UKTIN

Future Capability Paper

Non-Terrestrial Networks

Executive Summary

The incessant demand for digital connectivity has been the stimulus for innovation and investment by telecommunication operators for the last three decades. Telecommunication innovations in health and social care, transport systems, digital industries, energy system transformation, defence, security, and public safety have driven progress and improvements in our everyday lives. In each of these vertical service areas, Non-Terrestrial Networks (NTN) is able to compliment terrestrial networks in improving the quality of services, resilience, and coverage. The demand for mobility and ubiquitous coverage has driven developments, predominantly in terrestrial infrastructure, and satellites have played a minor role in these networks, mainly in coverage extension and resilience.

It is no surprise that satellites were not included in the mobile standards from 2 to 5G. However today we are seeing the beginnings of a major change in the status quo with the demonstrations of direct to mobile handheld via satellite connections heralding the convergence of the mobile and satellite worlds. This has been brought about by advances in on-board satellite technologies and the emergence of massive satellite constellations in low earth orbit.

There is now an awakening in the telecommunications world that satellites, and more broadly NTN, which include High Altitude Platforms (HAPS) and Unmanned Aerial Systems (UAS) lower in the troposphere, together can be a game-changer for future networks. Indeed, we see that all current visions of 6G incorporate NTN as one of their key enablers. This represents both a compliment to terrestrial networks that can be used to improve coverage and resilience as well as a potential threat of a new stand alone NTN operator.

NTN is virgin territory for R&D and innovation and thus represents real opportunities for the UK.

Currently satellites are the main bearers of NTN, whereas HAPS are an emerging technology that can offer advantages in bandwidth and latency within restricted coverage. UAS also represent an emergent market in lower flying vehicles and together with satellites and HAPS are proposed as a 3D space network in future 6G architectures.

The UK has a world leading heritage in wireless networking with leading mobile operators and a leading academic sector. It is also pre-eminent in the satellite manufacturing and satellite operations arenas. However, NTN brings new and different challenges which the academic base needs to embrace, and the industrial sector needs to restructure to address. This report contributes to a pathway for a UK strategy in NTN.

The UK Telecoms Innovation Network (UKTIN) NTN working group, comprising of industrial and academic experts have worked during 2023 to analyse gaps and strengths in the UK NTN ecosystem and to make initial recommendations to Government, academia and industry aimed at ensuring that the UK has a strong role in this key area.

The report examines the context in which NTN can play a part in the improvement of services in key vertical areas. The UK has a significant heritage and role in the current global satellite market, especially in the areas of satellite service provision and satellite manufacture. One of the threats brought out in a SWOT analysis is the challenge in adapting to the new direct to device markets involving manufacture of large satellite constellations. However, there is a massive opportunity in these future global markets, especially as NTN features largely in the 6G network vision.

Transitioning from a few large GEO satellites to production line techniques for very large numbers of LEO's will be challenging. Other threats are around the sustainability of supply lines, and in particular the reliance on overseas companies for key satellite on board semiconductors. The UK faces major competition in these areas from international companies that are already established in the area.

UK R&D in NTN is very reliant on ESA funding sources, while experiencing a break in EU funding due to Brexit. National funding is very limited and currently lacks coordination in the NTN area. Academic R&D resources in enabling technologies, such as wireless networking and RF are excellent but have so far been focused on mobile applications and now need to address the different challenges posed by NTN. The UK involvement in NTN standards activities has however been significant.

The working group have organised more detailed evaluations into six key topic areas considered as fundamental to future NTN R&D which are summarised in the following.

Value chain, business models and Convergence:

NTN is being brought to the market by a combination of new and existing operators. Some of the new entrants are deploying new business models, either driven by their own capabilities, or as a consequence of trends in spectrum allocation convergence, standards evolution, and manufacturing capabilities. There is no 'state of the art' business model as such, but a range of models exploiting one or more of these trends some of which gives them the ability to control the end-to-end value chain. Spectrum convergence is also changing the landscape especially with new satellite system use of unlicensed bands previously only considered for terrestrial services.

The convergence of non-terrestrial networks with 5G is a significant trend. Integrating satellite communication with 5G networks enhances global connectivity, high-speed data transmission, and low-latency communication. As well as spectrum convergence, there is also a trend in standards convergence. This will enable the concept of a ‘network-of-networks' and offers the potential for an end-user device to be served by a mix of terrestrial, satellite and HAPS platforms across a wide geography while using the same services and receiving the same quality of experience.

All of the new business model approaches raise the question of who owns the end customer and who controls their quality of experience as they roam between networks? There is a potential conflict between the Service Provider guaranteeing quality and the NTN operator maximising the use of its infrastructure. Therefore, business models can be seen to impact technical interfaces between networks which in turn can impact technology and research requirements.

The trend in network and service convergence, coupled with evolving business models, has implications for how NTN infrastructure is designed and operated. Development of new concepts and standards requires parallel investment in R&D to test and validate new solutions and trial them in a real-world context. The current standardisation activities and timelines need to be better coordinated with business requirements.

Sustainability:

Sustainability is arguably the most important consideration for future telecommunication networks as we move towards 6G but the most challenging. Economic sustainability in terms of energy reduction is key but NTN industrial sustainability is also of concern with longer timescale projects. Supply chain sustainability requires companies to have heritage and be in existence over long periods. Also of concern is the sustainability of space orbital regions where the increased debris due to mega constellations can be a showstopper for future constellations. These are issues today and these can only be solved by international agreements and policing.

Taking a more holistic view of future merged telecommunication systems there needs to be studies of where satellite or terrestrial might be the most acceptable in energy terms as well as looking at a complementary approach to optimise energy by for example turning off mobile infrastructure in favour of satellite in lighter traffic periods. Satellite and terrestrial operators will increasingly need to address environmental sustainability of their end-to end value chain and to use full Life Cycle Analyses to optimise systems. There is little R&D internationally on this topic, but the UK academic sector has several excellent centres of Environmental Sustainability that could seize the opportunity and in conjunction with industry to tackle such problems. A detailed comparison of the LCA for a variety of terrestrial and NTN, direct to device and backhaul services that sets good precedents for future converged network design is needed.

Future architecture and equipment:

Future architecture for 6G is moving towards a multi-layered space network converged with the terrestrial network as evidenced in ITU IMT 2030 and other visions. Satellites are major elements of this network and are evolving as interconnected multi orbits incorporating large constellations. The UK heritage is in large GEO satellites, but with the shift towards manufacture of constellations needs to undergo a change and restructure. The existence of a buoyant UK small satellite community should play a role in this change. Satellite operations has been another UK strength but with two of the three operators merging with major European and US companies in 2023 its continuation could be threatened. As on-board equipment becomes more reliant on digital processing, reliance on overseas supply chains for semiconductor storage and processors is a potential barrier to competition. Other components of NTN in HAPS and UAS are nascent elements but with some UK strengths which need to be nurtured.

New E2E network architectures are being studied in the standards bodies but there is a lack of business and value chain considerations to drive this convergence. The UK has strengths in what is now termed open networking which will be a key component of the new architecture and collaborative R&D between academia and industry should receive continued support. In contrast to the space segment the ground segment in the UK has lagged behind with no presence of a major equipment provider. The existence of new 5G satellite-based standards represents an opportunity for the UK to support the growth of emerging UK SMEs to build in this sector.

6G technologies:

New standards for 6G will be developed from 2025 to 2030 and thus R&D in new technologies that will form the basis of these standards is essential to drive the standards process. NTN is already accepted to be a part of 6G to provide coverage and resilience. The essence of 6G is in the new range of human-centric services being proposed. These require timing and positioning (PNT) beyond what 5G can provide as well as advanced sensing (ISAC) of the environment. The latter need to be combined with communications and thus PNT and ISAC take central roles in the NTN converged network architecture and represent key future R&D topics along with open-networking and AI/ML across the whole network. Other important R&D topics will be security, a unified air interface, higher frequency bands, antennas, reconfigurable intelligent surfaces (RIS), and interference mitigation to enable frequency sharing between elements of the networks.

There are UK academic groups with heritage in terrestrial wireless, engaged in R&D across most of these topics, but what is missing is the focus on NTN. The latter introduces challenges, not present in terrestrial applications of the technologies. The somewhat uncoordinated UK 6G R&D also lacks a business perspective and this should be addressed by a more collaborative industry/academic focused initiative in NTN.

Spectrum and Regulation:

The access to the radio spectrum is the lifeblood of NTNs. Such access is regulated Internationally by the ITU who update via World Radio Conferences (WRC's) every 4 years. WRC23 has just extended the allocations for mobile into the 6GHz band and proposed studies for further 6G allocations in 2027. They have also published the vision for 6G (IMT-2030) including use cases, and KPI's and passed this onto 3GPP who will develop the detailed specifications. ITU allocate operational spectrum and 3GPP standards for equipment, but there is an overlap in that 3GPP have now defined NTN bands, FR1(below 6GHz) and (FR2 above 10GHz) in which new NTN standards can operate. There is demand from new satellite service operators particularly in the FR1 band and national and regional Regulators need to prioritise spectrum release to facilitate early service provision.

Recently 3GPP have studied co-existence between NTN and TN bands based on adjacent channel interference. In 2024 3GPP will also study NTN bands in Ku band. R&D in co-existence between NTN and TN for co-channel interference has received little attention to date and should be prioritised. Developing techniques for modelling interference is key to future co-existence and efficient use of the spectrum and needs to be backed up by experimental evidence. As the number of large satellite constellations increase, there is also a need to develop techniques to study and mitigate interference between them. Adequate regulation on a global base for these large LEO constellations does not currently exist and the potential for inter system service degradation is thus increased. Thus, the need for policing and enhanced national monitoring facilities by the Regulator.

Skilled workforce:

There is a rapidly growing ecosystem in NTN for which skills at all levels are required to ensure business sustainability, from ground-breaking research through to delivery of infrastructure, products and services covering commercial as well as technical skills. Although mostly anecdotal, at the moment, there is widespread agreement that the supply chain is insufficient in both quantity and focus. This is true in telecommunications generally, but is especially so in the more focused NTN area in which the range of background skills is broader.

Starting from the early school level at which communications as distinct from Space is perceived as unattractive, to University level in which only two UK Universities feature satellite communications, and this is at MSc level. The issue continues to postgraduate research groups in communications of which only one in the UK really focuses on NTN activities. There is thus a need for more focused Postgraduate as well as conversion courses in NTN. The current reliance on overseas postgraduate students being recruited into UK industry is under threat from both funding and restricted visa issues. There is thus need for action at all levels.

A greater engagement from industry to promote the skills needed not only at postgraduate level but also in promoting apprenticeships to ensure the technical skills required. A complete overhaul of funding at postgraduate level to ensure the uptake of home-grown students with partial industrial employment would be attractive. Collaborative R&D with industrial involvement to act as a pathway to employment has proved a very successful method of recruiting.

In conclusion, whilst the UK has some real excellence in areas underpinning NTN, it is an area that has only recently taken on a much higher priority for future communication networks and thus deserves special focus as a growth opportunity. Implementation of the group's recommendations should help the UK establish itself as a leader in the field.

Recommendations to UK Industry

- R1. UK industry should work with 3GPP and other relevant standards entities to ensure that end-to-end management plane capabilities, including trans-TN-NTN boundary continuity, are included in future standards.
- R2. UK industry should work to identify any gaps and limitations in the current standards that would slow down the mass adoption of NTN technology. The UK industry should take lead to lobby with the relevant standard and regulatory bodies on the urgency to fix these issues in order to keep up with the pace of business trends.

Recommendations to Government R&D

- R3. It is recommended that the Government set up a Centre of Excellence in NTN for knowledge sharing between academia and industry and preparations for inputs to standards. In addition, that Government seeks ways to raise the profile of NTN within the National Space Strategy.
- R4. UK government should run collaborative programmes for developing, launching, and validating in-orbit/flight, the end-to-end service management capabilities required by the evolving market to enable UK industry to develop world-leading insight and operational solutions.
- R5. It is recommended that future R&D on 6G technologies be focussed on open networking between NTN and TN and coordinated across DSIT and UKRI being facilitated by larger consortia of industry and academic partners. Additional coverage should be extended to interference management/spectrum sharing, optical communications, AI/ML and on-board processing algorithms and semiconductors for on board processing.

Recommendation to UKRI

- R6. A detailed comparison of the LCA for a variety of directly comparable scenarios (terrestrial and non-terrestrial; direct-to-device and backhaul) that sets good precedents for comparing differing telecommunications services is required.

Recommendations to Government - Training & Skills

- R7. It is recommended that a wider evidence base on skills shortages in the telecommunications and NTN sector be commissioned in order to validate initial findings in this paper.
- R8. It is recommended that Test beds to assist in the training of skilled workforce be established. This would include bench testing capability for low level hardware as well as for NTN communications networking and would consist of simulation & modelling, laboratory 'device in the loop' tests with test equipment and extend to a 'in-orbit' test.

- R9. It is recommended to commission a rich research environment that brings together industry and academia in a cost-effective way with the dual aims of undertaking strategic pre-competitive research; and attracting and developing highly skilled PhD candidates with the means to facilitate entry into industry and become industry leaders in the area of NTN and satellite communications.
- R10. It is recommended to develop rich opportunities for apprentices in NTN technologies at all levels, with the required dual support of study and industry work, where apprentices would work along-side experienced practitioners with a pathway to such roles in the future.

Recommendations to Regulators

- R11. It is recommended that Ofcom engages in any future international discussions for the identification of suitable frequency bands and the development of appropriate technical conditions for NTN, supporting their broader harmonisation. That would avoid the risk of market fragmentation and allow NTN operators to deploy services more efficiently at a global scale. An early identification of frequency bands for NTN, would ensure speedy access to spectrum from the operators, encouraging an early uptake of systems using the new NTN standards.
- R12. It is recommended that Ofcom should be provisioned with a budget to create monitoring infrastructure suitable for ensuring compliance with future NTN systems.

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ABBREVIATIONS

3D	Three dimensional
3GPP	3rd Generation Partnership Project
5G	Fifth Generation
6G	Sixth Generation
AI	Artificial Intelligence
AKA	Authentications and Key Agreement
AR	Augmented Reality
ARTES	Advanced Research in Telecommunications Systems
ASIC	Application-Specific Integrated Circuits
CAGR	Compound Annual Growth Rate
CEPT	European Conference of Postal and Telecommunications Administrations
CLEO	Connectivity in LEO
D2D	Direct-to-Device
DARS	Defence Acquisition Regulations System
DC	Direct Current
DL	DownLink
DM-MIMO	Distributed Massive MIMO
DMSL	Digital Mobile Spectrum Ltd
DSIT	Department for Science, Innovation and Technology
DTH	Direct-To-Home
DVB-RCS	Digital Video Broadcasting - Return Channel via Satellite
DVB-S2X	Digital Video Broadcasting - Satellite - Second Generation eXtension
E2E	End-to-end
ECSAT	European Centre for Space Applications and Telecommunications
EDRSS	European Data Relay Satellite System
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESIM	Earth Stations in Motion
ESG	Environmental, Social, and Governance
ESN	Emergency Services Network
ETNO	European Telecommunications Network Operators
ETSI	European Telecommunications Standards Institute
eVTOL	electric Vertical Take-Off and Landing aircrafts
EWG	Experts Working Group

DVB-RCS	Digital Video Broadcasting - Return Channel via Satellite
DVB-S2X	Digital Video Broadcasting - Satellite - Second Generation eXtension
E2E	End-to-end
ECSAT	European Centre for Space Applications and Telecommunications
EDRSS	European Data Relay Satellite System
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESIM	Earth Stations in Motion
ESG	Environmental, Social, and Governance
ESN	Emergency Services Network
ETNO	European Telecommunications Network Operators
ETSI	European Telecommunications Standards Institute
eVTOL	electric Vertical Take-Off and Landing aircrafts
EWG	Experts Working Group
FAL	Final Assembly Line
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FPGA	Field Programmable Gate Arrays
FWA	Fixed Wireless Access
GEO	Geostationary Equatorial Orbit
GHG	GeenHouse Gas
gNB	Next Generation Node B (Basestation)
GNSS	Global Navigation Satellite System
GovSatCom	Governmental Satellite Communications
GPS	Global Positioning System
GSMA	Groupe Speciale Mobile Association
GSOA	Global Satellite Operators Association
HAPs	High Altitude Platforms
HH	HandHeld
HIBS	High altitude International Mobile Telecommunications (IMT) Base Station (HIBS)
IET	Institute of Engineering and Technology
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
ISAC	Integrated Sensing and Communications

ISL	Inter-Satellite Link
ISP	Internet Service Provider
ISR	Intelligence, Surveillance and Reconnaissance
ITP	Institute of Telecommunications Professionals
ITU	International Telecommunication Union
ITU-R	ITU Telecommunication Radiocommunication sector
KPI	Key Performance Indicator
LBR	Low Bit Rate
LCA	Life Cycle Assessment
LEO	Low Earth Orbit
LoRaWAN	Long Range Wide Area Network
LTE	Long Term Evolution
LTE-A	LTE Advanced
MEO	Medium Earth Orbit
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MNO	Mobile Network Operator
MR	Mixed Reality
MSS	Mobile Satellite Services
Mtoe	Million tonnes of oil equivalent
NB	NarrowBand
NFV	Network Functions Virtualisation
NGMA	Next Generation Multiple Access
NGMN	Next Generation Mobile Networks
NGSO	Non-Geostationary Satellite Orbit
NR	New Radio
NSPTF	National Space Propulsion Test Facility
NSTF	National Satellite Test Facility
NTN	Non-Terrestrial Network
OBP	On-Board Processing
Ofcom	Office of communications
ONS	Office for National Statistics
OPEX	Operational Expenditure
ORAN	Open RAN
OSS	Operations Support Systems
PNT	Positioning, Navigation and Timing
PWSA	Proliferated Warfighter Space Architecture
QKD	Quantum Key Distribution

QoE	Quality of Experience
QoS	Quality of Service
R&D	Research and Development
RAL	Rutherford Appleton Laboratory
RAN	Radio Access Network
RF	Radio Frequency
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surfaces
SatCom	Satellite Communications
SBA	Service Based Architecture
SDA	Space Development Agency
SDG	Sustainable Development Goal
SDG	Sustainable Development Goals
SLA	Service Level Agreement
SME	Small and medium-sized enterprises
SNO	Satellite Network Operator
SNS	Smart Networks and Services
SOLAS	Safety of Life At Sea
SSIG	Satellite Standards Interest Group
STFC	Science and Technology Facilities Council
SWOT	Strengths-Weakness-Opportunities-Threats
TCO	Total Cost of Ownership
TDD	Time Division Duplexing
TM	TeleManagement
TN	Terrestrial Networks
TRL	Technology Readiness Levels
TUDOR	Towards Ubiquitous 3D Open Resilient Network
UAM	Unmanned Air Mobility
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UK	United Kingdom
UKRI	UK Research and Innovation
UKSA	United Kingdom Space Agency
UKTIN	United Kingdom Telecoms Innovation Network
UN	United Nations

UL	UpLink
ULL	Ultra-Low Latency
UM-MIMO	Ultra Massive MIMO
UN	United Nations
UPF	User Plane Function
V2X	Vehicle-to-everything
VAR	Value Added Reseller
VDSL	Very high-speed Digital Subscriber Lines
VR	Virtual Reality
VSAT	Very Small Aperture Terminal
WRC	World Radio Conference

1/ INTRODUCTION

Non-Terrestrial Networks (NTNs) are an extension to existing terrestrial based mobile and telecom networks and include a layering in altitude of Geostationary Equatorial Orbit (GEO), Medium Earth Orbit (MEO), Low Earth Orbit (LEO) satellites, High Altitude Platforms (HAPS) and Unmanned Aerial Systems (UAS) in the lowest tropospheric layer. NTN forms the third dimension together with terrestrial networks in what is now known as a three-dimensional (3D) space network, as depicted in Figure 1. In a 5G system, connections across the 'network-of-networks' will form an integrated overall network, but as we move to 6G they will become a single unified network designed to new Sixth Generation (6G) standards. It is important to realise that NTN covers the end-to-end (E2E) network and not just the individual elements in the 3D layers, and thus design is about providing services across this layered network and integrating with Terrestrial Networks (TN).

