best balance between portability, robustness, ease of deployment, and system integration, while still supporting flexible use across multiple operational scenarios. The backpack-based configuration may still be considered for specific use cases requiring higher mobility, but it is not identified as the baseline solution.

In the future, with the evolution of terrestrial and non-terrestrial towards offering an integrated service - e.g., Direct-to-Device services to unmodified terminals - the architecture of the solution will be able to be simplified, reducing the number of elements and reducing the power requirements, impacting cost, size and weight of the solution.