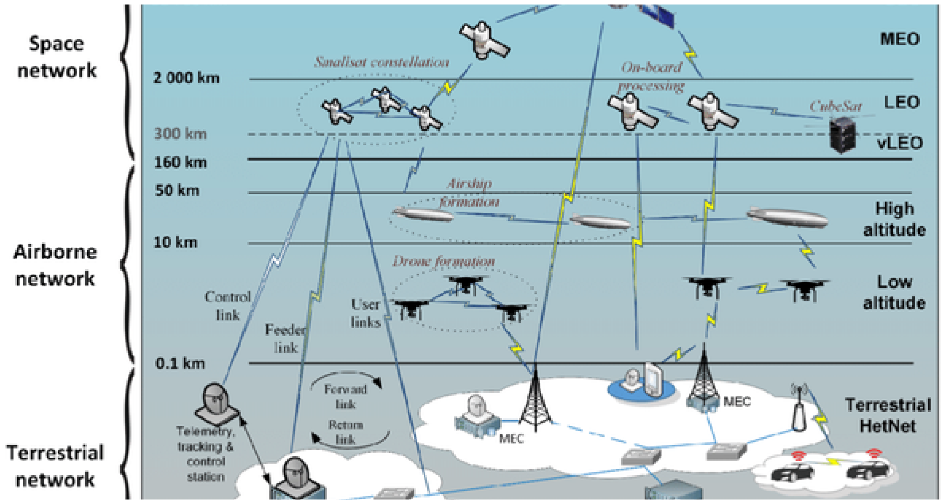

Figure 1. A 3D space network architecture.

The nature of space communications is changing rapidly from a single regional GEO satellite connected to fixed terminals, to constellations of LEO satellites providing improved coverage, reduced costs and latencies and opening up new service offerings with improved performance. In addition, we see a convergence of space and cellular with recent demonstrations of direct-to-mobile handset communications which challenges conventional business models. NTN has the capability of not only improving coverage and resilience but expanding the nature and range of new services that can be offered. The imminent next generation of heavy launchers will also drastically reduce system costs and provide opportunities for radically new satellite designs.

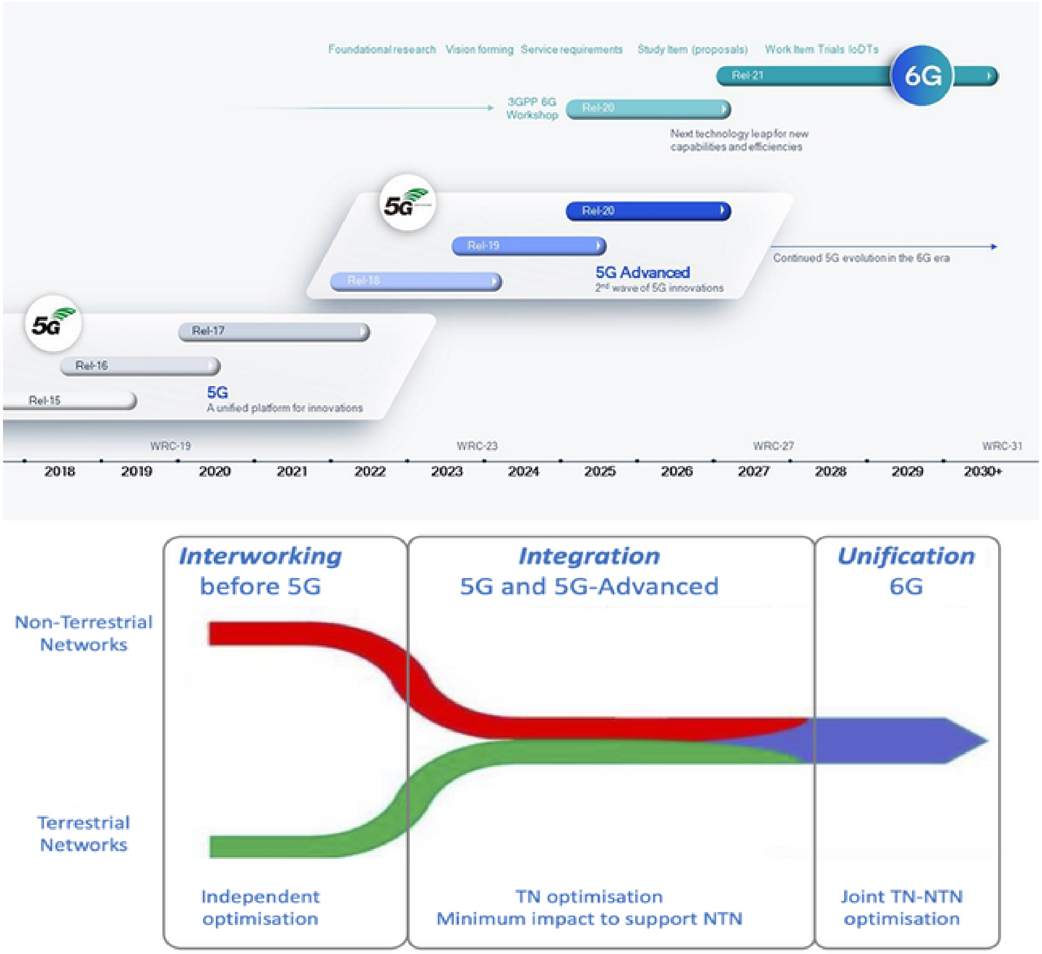

Figure 2. NTN-TN Roadmap from 5G to 6G: (top) 3GPP Roadmap, (bottom) NTN-TN Interworking-Integration-Unification Roadmap.

The timescales for the pathway from 5G via 5G+ to 6G are shown in Figure 2 and relate to the timetable of the 3rd Generation Partnership Project (3GPP) standards body. 5G was standardised in 2015, through 3GPP Rel. 15 but did not include any elements of satellites or NTN. Thus, the first phase was to configure the interoperability between TN and NTN, and an NTN group was set up within 3GPP to standardise architectures for applications, such as backhaul and Direct-to-Device (D2D). We then moved into a second phase called 5G+ in which integration rather than interoperability between TN and NTN was considered.

This produced the first standards relating to NTN in Rel. 17, in 2022, New Radio (NR)-NTN and NarrowBand (NB)-Internet of Things (IoT)-NTN, based upon the original 5G standards for TN but with modifications to allow NTN operation. This was an important development as it provided the basis for the first truly 5G NTN system designs. We have now entered the 5G+ stage, which for the first time includes regenerative NTN architectures (Rel. 19) and opens up the possibility of having some 5G network functions on board the NTN and enhanced performance for D2D services, opening up entirely new markets. In the final phase in 2025, Rel. 20, we will enter the 6G standards phase which includes NTN alongside TN from the start and represents a unified approach, which will be based on new and more open networking concepts. This will lead to 6G roll outs in around 2030.

The UK has an established 'large satellite' manufacturing sector with strong satellite operators as well as major mobile network operators. It also has a vibrant new space and embryonic HAPS and UAS sectors. NTN represents both an opportunity and a threat to UK industry. In this first Future Capability Paper, we examine the current UK industrial and academic sectors, and evaluate key R&D and industrial innovation needed to put the UK in the driving seat in this new technological area.

1.1/ Structure of Document

This document constitutes the first version of the Future Capability Paper on NTN that will be submitted to DSIT and published by the end of the UKTIN project (2025). The structure of the Future Capability Paper is as follows.

Firstly, the context of NTN, with respect to use cases for NTN, market trends and expectations, challenges and basic architectural solutions is provided. Next, a UK Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis is presented, highlighting the main strengths, weaknesses, opportunities, and threats regarding the NTN sector in the UK. The NTN EWG reviewed the SWOT analysis in respect of key drivers for UK R&D and determined six designated NTN topics key to UK R&D. These topics are discussed regarding the state-of-the-art developments, impact on business and R&D requirements, with a future recommendations section concluding each topic. These will be further developed to provide a strategic roadmap in the second and final version of this Future Capability Paper. A section on key preliminary recommendations, related to the key NTN topics is provided, with some initial recommendations.

2/ CONTEXT

2.1/ Socio-Economic Considerations – Use Cases for NTN

The value of digital inclusion to drive and sustain economic growth is widely acknowledged with multiple studies undertaken by many institutions, including the World Economic Forum which states:

“Having access to affordable digital services, as well as the digital skills required to use them, is no longer a luxury but a necessity”.

As far back as 2014, Deloitte undertook a detailed economic analysis that determined that the impact of digital connectivity on Small and Medium-sized Enterprises (SME) productivity was estimated to be 12%, and the impact on industry in a post-COVID society is recognised to be much higher.

The incessant demand for wireless digital connectivity, for both consumer and business customers, has been the stimulus for innovation and investment by mobile network and device manufacturers and operators for the last three decades. However, as each network generation has been developed, deployed, and brought into service, it is increasingly evident that the complexity, cost, and power consumption, of both infrastructure and devices, has been increasing despite massive advances in technology. Such trends are exacerbated by the need to support increased capacity, device density, and scramble for higher frequency spectrum bands that can support ‘greedy’ applications, such as personalised video content (consumer) and virtual team meeting technologies (business). These trends have resulted in the inevitable emphasis to focus delivery of services into high density urban communities as a priority for operators, with the business case for deployment into rural areas becoming extremely challenging, both from a cost and energy consumption perspective.

This brings opportunities for the UK supply chain to innovate and participate in this global revolution in connectivity. However, to determine the validity of the economic and business cases, it is imperative to evaluate the key use-cases for which such systems and services may be imperative, and this section frames the potential for such applications and services.

Many of the use cases below are associated with people living and working in remote communities and areas, with the UK being a microcosm of many global markets and cultures providing a great proving ground for technological innovations through the creation of large-scale living labs. These illustrate that the use-cases represent the potential for NTN to deliver both high economic value for UK and global market and incentivise commercial investment.

2.1.1/ Health & Social care

There is a global need to connect what is happening in hospitals and surgeries to the increasing focus on community-delivered services, supporting prevention, wellness management and long-term condition management. Furthermore, as evidently most healthcare systems are under pressure, there is a universal need to reduce the load on ambulances and urgent care departments. In addition, access to healthcare services can be a great challenge both for patients living in difficult-to-reach areas, with limited or no connectivity coverage, as well in emergency incidents, such as floods, earthquakes, etc.

The 5G ecosystem, combining the use of advanced 5GNR and satellite connectivity (especially LEO satellites), constitutes a key enabler for the delivery of efficient and effective services within national health facilities such as hospitals, GP surgeries or semi-permanent mobile units as well as for peripatetic staff. Moreover, satellite communication, via access and backhaul links, can provide robust and resilient connectivity, and support healthcare delivery by providing access to medical services in remote and underserved areas, as well as areas affected by natural disasters. NTN can support and enable remote diagnosis and treatment, telemedicine services, and remote monitoring of patients.

2.1.2/ Transport & Systems/Autonomy

The introduction of NTNs has the potential to drive transformative changes in the automotive sector. These networks can play a pivotal role in advancing ubiquitous Vehicle-to-everything (V2X) communication, fostering the growth of autonomous vehicle technologies, and enabling the provision of advanced telematics services. In addition, NTN could support improved rail connectivity for improved safety, control, and operation efficiency, as well as for improved passenger connectivity services. By doing so, these developments can significantly elevate safety, efficiency, and overall user experience within the automotive and rail industries, increasing perceived attractiveness of rail as a travel choice and helping to drive UK productivity.

Presently, autonomous systems like UAS are categorized based on their connection to either the terrestrial mobile network or satellite networks. However, the NTN initiative aims to unify all UAS, integrating them into both terrestrial and satellite networks within the 3GPP ecosystem. This integration anticipates a future progression wherein satellites will serve as fundamental base stations as the technology advances.

2.1.3/ Digital Industries

NTNs can enable the implementation of streamlined digitalization roaming solutions. This, in turn, ensures effortless and unrestricted connectivity, simplifying access to consistent and top-notch network services, irrespective of geographical boundaries.

2.1.4/ Energy System Transformation

The telecommunications sector has collaborated to produce an industry wide climate action roadmap to achieve Net Zero GreenHouse Gas (GHG) emissions by 2050, with over 30% of carriers having made public commitments [1]. In order to achieve Net Zero, telecommunication networks will have to actively manage their energy efficiency and carbon intensity, to meet this goal. Non-terrestrial networks also play a unique and increasingly important role in the energy system transformation by providing advanced communication and data transfer capabilities for various aspects of the energy sector.

NTNs enable remote monitoring and control of energy infrastructure in remote or challenging environments. This is particularly relevant for monitoring renewable energy installations such as solar and wind farms, where terrestrial connectivity may be limited. Non-terrestrial networks facilitate real-time communication and data exchange for smart grid management. They allow utilities to monitor and optimize the distribution of energy across the grid, integrating renewable sources efficiently and responding quickly to changes in demand and supply. Satellite-based technologies can contribute to more accurate forecasting of renewable energy production. Remote sensing and satellite data provide insights into weather patterns, cloud cover, and solar radiation, helping energy operators anticipate fluctuations in renewable energy generation.

NTNs enable continuous monitoring of energy infrastructure, including power lines, substations, and equipment. This facilitates predictive maintenance, reducing downtime and enhancing the overall reliability of the energy system. NTNs also enable global energy connectivity which is crucial for coordination between different regions in the global energy system. In remote or isolated areas where terrestrial infrastructure is limited, NTNs can provide essential communication links for energy projects. This is relevant for off-grid renewable energy installations and initiatives to electrify remote communities.

Overall, non-terrestrial networks enhance the resilience, efficiency, and global connectivity of the energy system. They enable the integration of renewable energy sources, improve grid management, and support innovative solutions that contribute to the ongoing transformation of the energy sector towards sustainability and reliability.

2.1.5/ Defence & Security

A key element of UK defence strategy is to understand the potential Space derived capabilities of any adversary. Widely available satellite imagery enables any organisation to plan or monitor activities anywhere on the planet. Small, cost-effective satellites with continuously improving technical capacity, enable connectivity to the most remote regions on earth. Global communications enable even fragmented and relatively poorly funded adversaries of the UK to operate from any geography on the planet.

Vulnerabilities of Global Navigation Satellite System (GNSS) to hacking or spoofing theoretically open a wide range of opportunities to an adversary, which could include attacks on the timing systems of power networks, misdirecting vehicles or ships, interference with drones or autonomous systems [2]. Furthermore, in-orbit capabilities are also developing rapidly. Low-cost launch and the advancements in autonomy, robotics, and Artificial Intelligence (AI) will soon put interference with satellites in LEO and MEO within the capabilities of non-government entities. This will require the UK government to increase the emphasis on the security of satellites and their data.

Increasingly, the defence communities are recognising the potential for dual use of civilian and commercial infrastructure to improve availability, capacity, and performance to enhance operational capability. The significant investment in satellite systems, to provide additional reach and resilience, is an important factor in the continued reassessment and development of defence doctrine.

2.1.6/ Public Safety Operations Enhancement

The augmentation of public safety operations is a notable benefit of NTNs. These networks offer resilient and dependable communication, crucial for the effectiveness of public safety agencies. They empower real-time coordination, rapid response, and smooth information sharing, even in demanding scenarios or when dealing with limited infrastructure resources.

These Use-Cases demonstrate the need for NTN in future networks and in all of them NTN provides both the coverage and the resilience needed for improved quality of service to the user. The evolution of the UK Emergency Services Network (ESN) network to provide enhanced effectiveness of the police, fire, ambulance, coastguard, and disaster response services should encompass consideration for exploitation of NTN capabilities. A crucial factor for UK government consideration is the exclusion of UK from participation in the evolution of the EU Governmental Satellite Communications (GovSatCom) activities leading to a future European IRIS [2] capability.

2.2/ Market Trends & Expectations/Demands for NTN

2.2.1 Market Analysis

Currently satellites are the main bearers of NTN as a sub-set of the overall telecommunications market. The provision of NTN communications from airborne vehicles, such as HAPs, is emerging and could offer advances in bandwidth and latency, compared to satellite platforms, at the expense of coverage. Satellite Communications (SatComs) is primarily used to support several important use cases:

- Satellite TV/video broadcast and video content/head-end distribution.
- Consumer (Fixed) Broadband or Direct-To-Home (DTH) services.
- Professional video capture – such as news gathering.
- Satellite Radio (Defence Acquisition Regulations System (DARS)).
- Fixed site two-way data (Very Small Aperture Terminal (VSAT)) – typically for remote locations such as oil rigs.
- Fixed private networks and broadband services – with telco backhaul as an important market, as well as consumer & business broadband.
- Mobile voice – e.g., using Iridium or Inmarsat handsets.
- Mobile safety services – primarily the safety of life at sea (Safety Of Life At Sea (SOLAS)) application.
- Mobile broadband – primarily for the maritime (cruise ship) and aviation markets where cellular connectivity is difficult.
- Government and military secure communications.
- Narrowband/Low Bit Rate (LBR) "IOT" applications such as fleet tracking.

These networks are based on proprietary protocols, which are carefully controlled by the operators to maximise the user experience over their diverse networks. The key emerging use cases, which are aligned with the overall telecommunications market, are:

- Consumer broadband – particularly with the emergence of Starlink's direct to consumer offer.
- "Cellular" D2D which can be split into SOS/text messages and voice/mobile broadband.

Context

Whilst all these SatCom use cases are, by definition, non-terrestrial, we can also consider a stricter definition as any non-terrestrial network which implements a non-proprietary protocol (such as Long-Range Wide Area Network (LoRaWAN)), and even more specifically, the protocols managed by the 3GPP for mobile broadband and narrow-band IoT. Since any NTN service using a 3GPP protocol could compete with the services using a proprietary protocol, the market potential of NTN with a 3GPP protocol is at least as large as the existing SatCom market.

Many of these use cases could potentially be delivered from airborne vehicles, particularly HAPS, flying in the stratosphere, but with the emergence of consumer broadband as a mass-market application, it might be expected that these services are likely to initially compete and potentially displace satellite services, before leading to net growth in the NTN market.

Table 1 shows an estimate of the global SatCom market broken down by use case with forecast growth rates. This compares with data from the Space Foundation for the global Space industry of 6% annual growth between 2020 and 2026, highlighting that satellite communications and non-terrestrial networks are an increasingly important part of the Space industry and a critical driver for overall industry growth.

Table 1. Estimates of use case market size in 2023 and 2033 based on the projected Compound Annual Growth Rate (CAGR) (Units: Millions of Dollars).

Sector	2023	CAGR	2033
Video	2,696	-8%	1,077
Fixed data	1,819	10%	5,191
Government	1,467	13%	5,627
Mobility	905	18%	5,586
Consumer broadband	840	23%	8,188
LBR IoT	543	20%	4,796
Total	**8,270**	**13%**	**30,466**

Context

Figure 3 shows a generalised illustration of the current satellite communications value chain, including estimates of the revenues in some segments. It is important to highlight that each satellite operator has their own sourcing and go-to-market approach, for example:

- SpaceX are highly vertically integrated, providing launch services to the majority of satellite operators (1), but also manufacturing and operating their own satellite communications network (Starlink) which sells directly to consumers.
- Iridium buys satellites from manufacturers and sell their services exclusively via value-added manufacturers and resellers.

At present, there are no operators of airborne platforms offering communications services, but it might be expected that if this supply chain emerges it could be similar to that for SatCom.

Organisations which support this ecosystem, such as Space agencies, government/defence customers, providers of orbital tracking data, academic organisations are not illustrated, but also have important roles to play. Table 2 shows an example of companies active in these market segment – note that this list is not exhaustive. Table 3 lists the associated revenue with different segments of the UK SatCom industry.

The satellite market has been significant for the UK both from the upstream side of major manufacturers and the operators, with Avanti, Inmarsat and Eutelsat-OneWeb (latter two now merged with US Viasat and EU Eutelsat), but the ground segment manufacturing side remains largely outside of the UK. Revenue from satellite operations comes not only from the UK but from coverage of the satellites worldwide. The growth of an NTN market globally offers potential for growing both existing SatCom revenues as well as creating new solutions and companies offering airborne solutions.

(1) Satellite operators paying SpaceX to launch their satellites which then uses the profit from this to build its own competing services creates an interesting commercial dynamic.

Context

Satellite communications has so far been dominated by large GEOs with transparent payloads (bent-pipes) and platforms covering 10-25kW, enabling satellites of up to 6+Tones. The LEO orbits have for many years been dominated by very small and cheap satellites (cubesats) of 100 Kg or less, and with less than 100W of Direct Current (DC) power and lasting just a few years. However, the LEO orbit is going through a second wave of innovation, characterised by a large growth in physical and DC power capability to enable infrastructure only previously envisaged for GEO's—the new Non-Geostationary Satellite Orbit (NGSO). Examples are current commercially operational first-generation LEO constellations for communications – Starlink and Eutelsat-OneWeb, with Telesat, Kuiper and Revada to follow; and prototype demo LEOs for Direct-to-Handheld – AST Mobile, and Lynk.

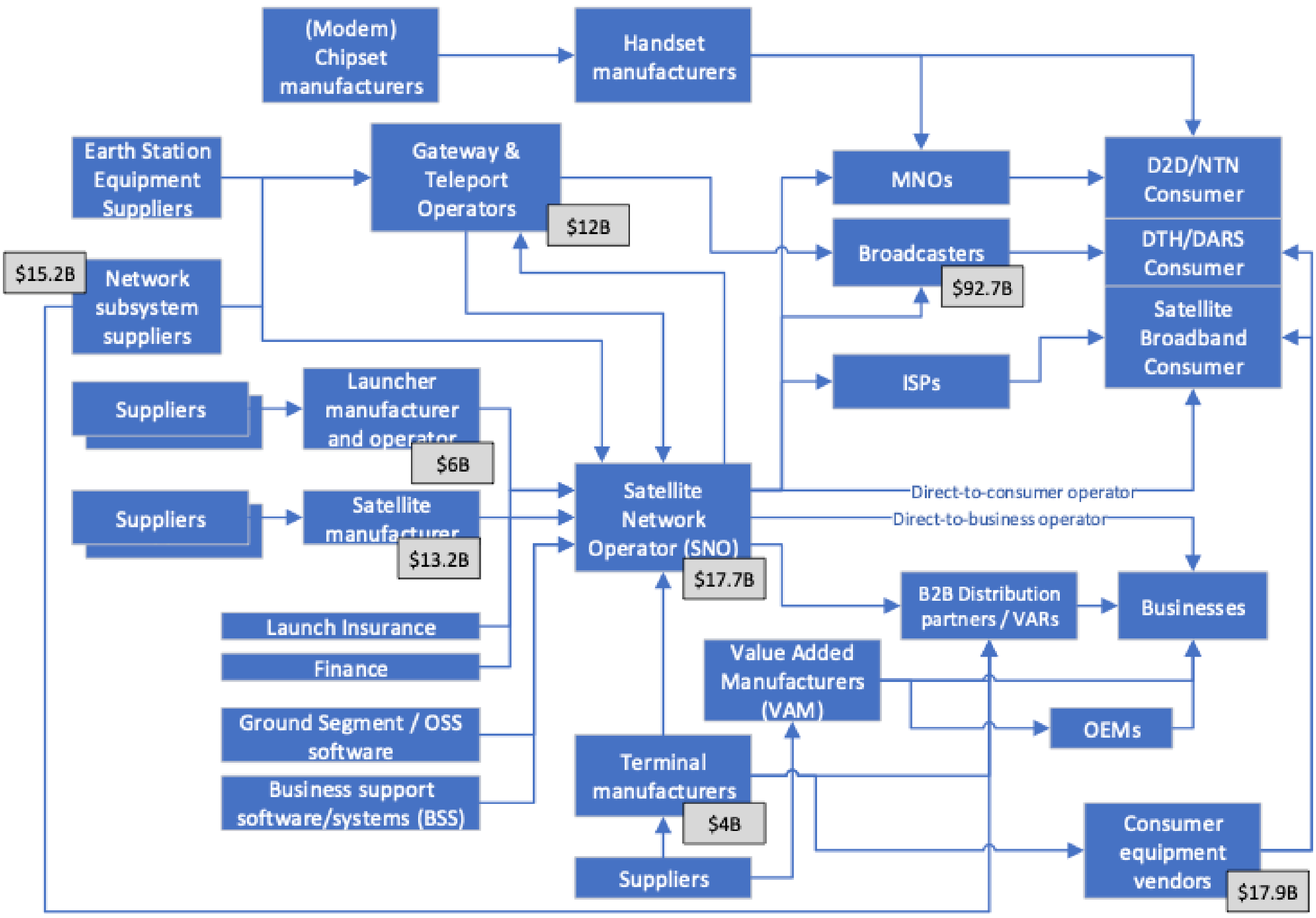

Figure 3. Value chain for satellite communications with illustrative segment revenues [3].

Table 2. Companies active in different segments of the SatCom market along with companies developing airborne alternatives.

Segment	Example companies with significant UK presence	Example other companies
Satellite Network Operators (SNO)	Viasat, Avanti, Eutelsat-OneWeb	SpaceX, Intelsat, Iridium, SES, EchoStar, GlobalStar
Satellite manufacturers	Airbus DS, Thales Alenia Space	Maxar, MDA, Boeing, Lockheed Martin, OHB
Launcher manufacturers and operators	Orbex	SpaceX, ArianeSpace, ULA, RocketLab
Ground Segment	Celectra, Intellian	GD, HNS, STEngineering
Terminal manufacturers	All.Space, SatIxFy	Kymeta, Hughes, STE-iDirect, Gilat, Comtec, Paradise Datacom, Datum, SPaceX, Intellian
Network subsystem suppliers	AccelerComm	Hughes, Gilat, STE-iDirect
Earth station equipment manufacturers	CPI, Kythera, Peak Communications, Kratos	RSI, Vertex, Andrew
Gateway and teleport operators	Goonhilly Earth Station, Vodafone, BT, Arqiva	SSC, KSAT, SES, Intelsat, Echostar, Speedcast, Encompass
Ground segment/Operations Support Systems (OSS) software	CGI	Hughes, Kratos
Consumer equipment vendors		Arris, Cisco, Huawei, Broadcom, EchoStar, Comcast, Vantiva
Broadcasters	Sky, Freesat	DISH, Sirius XM, DirecTV, Canal+
Internet Service Providers (ISPs)	Bently Walker	SpaceX, Viasat
Handset manufacturers	Bullitt	Apple, Samsung, Motorola
Terminal chipset manufacturers	Ublox, MediaTek, Samsung	Qualcom, Broadcom
Satellite technology consulting	CGI, PA, Cambridge consultants, TTP, e2e group,	
Companies developing airborne solutions	Avealto, Stratospheric Platforms Limited	Sceye, Aalto

Table 3. Estimates of the revenue associated with different segments of the UK SatCom industry (Units: Millions of Pounds).

Segment	Est revenue 2021	% of communications
Satellite Manufacturing	238	8%
Ground Segment Services	203	7%
Satellite Network Operators	2061	69%
Value Added Resellers (VARs)/Distributors	477	16%
Communications (excluding broadcast)	2,979	
DTH broadcast	8,110	

The first generation Starlink satellites have a capacity of approximately 16 Gbps and have DC power of around 4-6kW. Even with this capacity, the Starlink network can become saturated in high density regions including many operational users per cell and suffers reductions in quality of service. The second-Generation LEO constellations for Starlink and Eutelsat-OneWeb (5G+) due for launch in 2025/6 have already been defined and in the Starlink case these satellites are reported to be over 15kW in DC power with 100Gbps Optical inter-Satellite Links (ISLs) and able to achieve a capacity of 10x more than the first generation, e.g., 160Gbps. The satellites are also physically large weighing 1.2Tonnes and approach the capabilities of current GEO's. The increased processing required is demanding of the DC power, especially as we move from analogue to digital beamforming. The question is whether there is sufficient power to allow even more processing to accommodate network functions such as Next Generation Node B (gNB) or User Plane Function (UPF) or even core network functions.

Although LEO's are the current flavour, mainly for latency advantages, it is difficult to see how GEO or MEO covering a dedicated region can be beaten economically, and thus the future is likely to be a multi-orbit one with network functions positioned according to application requirements. Recent demonstrations have opened a potential new market in D2D and more specifically direct to hand-held commercial mobile, partly using 3GPP standards. These new market interventions fall into two categories split by their approach to spectrum.

2.2.2/ New Markets

Direct to Device using satellite spectrum

This is the approach taken by Apple, Qualcomm and others using S- and L-band spectrum already allocated to Mobile Satellite Services (MSS).

- Apple have invested $450m in Globalstar to secure 85% of their network capacity to provide emergency texting features to iPhones [4].
- Qualcomm have announced Snapdragon Satellite which enables Android phones to use emergency texting on the Iridium network, this has now been cancelled with expectations that a standards-based approach will instead be pursued.
- Skylo in partnership with several chipset and handset vendors (Bullit and Samsung) have started providing messaging services via leased satellite spectrum. Their service is based on 3GPP NB-IoT NTN standards.

In these cases, the main relationship is between the chipset/mobile phone manufacturers and the satellite provider. It is not yet clear what role Mobile Network Operators (MNOs) will play in this ecosystem, if any, since they are not providing spectrum.

Direct to Device using mobile spectrum

Since large blocks of dedicated satellite spectrum are only available above 5GHz, the proposed approach to providing broadband services to mobile/cell phones has primarily been via spectrum currently allocated for terrestrial use, working in partnership with MNOs:

- AST SpaceMobile has launched an experimental satellite operating in bands from 758-894MHz and announced partnerships with a range of MNOs including Vodafone and Rakuten.
- Lynk only offer occasional access with three satellites (617-960 MHz, 10-20MHz bandwidth, text messaging) with more to be launched later this year.
- SpaceX have announced that they will be offering direct-to-device services with T-Mobile and Optus.

These experimental systems have generated some specific debates around potential harmful RF interference into other countries as well as the regulatory status of using terrestrial spectrum for satellite services. These topics were debated at WRC23 but decisions deferred to the next WRC 2027.

The value of this market is also hotly debated with NSR claiming that it represents the “largest opportunity in SatCom’s history”, with 350-400 million subscribers by 2030, and a potential annual revenue of $68B.

- **It is recommended that a study be undertaken to analyse and evaluate the market opportunity for investment in NTN technologies and infrastructure.**

2.2.3/ International & Global Context for NTN Market Access

Telecommunications services are subject to both standardisation and regulatory processes that have both a global, regional, and national context, and Non-Terrestrial Networks will need to operate within these frameworks. Non-Terrestrial Networks which could include High Altitude Pseudo-Satellites (HAPS), non-geostationary satellite orbits (NGSO) and geostationary orbit satellites all have different licensing regimes for both the launch and operation of the platforms, and the utilisation of the wireless spectrum that will be used for access and service delivery. For HAPS, specific licensing will be associated with the operation of the airborne platforms over national airspace. For satellites, specific licensing will be associated with the orbital filings, with a nation state being willing or otherwise to be recognised as the ‘flag-state’ for any mission.

The standards and frequencies to be used for wireless communications systems are generally administered on a global basis for instance by ETSI, 3GPP, IEEE, and while proprietary systems exist, many administrations prefer to reference global standards to ensure maximum utility and value for money for citizens and to facilitate monitoring and ensuring compliance with regulatory constraints. While proprietary standards for satellite waveforms, networks and systems are not uncommon, quite often these are based upon variations from published international standards to maximise exploitation of existing technologies, with convergence, alignment, or adoption most prevalent at higher layers in the protocol stacks. The imperative to maximising the market penetration for NTN services will drive the network equipment vendors to converge as closely as possible or even directly adopt international standards for such systems.

From the perspective of delivery of communications services, wireless or otherwise, provision of licenses is almost always administered by national authorities (for satellite services these are often termed ‘landing rights’). Indeed, national communications regulators usually undertake technical monitoring of use of spectrum to ensure compliance with the conditions of awarded licences. Nation states therefore will be able to retain significant control over access to services, whether they are delivered from terrestrial or NTN systems, however it will be imperative for telecommunications services regulators and spectrum monitoring authorities to invest in greater knowledge, skills, and capabilities to ensure effective compliance monitoring in the increasing complexity of such future systems.

2.3/ Cost of Infrastructure

An Engineering and Physical Sciences Research Council (EPSRC)-Mistral study undertaken in 2016, by Edward Oughton et. al. [5], analysed the costs of 5G deployment and operation across the UK, for different performance and mix of network technologies, and estimated that the cost of delivering 50Mbps across the UK by multiple operators would have a total lifetime cost of £70Bn, and suggested that new approaches, such as shared infrastructure and a reduction in UK policy ambition, would need to be explored. The study has been shown to be remarkably accurate in the estimates of infrastructure cost but did not include considerations such as the rising cost of energy – a factor which is increasingly challenging for operators. Recently, operators, such as Verizon, have acknowledged (5G Networld 2023) that while 80% of their revenues are generated from users in the urban environment, 80% of their costs are incurred through servicing the extra-urban communities, and this is before we achieve the holy grail of ubiquitous connectivity for digital inclusion.

Initiatives, such as Shared Rural Network in the UK and the creation of the multi-operator entity Digital Mobile Spectrum Ltd (DMSL), aim to ensure that 99% of the UK geography is covered by wireless broadband services by 2030, but these ambitions are defined as delivering a user capability of 2Mbps (at the cell boundary), far below current definitions of enhanced mobile broadband promised by 5G. In addition, techniques to minimise infrastructure cost include ‘daisy chaining’ of Long-Term Evolution (LTE)/5G infrastructure, which can introduce failure modes leading to reduce network resilience and capacity, for instance during extreme weather events.

None of the existing studies have factored in satellite connectivity as part of the network infrastructure deployment, or indeed included the potential exploitation of satellite direct-to-device capabilities. The recognition that such capabilities bring the potential for rapidly extending service coverage at relatively low cost and improving resilience to the infrastructure is galvanising investment into the space industry. The potential integration of NTNs into upcoming 5G Advanced, and eventually 6G networks, has captured considerable interest within the research and industrial communities due to its ability to cater to a range of demanding future use cases.

Section 2.3 has provided an overview of the cost of mobile terrestrial infrastructure, as a driver for technology innovation in NTN, and constitutes a partial analysis, as an illustration, with a further recommendation to analyse the benefits of the new satellite paradigm to provide direct-home broadband services.

2.4/ Solutions/Architectures

Non-Terrestrial Networks include a variety of airborne and space-based networks, encompassing satellite constellations (GEO, LEO, MEO), air-to-ground networks, Low Latitude Platform Systems, and High Latitude Platform Systems. The NTNs are being amalgamated into the research of novel radio and communications networking techniques to enhance 5G-Advanced and forthcoming 6G technologies, embodying the concept of "anything at any time" anywhere. Enabling seamless services through a single device necessitates the development of novel integrated network architectures that encompass both traditional TN and NTN. Nonetheless, there are multiple obstacles that must be addressed to actualize a fully integrated network.

- The unified integrated network operates within a 3D heterogeneous framework, where each layer boasts distinct coverage extents and link qualities. Orchestrating synchronisation among these layers is essential to realise a seamless network access experience.
- The forthcoming 6G integrated network will encompass a diverse array of services marked by varying Quality of Service (QoS) prerequisites.
- The worldwide expanse of the integrated network mandates dependable control mechanisms that function universally. This frequently entails the deployment of a substantial number of ground stations across the globe, which escalates intricacy and expenditure. Delays spanning end-to-end communications can become considerable due to the concentration of core network functions at select ground sites, coupled with constraints imposed by inter-plane ISL communications, largely influenced by visibility and velocity considerations.

SWOT Analysis

3.1/ UK SWOT Analysis

The results of a SWOT analysis conducted by the Non-Terrestrial Networks EWG is shown in Figure 4.

These themes are examined in greater detail in the rest of the document.

Strengths

- Comprehensive Value Chain
- MNO, Telco & Satellite Expertise
- Innovative start-up culture
- SMEs in space sector
- Track record of investments in R&D
- Financial/investment attractiveness
- Academic Research
- Content & service delivery sectors
- Military satellite sector
- R&D in security & photonics

Weaknesses

- R&D not joined-up/promoted
- Lack of scope/scale in NTN R&D programmes
- Industrial/academic disconnect & no NTN community
- Failure to scale start-ups to significant global players
- Lack of chip manufacturers in the UK
- Lack of involvement in EU projects & IRIS2
- Reliance on international supply chains
- Reliance on international satellite launchers
- Skills shortage, specially in NTN
- Academic research base in NTN

Opportunities

- Direct to HH services
- Global/Wide area IoT
- Manufacturing/launch/support of large constellations
- Multi-constellation connectivity/integration
- Optical networking & earth-space communications
- Network integration & E2E service orchestration
- Changing value chain business models
- 6G & 3D space-technologies for the 6G standards
- Remote use of autonomy and AI
- HAPS technologies, platforms & services
- Integrated satellite-HAPS solutions
- Space debris removal
- Leverage from TN to NTN
- Closing the digital divide gap & enabling new working practices

Threats

- Secure satcoms future
- International competition
- Erosion of lead in GEO satellite business
- NTN & TN remaining separate communities
- Lack of large UK national investment programmes
- Restrictions as a result of Brexit
- Lack of awareness on NTN sector & scepticism on satellites - need to rely on ESA for R&D
- Perceptions that satellites are not 'green'

Figure 4. SWOT analysis of UK NTN capability.

SWOT Analysis

Strengths:

- Comprehensive Satellite Communications value chain in the UK: GEO/LEO satellite operators, space and ground components manufacturers, terminal suppliers, IT system integrators, value added resellers.
- Innovative start-up culture and community.
- Large SME New Space sector—SME's.
- Strong track record of public/private investment in R&D via Advanced Research in Telecommunications Systems (ARTES), including the European Space Agency (ESA) European Centre for Space Applications and Telecommunications (ECSAT).
- UK financial attractiveness to new businesses and for foreign direct investment.
- Academic research in related areas but not focussed on NTN.
- MNO and telecommunications industry engagement & expertise in satellites, including wholesale and emergency services.
- Content and service delivery sectors.
- Strong Military satellite sector.
- R&D in security and photonics.

Opportunities:

- Direct to HandHeld (HH) services (including spectrum).
- Wide area/global IoT connectivity.
- Manufacturing/launch/support of large-/mega-constellations.
- Multi-constellation connectivity/integration.
- Optical networking and earth-space communications (including Quantum Key Distribution (QKD)).
- Network integration & end-to-end service orchestration, supporting provision of downstream end-user services/applications.
- Changing the Value chain-business models.
- 6G and 3D space –technologies for the 6G standards.
- Remote uses of autonomy and AI (including vehicles).
- HAPS technologies, platforms, and services.
- Integrated satellite-HAPS solutions.
- Space debris removal.
- Leverage from Terrestrial mobile/wireless to NTN.
- Closing the digital divide gap and providing coverage to enable new working practices.

Weaknesses:

- R&D not joined up or not promoted.
- Skills shortage, specifically in NTN.
- Lack of scope/scale in NTN R&D programmes (technology rather than solution oriented today)
- Industrial/academic disconnect and no NTN community.
- Failure to scale start-ups to significant global players.
- Lack of chip manufacturers in the UK.
- Lack of involvement in EU projects and IRIS^2 (and no equivalent UK national programmes)
- Reliance on international supply chains.
- Reliance on international satellite launchers.
- Weak academic research base in NTN across the UK.

Threats:

- Secure satellite communications future—EU.
- International competition — Starlink & AWS (with strong domestic US opportunities).
- Erosion of lead in GEO satellite business.
- NTN and TN remaining separate communities.
- Lack of large UK national investment programmes means that we need to rely on ESA and EU SNS for R&D. which implies that we need those bodies to continue to evolve its agility.
- Restrictions because of Brexit—Horizon and IRISS.
- Lack of awareness of NTN sector and scepticism on satellites.
- Perceptions that satellites are not ‘green’.

We will revisit the topics in the SWOT analysis in the second version of this Future Capability Paper in order to provide key focus.

3.2/ International Comparison of R&D in NTN

It has not been possible to compile a detailed International R&D comparison in version 1 of the Future Capability Paper, however there are some indicators that are worth reporting.

The UK suffered from Brexit in relation to involvement in the Horizon Europe R&D programme. Having been a leading partner in the previous framework's flagship NTN project, SaT5G, there has been no significant UK involvement in the first 6 NTN projects in the current Horizon Europe and SNS JU programmes. However now that the UK has associated with Horizon Europe, there is an opportunity for both industry and academia to take advantage and engage in future NTN R&D projects. The UK has good representation of ESA projects in 5G and 6G in space and ARTES programmes. There are national programmes in NTN in Germany, Italy, and Spain. In the UK, the only national funded project that focuses on NTN is the Department for Science, Innovation and Technology (DSIT) funded Towards Ubiquitous 3D Open Resilient Network (TUDOR) open networking project which will be completed in 2025. There are very few projects funded by EPSRC in the academic sector that relate to NTN, which reflects the lack of NTN research in that sector.

UK industry is well represented in the Satellite Standards Interest Group (SSIG) which coordinates international inputs to the 3GPP NTN standards groups in SA and RAN as well as in European Telecommunications Standards Institute (ETSI) satellite standards groups. This includes both operators and equipment manufacturers. UK operators are also well represented in the Global Satellite Operators Association (GSOA) and its standards working group. GSOA acts as the market representation partner for the satcom sector into 3GPP providing policy and strategy inputs relating to its sector. Recognising the number of papers and attendance at NTN and satellite conferences, as well as in the literature at large, there appears to be major NTN activities in US, Canada, Japan, China, Korea, Singapore, and other countries. The size of the national programmes is not currently known. It is recommended that existing R&D in NTN should be pulled together to ensure that new inputs are based on the latest international information.

The R&D community, in academia and industry, is small compared to Europe and other major countries, and again judging from the international publications, the UK seems to be lagging behind these countries in several key technology areas.

- **It is recommended that the Government set up a Centre of Excellence in NTN for knowledge sharing between academia and industry and preparations for inputs to standards.**

4/ Topics

The expert working group decided to concentrate on a small number of key topic areas on which the future of NTN and its R&D programme would critically depend. A long list was constructed and finally reduced to the six topics that were further discussed and evaluated in the following sections.

4.1/ Value Chain, Business Model & Convergence

4.1.1/ Topic description

New NTN capabilities are being brought to market by a combination of existing players and new entrants. Some of the new entrants are deploying new business models, either driven by their own capabilities, or as a consequence of trends in spectrum allocation convergence, standards evolution, and manufacturing capabilities. There is no 'state of the art' business model as such, but a range of models exploiting one or more of these trends.

For example, some satellite system operators have expanded up and down the value chain to become monolithic entities able to design, manufacture, launch and operate their own satellite systems and associated ground infrastructure without dependence on third parties. This gives them the ability to control the end-to-end value chain. The difference between traditional and emerging satellite communications value chain is depicted in Figure 5 and Figure 6. It is likely that we will see further evolution of these business models to take advantage of new technologies, address specific use-cases and adapt to changing market conditions.

There has been a great deal of interest on NTN from some segments of the current 3GPP ecosystem. Handset vendors like Apple, Bullitt and recently Samsung have started offering the Satellite connectivity with their standard offering to improve their shrinking profit margins. We have seen interest with chipset vendors like Qualcom and Ublox partnering with satellite operators to provide satellite services.

Spectrum allocations for terrestrial mobile networks have been steadily moving up in frequency through 2G, 3G, 4G and 5G evolution. Terrestrial mobile services now have frequency allocations stretching from 700MHz through to 3.5GHz. This has resulted in ever closer proximity to the equivalent MSS bands in L-band (1.5-1.6GHz) and S-band (2-2.6GHz). Another development in spectrum is satellite system use of unlicensed bands previously only considered for terrestrial services, e.g., the LoRaWAN bands in 169MHz, 433MHz (Asia), 868MHz (Europe) and 915MHz (North America).

This convergence in some bands and adoption of others, coupled with ever improving chipset capabilities and RF element manufacturing techniques, has created opportunities for device and handset manufacturers to offer new capabilities to network operators and insert themselves into the value chain on new terms. The convergence of non-terrestrial networks with 5G is a significant trend. Integrating satellite communication with 5G networks enhances global connectivity, high-speed data transmission, and low-latency communication. This convergence is particularly valuable for applications like autonomous vehicles, IoT, and mission-critical communications.

Some new satellite and HAPS NTN systems plan to support spectrum already licensed to MNOs for use in terrestrial networks. This means that the NTN system can only operate with the agreement and cooperation of the terrestrial license holder in terms of locations where the NTN system can operate and how end-users can connect over the NTN infrastructure. The NTN system can offer coverage beyond that of the terrestrial network but there will be challenges, e.g., the need for buffer zones between terrestrial and NTN coverage areas using the same frequencies to avoid interference. The MNO is likely to evolve its use of spectrum on the ground over time, thus requiring adaptable coverage by the NTN operator. Therefore, there needs to be a comprehensive technical and commercial relationship between the NTN operator and the MNO, per band, per country, served.

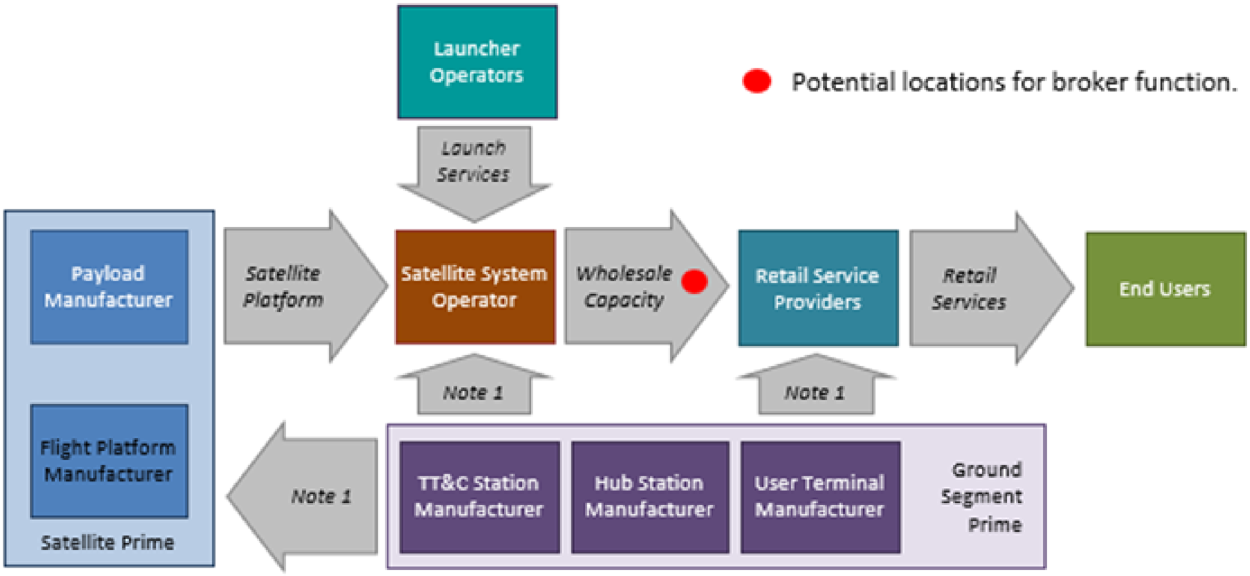

Figure 5. Outline of traditional SatComs value chain.

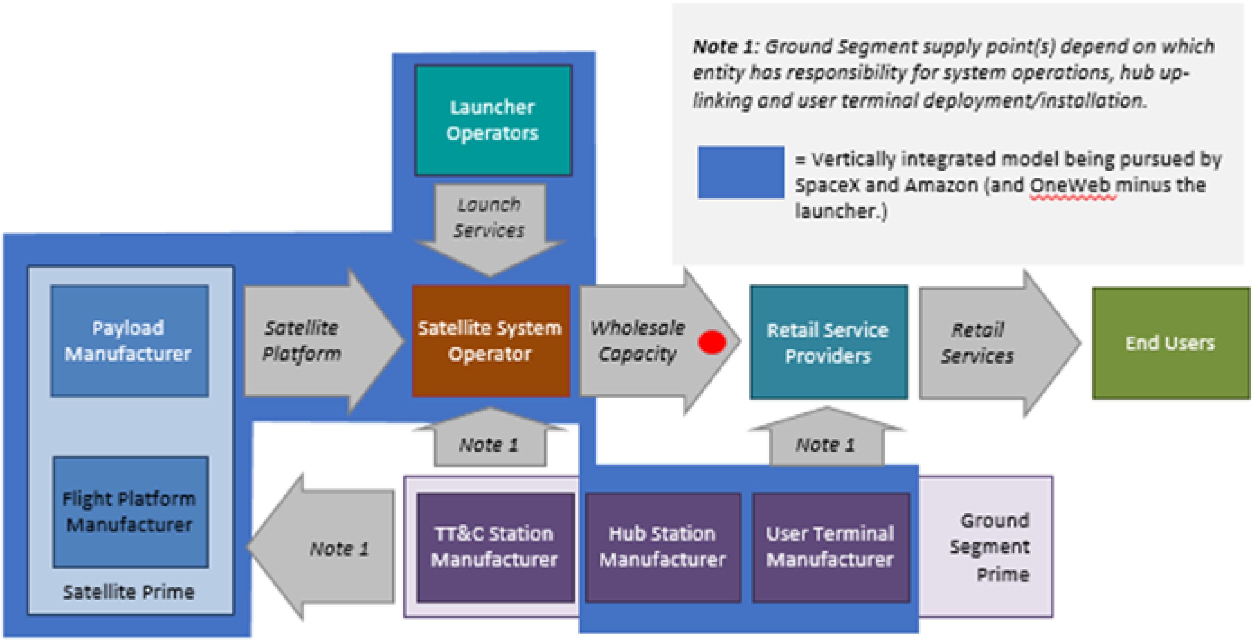

Figure 6. Example of the new type of emerging SatComs value chain.

In the UK, Ofcom licenses spectrum to MNOs for the whole of the UK including all Territorial Waters (out to 12 miles from the UK coast). Ofcom also issues licenses to UK operators for use in international waters, e.g. for oil and gas rigs, through its Spectrum Access Offshore Mobile License mechanism. Other national regulators have similar mechanisms. If NTN systems wish to use mobile spectrum over the oceans there would need to be some form of coordination between NTN systems and any co-frequency terrestrial networks operating in international waters.

As well as spectrum convergence, there is also a trend in standards convergence. The 5G standard has evolved through its various releases to encompass specific elements to lead towards seamless delivery of 5G capabilities over TN and NTN infrastructure. This will enable the concept of a ‘network-of-networks' and offer the potential for an end-user device to be served by a mix of terrestrial, satellite and HAPS platforms across a wide geography, while using the same services and receiving the same quality of experience. However, this also requires control plane extension across networks boundaries to enable service providers to maintain control of the customer experience.

4.1.2/ Impact on Business

All of the new business model approaches raise the question of who owns the end customer and who controls their quality of experience as they roam between networks.

The service provider, which the end-user contracts with, needs to be able to control the end-to-end network elements that provisions service characteristics and quality. This is the only way that it can ensure delivery of any Service Level Agreement (SLA) with the customer. This is of particular importance when supporting mission critical applications for the emergency services and other government agencies, connecting autonomous vehicles of various types (road, rail, air), and supporting global Private Network services for critical national infrastructure and corporate users, e.g., the energy sector.

However, this can conflict with an NTN operator's need to maximise the use of its infrastructure. The required service control mechanisms may not be extended across network boundaries, unless supported by a commercial agreement. Therefore, business models can be seen to impact technical interfaces between networks which in turn can impact technology and research requirements.

The above requirements need to drive input to activities such as 3GPP for future releases of 5G and the development of 6G standards. The current standardisation activities and timelines are not coordinated with business requirements. There is not much being done on end-to-end service management aspects at the moment. The main focus areas have been around identifying gNB function distribution options and issues related to the D2D market. There is a need to add more emphasis on broader use-cases.

4.1.3/ R&D Needs

The trend in network and service convergence, coupled with evolving business models, has implications for how NTN infrastructure is designed and operated. Development of new concepts and standards requires parallel investment in R&D to test and validate new solutions and trial them in a real-world context.
The following have been identified as areas that need exploring and further analysis:

- In the service management domain, there is a need to develop end-to-end management plane capabilities within evolving 5G and 6G standards to support seamless service delivery and customer experience ownership across network boundaries and service continuity across TN to NTN domains.
- To support seamless service delivery, there is a need to understand and demonstrate optimised distributed network functionality across the different elements of NTN systems, e.g., the different functional elements of a 5G gNB, plus identify the equivalent requirements of 6G standards.
- To facilitate more granular coverage and adaptable coverage areas for direct-to-device systems, there is a need for more compact, energy efficient, multi-band satellite antennas.
- To validate new architectures and technologies, plus demonstrate the required management capabilities, there is a need to develop, build and demonstrate these technologies in-orbit and in-flight.

4.1.4/ Recommendations

Key recommendations:

- **UK industry should work with 3GPP and other relevant standards entities to ensure that end-to-end management plane capabilities, including trans-TN-NTN boundary continuity, are included in future standards.**
- **The UK industry should work to identify any gaps and limitations in the current standards that would slow down the mass adoption of NTN technology. The UK industry should take lead to lobby with the relevant standard and regulatory bodies on the urgency to fix these issues in order to keep up with the pace of business trends.**
- **The UK government should run collaborative programmes for developing, launching, and validating in-orbit/flight, the technologies, services and associated end-to-end service management capabilities required by the evolving market to enable UK industry to develop world-leading insight, system elements and full operational solutions. This should include HAPS, LEO, MEO and GEO elements to facilitate full 3D network realisation (see later sections).**

4.2/ Sustainability

4.2.1/ Topic Description

Background (United Nations (UN)/UK sustainable development goals, corporate environmental, social, and governance)

The United Nations define sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [6]. This definition has been supplemented by defining seventeen Sustainable Development Goals (SDGs) [7]. The UK Government notes that “The SDGs apply to all countries, with all sectors playing a role in supporting their delivery. The UK is responsible for achieving the Goals domestically and for supporting their attainment internationally” [8], it reports [9] on the UK’s progress.

Another aspect surrounding this is the commitment by organisations to Environmental, Social, and Governance (ESG), that recommends taking environmental issues, social issues, and corporate governance issues into account. For example, the British Business Bank writes [10] “ESG is a collective term for a business's impact on the environment and society [...]. It measures how your business integrates environmental, social, and governance practices into operations, as well as your business model, its impact, and its sustainability”. HM Treasury is consulting [11] on creating a framework for reporting ESG.

Different ways to consider sustainability and NTN

One aspect of economic sustainability – for example [12] “Economic sustainability refers to a company's ability to continue its operations over a long-term horizon”. This aspect is being considered to some degree in Section 4.1.

The environmental sustainability of the NTN itself needs to be considered. Aspects such as the power consumption of the ground-based devices, the use of harmful chemicals perhaps during the launch of the orbital assets, and life-cycle assessments of the equivalent embedded CO2 are all worthy of consideration. Another way to consider the environmental sustainability of NTN is to consider how the judicious use of NTN based communications can be used to bring wider benefits in other sectors. For example, where and when is it environmentally better to use a satellite than a terrestrial link.

Finally, one can consider the long-term viability of orbital use as an aspect of sustainability. This covers factors such as space debris, space-situational awareness, end-of-life provisions, and light/radio pollution impacts. This issue is bigger than NTN as it covers all satellites and space craft, and it is the subject of much debate. Organisations such as United Kingdom Space Agency (UKSA) [13] and ESA [14] are already heavily invested in this, and the UK is leading the Astra Carta seal [15] initiative. The WEF and ESA have made recommendations to mitigate space debris [16] and NASA amongst others is looking at ways to clean up the debris [17][18][19]. Commercial companies like Astroscale, with its UK subsidiary, are looking to de-orbit defunct satellites and other larger objects. As the long-term viability of orbital use is a large area being covered already in these multiple arenas, such as the net zero space initiative [20] with "65 actors from 24 countries", this is not considered further in this review.

4.2.2/ State of the Art

Wider telecommunications context

The GSMA (Groupe Speciale Mobile Association) reported in 2021 [21] that "73% of the energy of the participating operators is consumed in the Radio Access Network (RAN). The network core (13%), owned data centres (9%) and other operations (5%)", that "the primary energy efficiency ratio in the RAN reached 0.24 kWh/GB" and that "In terms of secondary ratios, one mobile connection required an average of 14.8 kWh of energy during the 12 months, while one network site used 28,665 kWh for the same period". In 2022 they made predictions [22] of significant energy consumption growth by 2025. The Next Generation Mobile Networks (NGMN) alliance [23] "outline and prioritise the various options available…for energy saving approaches organised into three broad categories (and time-horizons): (short-term) process optimisations; (medium-term) engineering optimisations; and (long-term) new technologies".

In a detailed review of the energy use implications of 5G [24] sponsored by the UK Research and Innovation (UKRI) there is an extensive analysis of published material. They note that whilst there is significant research into the environmental sustainability of mobile communications there is not much information on energy consumption. They also note that the embedded energy associated with the equipment, despite being significant, is not well reported; and the assessed indirect impacts have not been reported.

Mackinsey writes [25] that the MNOs' energy bills are at least 5% of the operational expenditure and this was in 2018 before the significant post-Covid hikes in the cost of energy. They also noted that "Telecom operators already account for 2 to 3 percent of total global energy demand". The GSMA noted [26], two years ago, higher figures "energy represents between 15 and 40% of operators' OPerational EXpenditure (OPEX), and this is forecast to increase in the coming years". These can be contrasted with data from the Office for National Statistics (ONS) [27] that in 2021 telecommunications in the UK accounted for 0.06 Million tonnes of oil equivalent (Mtoe) compared with the UK total of 138.29 Mtoe (about 0.04%, a significantly lower figure). In other words, whilst energy consumption is significant for the operators the impact for the national ambitions may be significantly lower.

The European Telecommunications Network Operators (ETNO) association states their members' green ambitions, in a position paper [28] that primarily focuses on circularity and end-users' right to repair "Telecom operators have taken decisive measures to increase sustainability of their operations and increase circularity in their business". ETNO data has been used with other similar data to publish an analysis [29] of the electricity consumption and operational carbon emissions of their networks. This provides a good baseline for the CO2e for the operational aspects (6.6kg per subscriber in 2018), and identify that future work needs to supplement this with an LCA of network upgrades, for example to 5G and full fibre.

Lifecycle assessments and power consumption analyses for NTN

ISO helps with quite a few related standards [30] from its TC 207 Environmental management committee; including 14040 [31] that describes the principles and framework for Life Cycle Assessment (LCA) and ISO-14044:2006 [32] that provides guidelines on LCA and inventory. The ETSI details how LCAs can be made for ICT systems in TS 103 199 [33] and ETSI ES 203 199 [34] as does International Telecommunication Union Telecommunication (ITU-T) standardization sector in L.1410 [35].

ESA has been performing significant work supporting the space sector in the analysis of its greenhouse gas impacts; for example, "adaptation and application of the environmental LCA to space activities and progressed with the development and publication of the Space System Life Cycle Assessment Guidelines and the ESA LCA Database" [36]. They have not published any findings for satellite communications connections. A conference paper [37] from 2021 provides a good insight into their work up to that time. In 2014 the EC FP7 project BATS produced a deliverable (D5.3) [38] on the comparative LCA for Very high-speed Digital Subscriber Lines (VDSL), LTE-Advanced (LTE-A), and satellite broadband using GEO satellites in rural areas showing that satellite broadband can have a lower LCA in these regions.

Very few academic papers addressing the query "life cycle assessment satellite communication" show up when using popular search engines. Recently a paper was uploaded to the pre-print server ArXiV [39] making a "Sustainability assessment of LEO satellite broadband mega-constellations". This uses the ESA LCA database to assess the impact of multiple launches on the LCA of satellite broadband however at the time of writing it then compares the impact of the LCA of the launches to deliver a high-end household consumer/small business service with the ongoing energy costs only of delivering cellular data services to a single smartphone without considering any embedded carbon in the initial deployment and upgrades of the base stations nor related backhaul fibre connections. Nevertheless, the key point of the analysis that the environmental impact of the high launch cadence needed for mega-constellations including those for broadband needs to be properly assessed. In addition, the LCA for the mega-constellations should be compared with full LCAs for rural terrestrial broadband (such as fibre, VDSL, Fixed Wireless Access (FWA)) and traditional GEO satellite broadband delivery to understand the trade-offs from this vital perspective.

Traditional satellite connections rely on a clear line-of-sight between the user terminal and the satellite. The waveforms used today generally operate close to the Shannon limit for whatever trade-offs between terminal and satellite are appropriate for the service. This means the terminals can be energy efficient. The move to add LEO constellation connections requires the use of electrically steerable antennas. These inherently consume more energy than the fixed antenna systems used for GEO satellite connections though the difference is not well-defined. One market leading GEO provider quote [40] a maximum of 55W for its GEO consumer terminals (and typically perhaps 35W), and various reports (e.g., [41], [42]) suggest a typical figure of a bit over 100W for Starlink LEO user terminals.

Cellular TN connections are also very efficient though the waveforms and coding are designed to work in links subject to higher levels of reflections and interference. Work is ongoing at ETSI [43] to better understand how the 5G new radio waveform performs over conventional satellite and NTN links but the power consumption implications are not part of this.

Wider benefits of NTN

There are many ways that NTNs are and will contribute to the UN Sustainable Development Goals (SDGs), for example ESA provide a comprehensive list [44] of their activities (which is wider than telecommunications) and UKSA contribute directly to this [45]. Many of the benefits identified by ESA derive from earth observation and/or positioning though some satellite communications benefits are clearly shown, such as those related to inclusivity, healthcare, and education. Satellite service providers promote their business in these areas and as part of the ESG commitments (for example in the UK [46]). Another area promoted that is closer to environmental sustainability under consideration is the use of satellites to transport the collected data, e.g., [47] and [48]; and in disaster management [49]. Within 3GPP, the use of NTN satellite connectivity direct to the IoT systems is being studied for inclusion in their standards [50]. These benefits have not been analysed or reported in terms of the change in overall LCA nor any other way of expressing their overall environmental benefits.

4.2.3/ Impact on Business

ESG commitments (e.g., carbon footprint)

The satellite operators will need to be increasingly aware of the environmental sustainability of their end-to-end value chain including satellite build and launch; gateway antenna system build erect and operate; and user terminal build, deliver and potentially operate depending on the offered services. Ideally this can be expressed as kg CO2e per gigabyte carried or some similar metric.

Power consumption reduction

Part of this awareness should look to use renewable power for the gateway antenna systems along with best practise data centre operational practises to minimise their impact. Additionally, the vendors supplying the user terminals should be encouraged to reduce the power consumption of their systems, to use sustainable packaging, and to minimise the use of rare and/or dangerous chemicals.

The use of multicast over satellite is used to broaden the reach of education to very remote schools in, for example, sub-Saharan Africa. The same concept could be used to provide an energy efficient distribution of more focussed further education in the UK. What is not clear is where the environmental cutover point for transmitting this terrestrially and via satellite.

Resulting potential use cases

Terrestrial planning tools should be able to show when the satellite connection will result in a lower overall carbon footprint, and where the satellite connection will use less power.

Another use is to consider that today MNOs will switch off higher band radios at times, such as overnight, when traffic demand is light leaving the residual traffic on fewer lower band radios with wide coverage. In the future, the evolutions being planned for 5G will allow standard user devices such as smartphones to connect directly to NTN. Analysis is needed to see if this would allow the MNOs to power off their low band rural coverage radios in a similar way.

The use of IoT to support digital twinning is an area undergoing significant research and development to deliver smart cities and so on. The use of satellite to extend this to smart villages, smart vehicles, smart farms, and many other rural applications can play a beneficial role either direct to device such as NB-IoT-NTN or using application optimised for low power satellite terminals.

4.2.4/ R&D Needs

LCA and other policy lead work

Guidelines, methodologies, and a UK specific database, based on international standards, to define telecom sector LCAs need to be defined to allow comparisons to show where and when an NTN solution can be the optimal approach from an environmental perspective.

Academic research supporting this, providing reports on multiple use cases and applications would help the industries focus their efforts where it is most needed.

Research lead work (lower Technology Readiness Levels (TRL)

Research into how and where the non-satellite variants of NTN can be best deployed in the UK to complement both TN and satellite delivered NTN services.

Development of lower power NTN antenna systems, and of NTN terminals that can switch between a steerable LEO mode and lower power static GEO mode.

Building a detailed understanding of the environmental trade-offs between more powerful satellites (I.e. payload RF power) and more powerful ground segment.

Business development lead work (higher TRL)

NTN operators (satellite, HAPs and UAS) need to understand how they can minimise their service LCAs through choosing:

- The most environmentally sustainable launch vehicles, including the impact of shipping the satellites to the launch site.
- The most environmentally sustainable practises for their gateway sites.
- The most environmentally sustainable user equipment.

TN operators need the information to be able to supplement their systems with NTN components to reduce their own overall LCA.

As well as planning tools perhaps there maybe applications where dynamic switching between TN and NTN can improve the carbon footprint for the end user. The roles for AI/Machine Learning (ML) in this should be considered.

Identification of areas which would benefit from different kinds of NTN support for their smart applications and digital twinning aspirations.

4.2.5/ Recommendations

- **A detailed comparison of the LCA for a variety of directly comparable scenarios (terrestrial and non-terrestrial; direct-to-device and backhaul) that sets good precedents for comparing differing telecommunications services is required.**

This overall recommendation will be further explored in the second version of the Future Capability Paper.

Future R&D
The overall recommendation should build on this paper and report on the following:
- Can the use of LEO NTN allow MNOs to switch off more cells overnight?
  - If so, what are the energy savings and how does the LCA pan out?
  - Potential additional use case to get included in 3GPP by UK members.
  - Would this be better from an environmentally sustainability perspective using HAPs in some locations?
- Where and when is it better to use resilient satellite backhaul than terrestrial from energy consumption and LCA basis?
  - Build into planning tools and perhaps network management and orchestration systems.
  - Differentiate between active and passive satellite antennas.
- How can we reduce the power demands and LCA of NTN ground segment systems?
  - Is there a role for AI/ML and/or Network Functions Virtualisation (NFV) in this?
  - Traditional (VSAT, DTH TV) and emerging (direct to IoT, direct to handset, HAPs and UAS)
  - Is the trade-off between ground and space segments optimised for this?
- Indirect benefits
  - How and where can satellite communications best help other sectors reduce their greenhouse gas emissions above and beyond current implementations?
  - How and where can satellite communications best help national and regional government directions in delivering against their environmental commitments?

Government Support
- In addition to supporting the R&D identified above; providing guidance and tools for a common methodology for making LCAs across the telecoms sector and beyond to allow industry to make valid comparisons with the same level of assurance that they currently make cost-based comparisons between different solutions.

4.3/ Future Architectures/Equipment

4.3.1/ Topic Description

Future architectures for NTN will encompass not only GEO, MEO and LEO satellites, but also HAPS, operating in the stratosphere at 20km altitude, and lower altitude Unmanned Aerial Vehicles (UAV) and Unmanned Air Mobility (UAM) vehicles. The satellite segment of NTN is experiencing significant growth in the number and size of LEO constellations and their capabilities, ultimately brought about by the significant reduction in launch costs. Aerial platforms, including drones and UAVs, as well as UAM vehicles, facilitate more densely packed and rapidly adaptable communications compared to the satellite sector. They bridge the technological gap between NTN and TN.

NTN can be used to deliver backhaul and/or fronthaul links for TN, reducing the amount of infrastructure required. NTN increasingly will support direct to the UE or direct to the device communications. In the case of LEO satellites, this will deliver (sometimes limited) services to users in low-capacity density situations, e.g., rural or extreme rural areas; with either adapted traditional systems, modified devices/UE or with those operating unaltered from TN scenarios. 3GPP standardisation is also underway to ensure seamless integration. In the case of HAPS and UAVs, direct to device operation to unmodified terrestrial UEs will be the norm, with services provided to rural, suburban, and cherry-picked urban users. These deployments will focus on permanent or temporary gap filling, operating alongside terrestrial cells with harmonised spectrum. Given the roll-out of Open Radio Access Networks (ORAN) within TN, it is likely that these will be extended to different parts of NTN. The disaggregation of networks that ORAN brings could be readily adopted by aerial platform networks, with different functional splits being used, depending on circumstance, to better fit within the size, weight, and power requirements of the satellites or UAS. Additionally, combined NTN and TN architectures offer the prospect for split control and user planes, differentiated and hierarchical QoS, additional resilience via multipaths, network load balancing, and use of optical communications in some parts of the network.

4.3.2/ State of the Art

Networks

Today, networks are fragmented with little integration between satellite and other aerial networks. Standardisation efforts are underway in 3GPP to provide an integrated approach to non-terrestrial networks. Satellite networks, including the more recent constellations of LEO, are well developed and approach their second generation, whereas HAPS and UAS are less so and are at the demonstration stage rather than commercial operation. In the case of HAPS, the big players include BAESystems, Airbus, Boeing, along with other smaller players, e.g. UK based Stratospheric Platforms Ltd, Japan based Softbank/HAPS Mobile. Commercial operations can start with as little as one HAP, due to the quasi-stationary position over a regional coverage area (120-150km diameter, delivering up to 450 cells), rather than needing multiple in a constellation like LEOs. Once the technology has been shown to be robust, manufacturing scale-up is 3-5 years, based on industry models. The HAPS market is likely to accelerate similar to LEOs, but for different reasons (airports needed, updated regulations) but it is currently 5 years behind LEOs.

A conservative market assessment for the UK is likely to be 50 - 100 aircraft (plus replacements), extending to 1000 for Europe, 10000 worldwide. Similar to base station towers, higher capacity density can be supported through constellations of HAPS, with the eventual market depending on the eventual cost per user of competing technologies like fibre, terrestrial wireless, and LEO satellite. Figures quoted privately within the HAPS industry could multiply the above by 5 - 10, depending on the services offered. The costs per HAPS are £2-£10M for fixed wing aircraft, £50M - £100M airships.We are currently in the transition stage having extant 5G networks but moving into 5G+ with ORAN and some network functions being considered for disaggregation amongst the layered 3D network and working towards 6G with a completely open networking structure as shown in Figure 7.

Current R&D in the UK, funded by DSIT under the 'networks of networks' programme, has brought together industry and academia to capitalise on UK heritage in advanced wide area networks to develop a converged architecture between NTN and TN. We have a unique opportunity here to focus on the E2E issues as the only way to design future efficient converged networks, this being a unique UK element when compared with other countries' NTN programmes. A key feature of this R&D is in the management and orchestration of networks, and the provision of sufficient openness to allow a variety of different business models to be accommodated by stakeholders as we move to 6G.

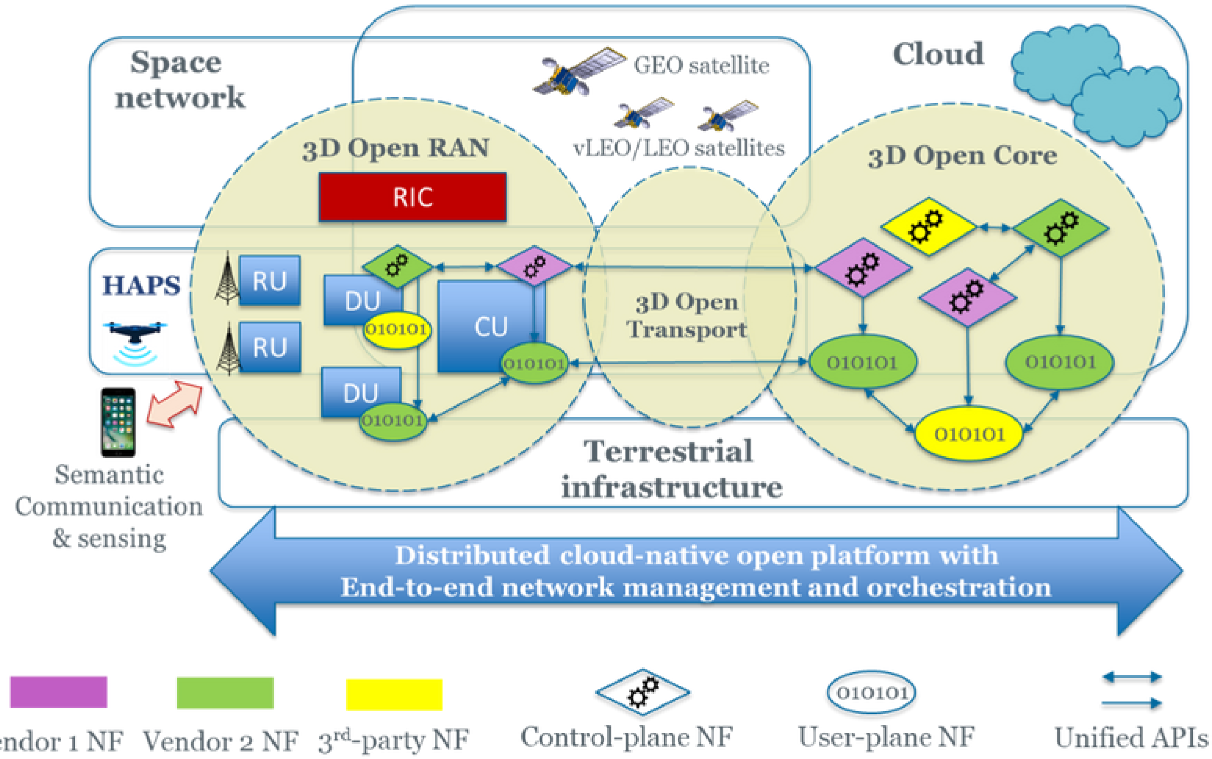

Figure 7. Converged open networking architecture for 6G (DSIT TUDOR project).

Satellites

The space domain and the satellite communications industry are undergoing a radical and highly strategic transformation. Space is becoming increasingly militarised and contested. At the same time the commercial telecommunications industry is transforming at a rate previously unseen. With the paradigm shift in launch cost shifting the balance from systems based exclusively on large geostationary satellites towards systems that will rely increasingly on GEO, MEO and LEO satellites.

US, Russia, China, and EU are all heavily investing in satellite systems, as shown in Figure 8, having noted the strategic importance, and freedom of action provided by a sovereign satellite manufacturing capability. The investments made by the US, across programs such as Global Positioning System (GPS), Space force (Space Development Agency (SDA)) Proliferated Warfighter Space Architecture (PWSA), Space X Starlink and Starshield, AMAZON Kuiper, WGS, SBIRS and TDRSS total many $100's of billions. Far less is publicly known about investments made by Russia and China, nevertheless it is well known that China is aiming to beat the US and dominate the space domain. Indeed, China has recently announced the ongoing development of the Great Wall constellation of 13,000 satellites aimed directly at matching and beating/suppressing Space X Starlink.

Closer to home, the EU is seeing the potential threat of a tri-polar/bi-polar domination of the space domain by the US, Russia, and China, and has reacted strongly with major investments through the latest ESA ministerial in the 6Bn euro EU IRIS^2 constellation. Indeed, France has committed 300 MEuro and Germany 190 MEuro to kick start this programme, and this will also be supplemented by corresponding commercial investments from European companies such as Eutelsat and SES.

The UK government invested in the OneWeb satellite constellation to secure the business of the UK based operator (now merged with Eutelsat). Further developments are foreseen in term of Eutelsats' constellation, network products and services, which represents a major opportunity for the UK to consolidate its' investment, establish a strategic industrial footprint and deliver critical national capability.

Hence with this as an example opportunity, it is key that the UK leverages investment funding such as the recently announced UKSA Connectivity in LEO (CLEO) programme, along with political lobbying to ensure that the UK industry maintains a strong design, development and industrial delivery role within the area of LEO connectivity, including related technologies, capabilities and supply chain. For example, this can be considered as critical support for further developments of the Eutelsat-OneWeb constellation and network (which encompasses both LEO and GEO) as well as other constellation opportunities anticipated in the future. Furthermore, it could be used to leverage the development of critical technologies and capabilities that underpin dual-use systems in LEO, as well as more traditional GEO orbits for leading edge commercial and military systems.

The technologies needed to support such developments are those for which the UK has made previous strategic investments to secure a leading global position, namely:

- end-to-end system design
- low-cost, high-power satellite platforms
- digital signal processors
- regenerative processing
- active antennas
- inter-satellite links.

To maintain or improve the UK capabilities for these key building blocks requires further targeted investment that must be carefully coordinated to maximise return and to grow the UK supply base. These technologies will be key, not just to support the Eutelsat-OneWeb developments, but for all commercial and dual use satellites in the future.

The future vision of satellite communications is a multi-orbit MESH network of LEO, MEO, and GEO satellite nodes all communicating seamlessly with each other, and towards terrestrial gateways & user terminals including direct to handset applications. Of course, with the OneWeb / Eutelsat merger, this is an example of a multi-orbit offering of LEO/GEO services. In simple terms, satellite communications will trend towards a "space wide web" having similar properties and networking capabilities to the existing terrestrial worldwide web. Data will be globally routed around this space wide web using internet and 5G/6G protocols based on satellite packet switching, edge processing and edge memory. This space wide web will truly become a "Non-Terrestrial-Network" with the 5G and 6G standards progressively (from Release 17 and onwards) taking greater benefit of the capabilities offered by satellite communications.

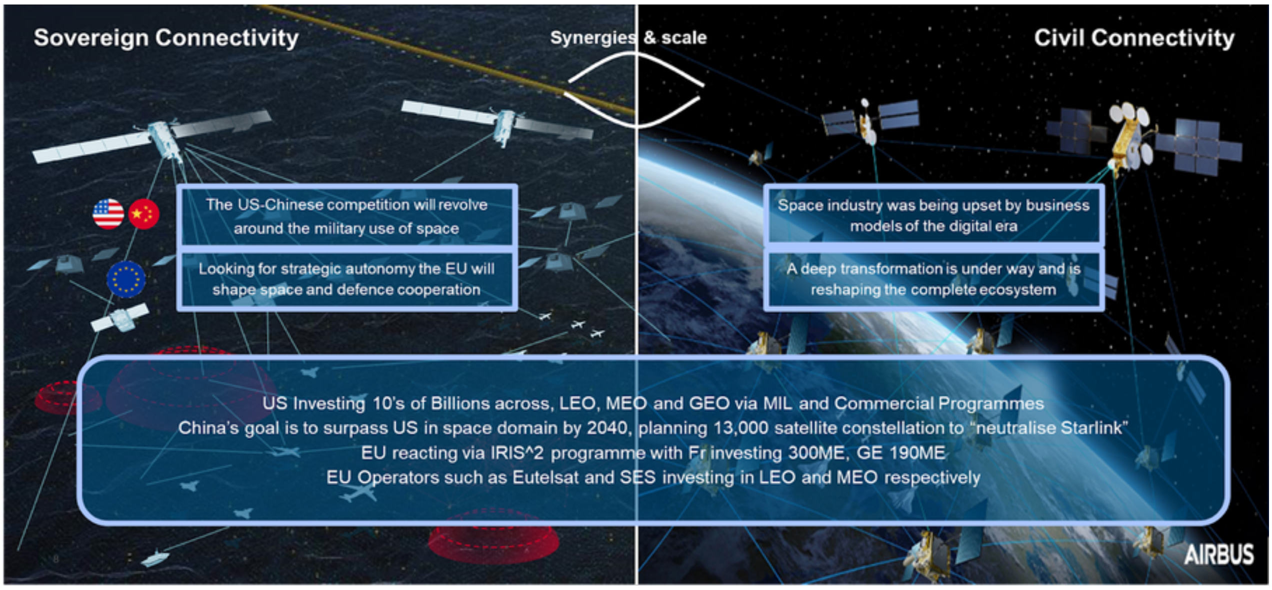

Figure 8. Synergies and scale for Satellite Manufacturing (Provided by Airbus UK).

HAPS and Aerial Systems

Aerial platforms such as UAVs or UAM vehicles or HAPS are increasingly finding diverse practical applications, including military operations, disaster relief efforts, and exploration of remote and hazardous regions. Aerial technology has spurred significant advancements in communication systems, primarily owing to its rapid environmental awareness and its capacity to swiftly gather, transmit, and process data in specific situations. Leveraging its remarkable flexibility and cost-effective deployment, for example UAVs and HAPS can serve as auxiliary relay communication systems, establishing communication links between mobile resources and distant target nodes during flight. The retail sector, which is already shifting from traditional bricks-and-mortar stores to e-commerce, is poised to transition towards full automation, through the implementation of 3D aerial highways.

Aerial platforms are flexible and have become increasingly valuable for providing widespread wireless connectivity during disasters or temporary events, as well as relaying services for mobile devices on the ground. One advantage of aerial platforms is their on-demand deployment, which enhances energy efficiency compared to constant operation of fixed terrestrial infrastructure. However, they face challenges related to high energy consumption for propulsion and movement, leading to significant power management constraints. On the other hand, they offer quick deployment and can cover vast geographical areas, spanning hundreds of kilometres, making them a cost-effective solution for wireless services without the prohibitive costs associated with terrestrial infrastructure. Nevertheless, HAPS may encounter challenges, such as the need for refuelling and stabilisation in the air.

In addition to export potential, even in UK and Europe, coverage cannot be delivered economically to the level required for many 5G services and applications. Several companies' business focus is on delivery to Europe for rural connectivity, as shown in [51] and [52]. The key benefit over LEOs is the capacity density that can be provided and the reduced cost of delivering 5G coverage/capacity density in rural areas by other means, including fibre. A very pertinent issue for the UK is poor service delivery to Northern Scotland and Western Isles and the National Parks.

The UK is at the forefront of research and development of Intellectual Property (IP) for HAPS, e.g., University of York has been working in this area with industry since the early 2000s. HAPS technology has now reached a stage of maturity that has enabled trials of the aircraft/airship technology to be undertaken, alongside bespoke telecom and other payloads.

The UK boasts several HAPS developers/manufacturers, including Stratospheric Platforms (Deutsche Telekom supported), with a high capability liquid hydrogen concept supporting 100+ cells, which has tested 5G, Prismatic (BAE Systems) and Aalto (Airbus) with long endurance solar power small payload aircraft. These are complemented worldwide with activities from Sceye, a high capability solar powered airship that has been tested multiple times in the stratosphere and HAPS Mobile (Softbank), with a solar powered aircraft which has tested 5G in the stratosphere. The HAPS Alliance is a worldwide industry body promoting the HAPS ecosystem.

Cranfield University has conducted extensive research on aerial vehicles in collaboration with industrial partners such as Skydrones, Drone-sky, Verticals, and others. These multi-tier architectures now allow for the widespread deployment of 5G and the anticipated future 6G, with the specific tier or tiers responsible for delivery determined by the required capacity density and services.

User Equipment, Devices, and Core Technologies

Traditional satellite communications terminals fall into four broad categories: VSATs, Earth Stations In Motion (ESIM), modified phones and specialist systems from organisations such as Hughes and IDirect, generally based upon ETSI Digital Video Broadcasting - Satellite - Second Generation eXtension (DVB-S2X) & Digital Video Broadcasting - Return Channel via Satellite (DVB-RCS) standards. These technologies generally rely upon centralised control systems and centralised or distributed satellite gateways sometimes referred to as 'hubs'. The UK has some presence in these areas; for example, Global Invacom manufacture parabolic antennas and some VSAT components, "All.Space" offer electrically steerable antennas, and Satixfy (recently acquired by MDA) develop everything from chips to modems and hubs.

For future NTN services, including Direct-to-Device, the end-user User Equipment (UE) is a critical consideration from the perspective of ensuring cost-effective access to services. For consumer grade services, the ideal scenario is that all 5G and 6G devices would have native support for the standardised waveforms and frequency bands that will be available on a global basis. This implies a significant investment in the semiconductor devices to exploit and extend the capabilities of software radio architectures, as it is highly unlikely that device manufacturers will tolerate the cost of additional devices for incorporation into mass-market end-user products.

Very few satellite systems took the approach of specifying waveforms with the intent to ease integration with terrestrial cellular devices, a noticeable exception being Ericsson's investment in the GMR-2 standard for GSM voice services over satellite during early 2000's, targeted for the ill-fated ACeS system. Current state of the art is the transport of NB-IoT (Inmarsat/Viasat) and LoraWAN waveforms (Echostar, Lacuna) for highly resilient wide-area direct-device communications.

A further key area will be the development of standards-based protocol stacks for integration into future user equipment, with at least two vendors licencing 3GPP DVB-S2X stacks. Examples of UK leadership in 5G NTN protocol stack implementations include TTP Ltd (Cambridge) and Accelercomm Ltd (Southampton) amongst others. A more detailed analysis of this will be provided in version 2 along with the provision of hub systems and the related software stacks and increasingly the virtual network function software.

4.3.3/ Impact on Business

Satellites

The strategic transformation of the telecommunications satellite manufacturing industry is both an opportunity and a threat to UK industry depending on how industry and government work together to quickly secure and grow the UK role in producing next generation LEO, MEO and GEO satellites.

Indeed Airbus, a major UK player in the satellite manufacturing industry, as shown in Figure 9, has identified a potential manufacturing market of between 30 and 40 billion Euros spanning GEO, MEO and LEO Civil and Sovereign Systems. Nevertheless, whilst the future satellite manufacturing market has huge potential, we should not take for granted the fact that the UK will be successful in securing this capability without strong and targeted coordination across government, major primes, SMEs, and Universities. The competition for this prize is formidable (US government, EU, Space X, Amazon) and the UK must provide an equally formidable response to secure the UK's future in this strategic domain.

HAPS

The UK already has several HAPS manufacturers, including Stratospheric Platforms, BAE Systems and Airbus. As HAPS technology matures, there is scope for a worldwide market of 1000s of crafts. Currently, numbers are low and manufacturing largely bespoke, but there is scope for large robot driven manufacturing facilities to be built. Alongside the craft themselves will be associated support industries, e.g., telecoms supply chain with NTN equipment to be provided for the craft, including bespoke antenna array technology, edge computing, telecoms hardware and software, alongside bespoke battery, solar/hydrogen technologies. HAPS, acting as pseudo-satellites in the stratosphere, can extend the reach of telecommunication networks, providing internet access to remote areas. This could open new markets and opportunities for businesses operating in those regions. It can also produce substantial cost savings compared with TN roll-out to serve uneconomic low-capacity density areas, which still need to be supplied services, as part of the universal service obligation.

UAVS & UAM

In recent years, there has been a growing interest in the potential of UAVs and UAM to play a pivotal role in smart cities and interconnected regional transportation systems. Aerospace, a UK-based industrial UAV and UAM manufacturer with leading entities such as Sky-Drones, Vertical aerospace, Leicester Drone, Coptrz, Drone AG, Skyports, Sky-Futures, Drone Defence, and Altitude Angel. Also, the Digital Aviation Research and Technology Centre (DARTeC) at Cranfield University, a £65 million world-leading facility, is located next to Cranfield's airport in the UK, and consists of a central building containing a suite of digital aviation and advanced communications systems research laboratories. This development is poised to enable the UK to unlock new markets and business prospect for the telecommunications sector. The potential benefits can be extended to supporting industries, government initiatives, and universities, creating a platform for substantial growth and innovation.

User Equipment & Core Technologies

The impact on business of the availability (or lack thereof) of cost-effective and well supported user equipment is profound. Without such devices being available, the services are simply unattainable, while if the characteristics of the devices are not a good match to the end-user expectations (including with reference to cost/form-factor/power consumption/performance/useability) then the services will have poor market penetration, and revenue will not be secured or sustained.

An analysis of the impact on business related to UE and core systems will be provided in version 2 of the Future Capability Paper. This will look at the impact of the changing network architecture (and services) to be supported in the future, with the implementation of 3D networks within 6G on their products and identify gaps in the market.

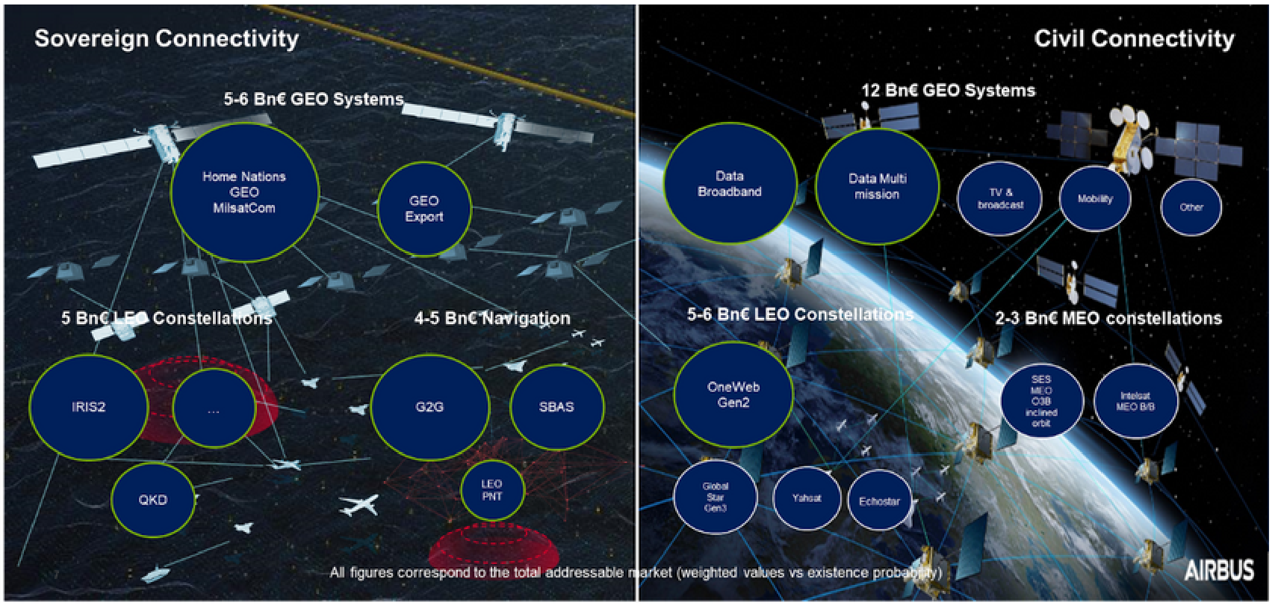

Figure 9. Potential Business Opportunity for Satellite Manufacturing (Provided by Airbus UK).

4.3.4/ R&D Needs

Satellites

The design of a global satellite constellation is a highly challenging and complex activity requiring highly strategic knowledge of orbital dynamics, launch parameters and capabilities, link budgets, atmospheric attenuation, scanning agile user terminals, strategically placed gateway locations with internet points of presence, optical inter-satellite links and regenerative wave-form design. The UK has excellent heritage in all these skills, but now needs to consolidate between academia and industry in nurturing them towards the needs of future systems. The following are key areas of R&D for future satellite communications:

- **Scalable Regenerative LEO, MEO, GEO Satellite Payloads**
  There is increasing demands for on board processing payloads including regeneration, dynamic antenna beam forming and Optical ISLs with possibly some network functions. How to accommodate these with limited payload power and the constraints of ASIC technology is a key challenge. Given the future multi orbit requirements there is a need for scalable satellite platforms.

- **Analogue and Digital Beam-forming Active Antennas**
  In the medium term, the limitations of payload power will restrict beam forming to Analogue. However, such satellites will have a relatively low capacity per satellite and beam due to the limited satellite DC power and the limited number of beams that can be formed at any one time in a relatively narrow bandwidth. In the near / medium term analogue beamforming will be a key technology for the UK to remain competitive in LEO constellations.

  Digital beamforming is the holy grail of active antennas. Digital beamformers offer the ability to produce 1000's of simultaneous beams. Because digital beamformers can produce wider bandwidth beams than analogue beamformers, they are the natural technology answer for high throughput satellites. The digital processors currently used within GEO products consume too much DC power and mass to be proposed for large active antennas in MEO and LEO satellites. Nevertheless, with the huge advances in Silicon technology efficiency with the latest commercial products leveraging 3nm Application-Specific Integrated Circuits (ASIC) technology. Recent analysis has shown that such technology can provide a Gbps per kW improvement of nearly 100 times with respect to the current state of the art offered by current products. This will enable a massive reduction in the DC power needed for digital beamforming so that it becomes the natural choice for telecoms satellites in all orbits (GEO, MEO and LEO). Hence the UK needs to continue to invest in the digital processing technology needed to provide the highest number of antenna elements and beams from the lowest DC power possible. This will then enable the satellites to provide the highest amount of Gbps per kW.

- **Optical Inter-satellite Links**
  A key technology aspect of the future 3D multi-orbit MESH network is optical inter-satellite links. There is no UK manufacturer of Optical ISLs, but Airbus has a subsidiary TESAT in Germany who are leaders in the field of Optical ISLs technology having developed the core technology over 15 years ago and operated many hundreds of thousands of GEO to LEO optical links since via the European Data Relay Satellite System (EDRSS) programme. Optical ISLs are envisioned to also be a key core technology for all future LEO constellations. The UK footprint and industrial capacity for optical ISLs is currently limited in scope and this is a gap in capability.

- **Positioning Navigation and Timing (PNT)**
  Accurate PNT data is an essential need for the UK economy and UK military as well as being essential for timing and positioning in 5G and 6G constellations. UK was a founding member and technology leader within the Galileo programme, and the UK has broad capability in PNT system design, however post Brexit is now excluded from the development of the second-generation constellation and excluded from the military waveform definition yielding the highest accuracy. This leaves the UK commercially and technically exposed. Much work has been done to explore alternative PNT solutions and commercial LEO programmes such as Eutelsat-OneWeb generation 2 (has been identified as a potential commercial LEO programme/platform onto which an alternative PNT capability could be established by the UK government). There is a need to establish a sovereign UK alternative PNT capability as well as integrate PNT with NTN Communications on future constellations to serve 6G use cases.

- **Constellation Final Assembly Line**
  LEO and MEO orbits are increasingly strategic for telecommunications, PNT and Intelligence, Surveillance and Reconnaissance (ISR) applications. We recommend that the UK government invests in the key technologies identified to enable the UK to grow its industrial footprint in LEO and MEO constellations but also to invest in a final assembly line needed to integrate the key technology building blocks of the satellite. A few Final Assembly Lines (FALs) will be required, covering payload, active antenna, and satellite, and each of these could provide a strategic capability and will also generate many high values satellite integration and test jobs. A FAL will provide value across multiple orbits and applications covering:
  - LEO, MEO and GEO satellite platform products, particularly as LEO platforms increase in size becoming scalable building blocks for MEO and GEO.
  - Telecommunications, ISR and PNT applications, for both commercial and military applications
  - Semiconductors and Software radio platforms
  - NTN Protocol Stack implementations
  - End-User Device Manufacturing scale-up

  The FAL will be a flagship centre piece of UK investment and could be accessible to UK and EU other five eye countries supporting export sales and further simulating future inward investment.

HAPS, UAV, UAM based Future communications Architecture

Unlike satellites, HAPS, UAVs, and UAM flying vehicles do not have a commercial operating heritage and are relatively new technologies in the context of provision of telecommunication services. HAPs is suited to provide higher density connectivity as well as fast set ups as in emergency situations or in military theatres. UAVs can be employed in remote coverage or extensions of terrestrial systems or rapidly changing military scenarios. Each of these areas has their specific R&D challenges, some of which are similar to satellites, but as we move to 6G, the challenges are for their integration into the multilayered 3D space network. Urban air mobility has the potential to revolutionise passenger transportation by facilitating the aerial carriage of passengers supported by communications data link.
Here in particular networking across multi systems with high mobility is a major challenge. The NTN concept recognises the need for even more stringent requirements and advanced Key Performance Indicators (KPIs). These evolving KPIs encompass a range of critical factors, including E2E latency, reliability, positioning accuracy, mobility support, energy efficiency, and extended coverage. This paradigm shift in KPIs is a direct response to the growing demand for emerging services and applications that go beyond the capabilities of 5G. Some of these innovative include:

- Holographic: Enabling lifelike and immersive teleconferencing experiences with real-time 3D holographic projections.

- Digital Twins: Facilitating real-time digital replicas of physical objects, systems, or environments for monitoring and control.

- Terahertz spectrum (THz): The Federal Communications Commission (FCC) opened the spectrum between 95 GHz and 3,000 GHz for experimental use and unlicensed applications to encourage the development of new wireless communication technologies.

- Cell-free networking: Recently, Ultra Massive Multiple-Input Multiple-Output (UM-MIMO) and Distributed Massive MIMO (DM-MIMO) have been introduced to provide continuous connectivity anywhere and anytime using large, co-located antenna arrays and spread-out antennas, respectively. Deploying THz waves with both UM-MIMO and DM-MIMO incurs several challenges, including environmental conditions. Therefore, networking technology is needed to bring the antennas closer to the UE to provide a high data rate and fewer effects from the environmental conditions.

- RAN Intelligent Controller (RIC): A RIC is a software-defined component of the ORAN architecture that is responsible for controlling and optimising RAN functions. The RIC is a critical piece of the Open RAN disaggregation strategy, bringing multi-vendor interoperability, intelligence, agility, and programmability to radio access networks. The RIC enables the onboarding of third-party applications that automate and optimise RAN operations at scale while supporting innovative use cases that lower mobile operators' Total Cost of Ownership (TCO) and enhance customers' Quality of Experience (QoE). The RIC helps mobile operators reduce both infrastructure and operational costs, improve network performance, and increase business agility. It also helps them build new revenue streams with personalised services, network slicing, and indoor location tracking capabilities.

4.3.5/ Recommendations

- **It is recommended that the increased collaborations between industry, government, and academia be continued. These partnerships are accelerating innovation and provide opportunities for shared resources and knowledge, which will be crucial for the development of future wireless architectures.**
- **It is recommended that the UK supports research, development, and standardisation efforts to put the UK at the forefront of combined non-terrestrial and terrestrial network integration for 5G and future 6G developments.**
- **It is recommended that the UK leverages investment funding such as the recently announced CLEO programme, along with political lobbying to ensure that the UK industry maintains a strong design development and industrial delivery role within the future constellation opportunities, whilst at the same time developing critical technologies and capabilities that underpin dual-use systems in LEO.**
- **It is recommended that funding be focused for R&D initiatives on advancement of communications system integration in UAV and UAM technologies. Such investment can support enhanced radio coverage, monitoring of critical infrastructure as well as contributing to lowering carbon emissions, supporting the UK's sustainability goals.**
- **It is recommended that investigation into requirements and business case for investment in next generation semiconductor technology, for instance for space/NTN.**
- **It is recommended that investigation into the need for investment in full NTN-NR protocol stacks is encouraged and supported.**
- **It is recommended that investment in interoperability testbeds is supported by UK government to expedite the process of ensuring that products and services are available for UE developers early in the development lifecycle.**

4.4/ 6G Technologies

4.4.1/ Topic Description

The vision of 6G is one which incorporates a range of human multi-sensory experiences enabled by digital solutions and hyper fine geolocation with context awareness provided by massive, localised sensors. In addition to human and local information sensing, system level sensing will be essential for efficient and intelligent system operation [53], [54], [55], [56]. This implies fine time and frequency synchronisation to microseconds and guaranteed Ultra-Low Latency (ULL) not provided by 5G. This will enable the provision of a tranche of new services for verticals across future telecom networks. The vision is of a hybrid network of networks from short range and ultra-high capacity to widest coverage via the space network.

The addition of the extra dimension of space to create a 3D network is implicit in the 6G vision and this is where satellites fit into a broader picture. As shown in Figure 1, this leads to the concept of a multi-layer network which adds satellites in GEO, MEO and LEO to lower altitude HAPS and even lower aerial devices such as drones. The architecture connecting these components will be service dependent as some architectures will better suit the requirements of specific services. The network functions can also be distributed amongst the entities to optimise performance. In all cases, we will have a highly integrated E2E cross network system.

A further point to note is that 6G services will be much more human centric and incorporate massive local sensing and context awareness (Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR), holographic, tactile/haptic, digital twin). These will require higher bandwidth and more spectrum pushing into higher millimetre frequency bands and optical. The synchronisation of multiple flows to multiple devices requiring latency at the air interface <1ms and precision tracking of the order of 1cm in 3D space. This exceeds what is available in 5G and especially for the air interface design to incorporate elements with high mobility. PNT and positioning will be key challenges in the search for an integrated air interface as well as in integrated management of 3D networks and earth sensing services (Integrated Sensing and Communications (ISAC).

It is important to distinguish here the difference between a 6G network and what we are currently seeing in R&D as a 5G+ network. The latter also contains the 3D space network and integration of NTN and TN but is based on a 5G Service Based Architecture (SBA) with network functions defined in 3GPP, up to Release 18. Whereas the 6G network will be based on a more open network architecture (see Figure 7) with maybe new network functions. These topics are to be researched in 3GPP Rel. 20 onwards and thus far there has been little preparatory work on the topic. The 6G vision documents from International Telecommunication Union (ITU), Next Generation Multiple Access (NGMA) etc highlight technologies that could contribute to 6G networks and be part of future architectures and herein we concentrate on these.

4.4.2/ State of the Art

We herein list some of the key technologies that were considered central to the 6G architecture vision.

Open networking architectures

Within 5G+ we are seeing research on ORAN, and this is being extended into the NTN domain and we are likely to see some first applications of this with ORAN splits providing some network functions on board satellites or HAPs in the next 3-5 years. This is a useful pathway to the next step of extending the openness to the core network to produce a truly open network which will be 6G, incorporating NTN and TN from the start. As part of such future architectures, it will be important to include security studies as multi cross networks and higher mobility raise challenges to existing network security systems. In 6G both PNT and ISAC will need to be incorporated into the architectures.

Interference Management:

Interference between space and terrestrial elements has been managed by the International Telecommunication Union (ITU) having exclusive frequency bands or geographic separations but non-GEO constellations have raised new challenges for these procedures. Although we have processes to manage Non-GEO into GEO interference, there are no processes for Non-GEO to Non-GEO constellation interference. With the increase in the numbers of the latter, using the same frequency bands is becoming a limiting factor.

There is also the problem of newly defined 3GPP NTN bands overlapping or abutting satellite bands. The management of interference has become a dynamic problem as we move inevitably to full frequency sharing. Satellites in 6G will need to have the capability to sense spectrum interference as they process in orbit and use this to dynamically drive their resource allocation algorithms. AI and ML can be used here to manage this highly complex and dynamic process.

On-board processing/optics/semiconductors

Most existing satellites have digitalisation on board but remain bent pipe in that demodulation/decoding does not take place due to the lack of payload power to support processing algorithms. Second generation LEO constellation designs, which have resulted from a second wave of innovation (Starlink, Eutelsat-OneWeb), will include OBP functions as well as hybrid beamforming, beam hopping and optical inter-satellite links. The most optimal deployment for next generation 5G NTN LEO constellation will require some of the gNB functions on the payload and optical inter-satellite links. These LEO satellites are no longer small and have dramatically increased power, enabling them to have similar capacity to previous GEO's and the associated economics of scale in respect of cost per Gbps. Payloads with circa 10KW with 50Gbps processing and Optical ISLs of 100Gbps are foreseen by 2025. Further developments in digital ASIC and FGPA technologies will push this higher and allow full digital beamforming. The On-Board Processing (OBP) ASIC and Field Programmable Gate Arrays (FPGA) components will need to undergo space qualification to extend the operational life of the LEO satellites. Improved battery technologies and solar cells are also needed. Full optical payloads are a longer-term aim but, in the meantime, Radio Frequency (RF) to optical interface design is needed.

Antennas/Reconfigurable Intelligent Surfaces (RIS)

Antennas are a key element on board the space structure as well as in the ground segment for gateways and user terminals. For on board applications dynamic beamforming is essential and this is associated with the beamforming networks. Here again this relates to payload power and will move from hybrid analogue/digital to fully digital as higher power becomes available. The next generation LEO constellations will be required to synthesise many narrow spot beams, which will require innovative mixed signal ASIC space grade components. In the ground segment, terminals need the ability to electronically track multiple satellites, and flat plate antenna technologies are being developed, but are currently expensive and their power consumption may be too high for some applications. RIS have been developed for terrestrial use but there is little application so far for space use.

Uniform air interface

In 5G+, NTN have adopted the TN NR air interface and produced a modified version to work over satellites. This has also been followed for NB-IoT which for NTN is a modified version of 4G. In 6G we need to develop a completely new air interface from scratch that incorporates both TN and NTN and multiple service types. R&D in this area largely resides in academia but is not well coordinated and not business lead.

Security

Moving towards 6G there are key security research challenges:

- ISAC together with Physical layer security and accurate timing and positioning could provide enhanced security performance and allow upper layer security to be simplified.
- AI integration with 6G security will enable some radical ways to move away from the traditional 5G Authentications and Key Agreement (AKA) into a more AI oriented authentication promoting security scalability and adaptability for the future 6G use cases.
- QKD needs more research to simplify the technology (photon entanglement) to make it more affordable.

Artificial Intelligence & Machine Learning

In 6G networks, 6G edge nodes will have capabilities for AI resource runtime scheduling and orchestration. Neural centres and global AI capabilities will provide services to users. This constitutes an overall native AI network with significant sensing and ML at the user terminals but with AI and ML permeating through the network. Next generation AI will be a key technology, deployed across edge and core computing domains, supporting both integrated network control functions, such as networks orchestration and QoS management, and intelligent user and machine level services. The future satellite OBP platforms will have enhanced capabilities to support the AI models deployment and some edge computing capabilities.

Higher Frequency Bands

NTN and specifically satellites currently operate in frequency bands L (1-2GHz), S (2-4GHz), C (4-8GHz), Ku (12-18GHz), Ka (26.5-40GHz) and in these bands have some exclusivity for satellite alone. Above this, there is no such exclusivity and already Q (40-50GHz) and V (40-75GHz) bands are being used for gateways but so far not for user links [57]. There have been some proposals for use of E (60-90GHz) band also. Terrestrial systems are looking at Terahertz bands for short distance links, but thus far NTN has not proposed use of these bands. Optical is used for ISL and there are proposals for use in future feeder links.

Manufacturing, Assembly, & Testing

Volume production of LEO/MEO satellites will drive down the cost and have a knock-on effect on the cost of larger GEO's. This together with new heavy launch vehicles will drastically change the economics of these systems. The manufacturing in very large numbers of LEO/MEO satellites will require production line, final assembly, and automatic testing facilities currently not available in the UK. In addition, advanced manufacturing techniques such as printed electronics and multi-functional composites will be required.

Aerial Systems

NTN in 6G is shown as 3D with aerial devices in the troposphere but there is a tendency only to consider satellites. In the shorter-term consideration has been for 3D connections of satellites e.g., LEO/GEO for traffic steering and control/user plane splits. These could equally well apply to a satellite HAPS architecture. Looking towards 6G, Aerial devices in the troposphere should also be considered in this architecture for applications such as air taxi's (electric Vertical Take-Off and Landing aircrafts (eVTOL's)) and drones used for remote surveillance or event connections. The latter provide additional challenges of high mobility and constrained on-board facilities.

4.4.3/ Impact on Business

It is important that the UK secure an early foothold in R&D in the 6G technologies, not only to input and influence the 6G standards themselves but to generate new businesses in these areas. Given the longer timescales of up to ten years, and industries relatively short horizons this means emphasis on the academic sector and lower TRL. However, this needs to be driven by a business model for 6G in order to shape the R&D programme, which means close cooperation between the business sectors and academia in the future.

4.4.4/ R&D Needs/Gap Assessment

R&D in 6G technologies is currently at low TRL levels and mainly based in academia and is dispersed and uncoordinated. The model adopted in the DSIT programmes in 'Networks of Networks' focused on open networking which brings together academia and industry which is working well, and this should be extended into other technology areas to capitalise on scale. There is a need to coordinate UKRI and DSIT programmes to optimise coverage and value for money. In the following, we highlight the UK gaps in R&D in specific technology areas covered above.

Open Networking Architectures

Some work has started in the UK in the TUDOR project but needs to be continued specifically bringing in areas of PNT and ISAC.

Interference Management

There is little work in this area in UK academia or industry although ESA is starting to focus on it. It will be key to opening up spectrum sharing for future systems.

On-board Processing/Optics/Semiconductors

UK industry is leading on board digital processing capabilities which can be transferred to LEO constellations, but semiconductors, particularly rad-hard for space are not all available in the UK and have long procurement lead times. There is no UK manufacturer of Optical ISL's and little work on RF to optical interface standards. These are seen as bottlenecks that need to be addressed.

Antennas/RIS

On board antenna designs from the GEO side can migrate to LEO and UK industry has good capabilities here but academic research is lagging in this area. There is some UK capability in terminal antennas but no major manufacturer. There is a need for study on RIS which is established for TN but not addressed for future NTN systems.

Uniform Air Interface

The UK has good academic competencies in this area but there is a need to link with business to ensure that an economic solution results. This area would benefit from an academic/industry collaborative project.

Artificial Intelligence & Machine Learning

AI/ML are key enabling technologies for NTN in 6G. UK competence is high in these areas, but the community need be made aware of the specific requirements of NTN. An R&D programme in AI/ML for NTN would bring together the AI community with the NTN to focus R&D efforts.

Security

The KPI 's associated with 6G for security, privacy and trust cannot be supported by existing 5G security systems and the inclusion of open networking results in increased security threats. Also, as 6G systems may have simultaneous connectivity up to about one thousand time greater than in 5G, privacy protection (identity hiding) should be considered an important performance requirement and a key feature in wireless communication in the envisioned era of 6G. Thus, there is a need for a radical change from the traditional 5G security approach.

There are a few very good academic security research groups in the UK, but the gap is in their links with mobile and satellite operators especially to tackle security issues beyond 5G.

Higher Frequency Bands

Currently there is no R&D in the higher frequency bands in the UK for NTN. There could be applications for W and E bands that are worth exploring in the future for feeder links, but it is difficult to see use of these higher bands for users where the effects of the troposphere would be difficult to mitigate. However multiband switched operation would be worth further study.

Manufacturing, Assembly, & Testing

For large infrastructure projects such as the LEO constellations proposed for the future there is a need to invest in new conveyor belt manufacturing techniques for very large numbers of satellites. UK industry alone may have difficulty in such large investments and thus there is a case for a Government-Industry partnership scheme.

Aerial Systems

R&D into 3D architectures with high mobility aerial devices is at a low level in the UK and needs to be promoted in both academic and industrial sectors.

4.4.5/ Recommendations

- **It is recommended that R&D programmes involving academia and industry should focus on open 6G architectures with integrated terrestrial and space elements.**
- **It is recommended that future research is focussed on the management of interference in integrated space and terrestrial networks as a pathway to open spectrum sharing.**
- **It is recommended the creation of an NTN focussed R&D programme in AI/ML incorporating integration of PNT and ISAC.**
- **Recommend that there is encouragement of more UK industrial activity in the field of optics in space.**
- **It is recommended that Investigation into requirements and business case for investment in next generation semiconductor technology, for instance for space/NTN.**
- **It is recommended that investigation into the need for investment in full NTN-NR protocol stacks is encouraged and supported.**
- **It is recommended that the UK addresses the future production of radiation hard semiconductors for space.**

4.5/ Spectrum & Regulation

4.5.1/ Topic Description

The two major standards bodies operating in this domain at the moment are the ITU-Radiocommunication sector (ITU-R) and 3GPP. The ITU-R is overall responsible internationally for spectrum allocation to services (satellite, mobile, broadcasting etc.), which it does via periodic World Radio Conferences, one of which, the WRC-23, is in session as we draft this report. It is also responsible for setting R&D directions, visions and KPI's for new wireless technologies e.g., the Radio Assembly of WRC-23 has just approved the principles, framework, and objectives of 6G (IMT-2030). The latter are passed to the technical standards committees e.g., 3GPP to work on the technical specifications which then are referred back to ITU-R publications. There are also regional standards groups e.g., ETSI in Europe who work closely with the ITU-R. The ITU-R is also responsible for setting the rules of orbital filings (these can be made by national Regulators e.g., Office of communications (Ofcom) in the UK) together with conditions which take account of managing interference globally.

In the satellite world, DVB is a standards group built around broadcasting but also has a current de facto standard used widely on satellite systems for broadband. In addition, other groups such as the Internet Engineering Task Force (IETF) produce recommendations concerning internet issues but do not produce standards. Other groups such as ETSI and the TeleManagement (TM) Forum produce standards and recommendations for the management and control systems.

Thus, this topic covers the setting of standards, the allocation and management of spectrum and the regulation of satellite orbits.

4.5.2/ State of the art

NTN in 3GPP

In the original releases (Rel's) of 5G standards there was no inclusion of NTN and the standards on which 5G is rolled out terrestrially today (Rel15/16) do not include NTN entities. Subsequently NTN groups were formed in 3GPP and have published two NTN standards in Rel 17—NTN-NR and NTN-NB-IOT. These standards are now being started to be used for D2D systems and for satellite constellations offering wide coverage IoT applications. They are based upon terrestrial standards with modifications for longer delays, timing and the movement of satellites.

In addition, 3GPP have defined some NTN spectrum bands for operation. In the sub 6GHz region these are designated as FR1 and above 10GHz as FR2. It is to be noted that these bands overlap and are adjacent to TN bands used by terrestrial mobile services. In Rel 19 work in 2024, there are proposals within 3GPP to investigate additional NTN bands, such as e.g., the Ku-band.

NTN in ITU-R

Despite the absence of existing harmonised global regulations for NTN by ITU-R, various countries around the world have enabled the deployment of NTN networks, through national licensing agreements, using different parts of spectrum. The two main NTN use-cases that we see today, are Direct-to-Device connectivity and Wireless Backhaul. In Table 4 and Table 5, an up-to-date list of industry collaborations and NTN deployments is presented, categorised based on the spectrum band used, as identified in Radio Regulations.

Table 4. D2D communication using terrestrial spectrum bands.

Existing & planned NTN deployments	Spectrum band	Use-cases
Starlink and T-Mobile [58]	1900 MHz	SMS and voice
AST, Nokia, AT&T, Vodafone [59]	Low band mobile spectrum and Q/V bands	Messaging and voice
Lynk [60]	600/900 MHz	Messaging

Table 5. D2D communication using satellite spectrum.

Existing & planned NTN deployments	Spectrum band	Use-cases
Globalstar and Apple [61], [62]	2.4 GHz	SOS messaging
Beidu and Huawei [63], [64]	L-band	SOS messaging
Bullit and Echostar + Inmarsat [65]	S-band (Echostar) L-band (Inmarsat	Messaging

IA common feature of the above collaborations, either using terrestrial or satellite spectrum, is that NTN D2D use-cases are performed over Frequency Division Duplexing (FDD) bands. This enables TN-NTN coexistence to be managed more efficiently, since communication in the UpLink (UL) and DownLink (DL) directions is made over separate frequency channels. Aspects of coexistence are further discussed in a later section.

The use of NTN for Wireless Backhaul applications is a more mature deployment case. There are already various existing industry collaborations for 4G and 5G backhaul to extend connectivity in remote areas. Some of the current NTN Wireless Backhaul deployments are shown in Table 6.

Table 6. NTN wireless backhaul partnerships.

Existing & planned NTN deployments	Spectrum band
Kuiper and Verizon	Ku and Ka-bands
Telesat and Telefonica	Ku and Ka-bands
Eutelsat- OneWeb and AT&T	Ku and Ka-bands
Starlink and KDDI	??

Co-Existence Aspects

The identification of suitable frequency bands for NTN is critical for its coexistence with TN. 3GPP is currently focused on examining the adjacent band coexistence of NTN MSS in S-band with TN in FDD band n1 and Time Division Duplexing (TDD) band n34 (FR1 bands). The two coexistence scenarios are discussed below.

In the scenario shown in Figure 10, the satellite (NTN) cell overlaps with multiple TN cells in the same location and the UL/DL bands of TN are adjacent to the UL/DL bands of NTN. As it can be seen, in the DL direction, NTN or TN UEs, may experience adjacent band interference from the out of band emissions of gNBs or satellites, respectively. Similarly, in the UL direction, satellites or gNBs may experience adjacent channel interference from the out of band emissions of TN or NTN UEs, respectively.

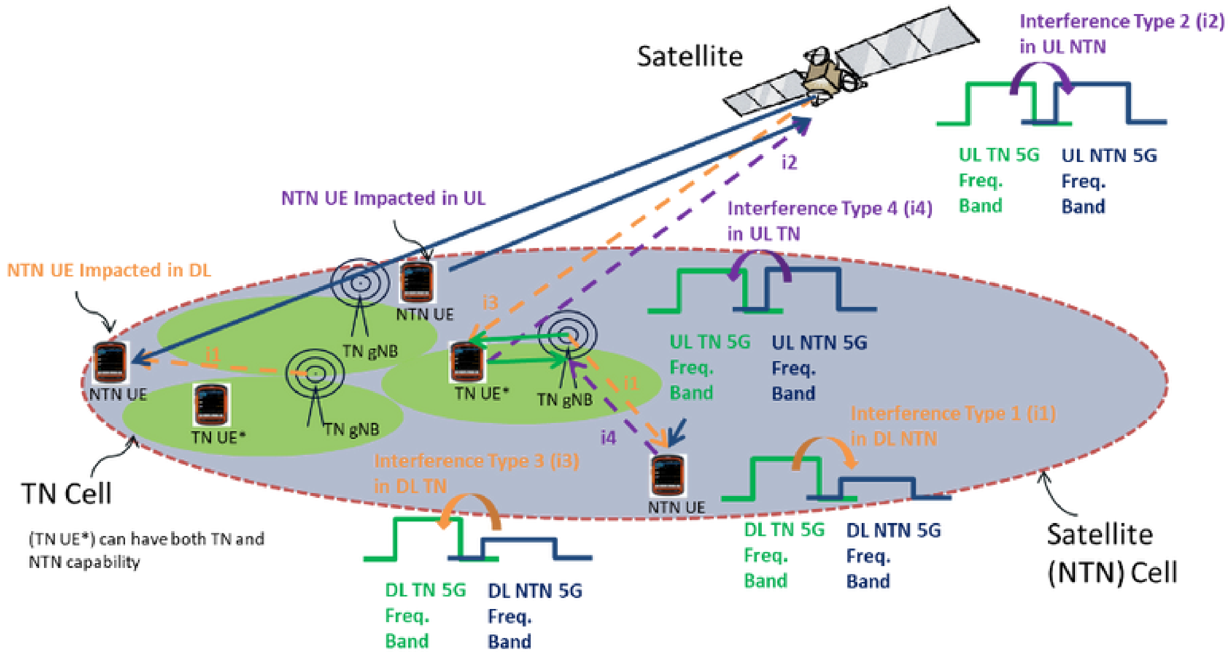

Figure 10. TN (FDD) - NTN (FDD) coexistence scenario [66].

In the scenario depicted in Figure 11, the satellite (NTN) cell again overlaps with multiple TN cells in the same location and the NTN UL band is adjacent to the TN TDD band. As it can be seen, the satellite may experience adjacent band interference from the out of band emissions of the TN gNB, while also the TN UE may experience adjacent band interference from the out of band emissions of the NTN UE.
3GPP is currently working on the above coexistence scenarios to identify appropriate parameters to be added in the standards, to enable coexistence of TN and NTN in FR1. A similar exercise is currently in progress for FR2.

Although other aspects of coexistence are not currently being discussed (particularly co-channel interference) in the relevant 3GPP or ITU-R standardization groups, it is worth mentioning that significant regulatory consideration should be given to minimise the interference potential in the coexistence between TN-NTN in-band, as well as the interference potential across national borders. Currently, the MNOs offering NTN services operate on a self-interference management basis, but additional challenges may arise when the adoption of NTN services expands to a larger scale. Therefore, the development of suitable harmonized technical conditions is necessary to ensure non-interfered coexistence between NTN and TN at a global level.

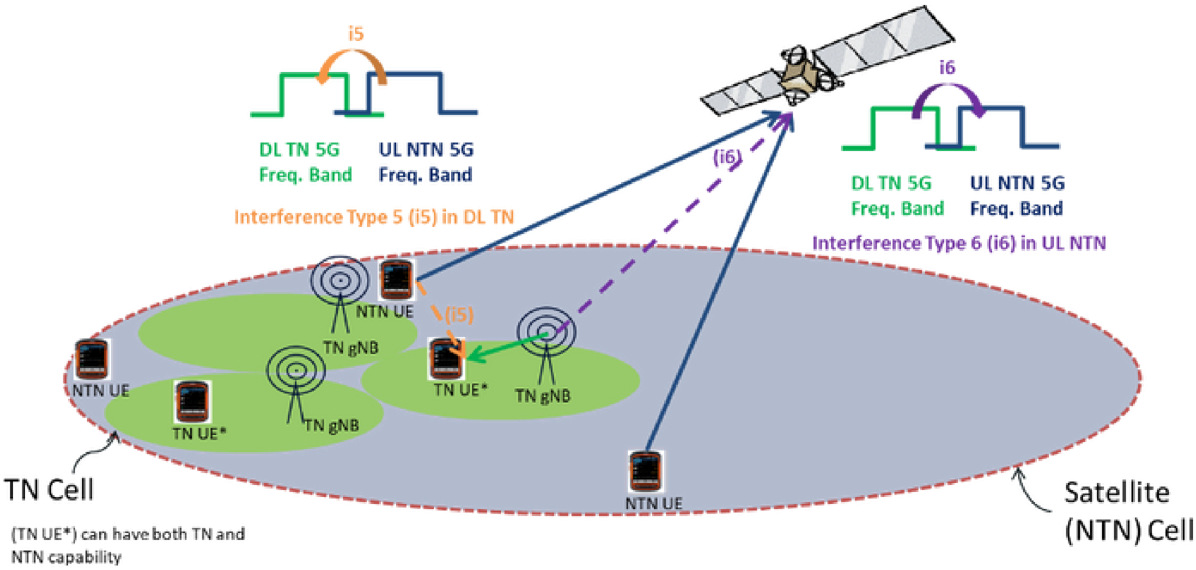

Figure 11. TN (TDD) - NTN (FDD) coexistence scenario [66].

Current Spectrum Proposals for NTN in ITU-R

In the current ITU-R WRC-23 cycle, Agenda Item 1.4 discusses the use of High altitude International Mobile Telecommunications (IMT) Base Station (HIBS) in bands below 2.7 GHz which are already identified for IMT on a global or regional level. In addition, there have been national and regional proposals under Agenda Item 10 for the identification of suitable frequency bands for NTN for the next WRC-27 cycle. These proposals are shown in Table 7.

Table 7. NTN spectrum proposals under ITU-R WRC-23 AI 10, to be studied in WRC-27 cycle.

WRC-27 NTN proposal source	Proposal description
APT (Asia Pacific Telecommunication)	Study potential new allocations to the MSS for the satellite component of IMT in frequencies allocated to MS below 7 GHz
China	Identification of the frequency band 6425-7025 MHz for the terrestrial component of IMT in Region 3
Russian Federation	Consideration of the following frequency bands for the satellite component of IMT: 1518-1544 MHz, 1545-1559 MHz, 1610-1626.5 MHz, 1626.5-1645.5 MHz, 1646.5-1660.4 MHz, 1668-1675 MHz, 2483.5-2500 MHz, 1980-2010 Hz, 2170-2200 MHz and 2500-2520 MHz and 2670-2690 MHz for in Region 3

WRC-23 has agreed to include study items in the WRC-27 agenda relating to the use of NTN in the above proposed bands. In addition to the WRC-23 discussions, European Conference of Postal and Telecommunications Administrations (CEPT), the European regulatory body, in its FM44 group has initiated discussions with the objective to develop an ECC Report exploring the relevant regulatory and national licensing issues around the NTN direct-to-device communication.

The WRC-23 did not make any major recommendations that would produce barriers to NTN development and indeed no IMT 2030 recommendations for use of Ku band were welcomed. However, many study items for WRC-27 that involve IMT 2030 do involve bands currently used by satellites.

Satellite Filings and Global Constellations

Filings for new satellite orbit positions in GEO and for LEO/MEO constellations are currently being made via National Regulators. The process for the GEO orbital authorisations has been in existence for decades and is well honed. However, the rather rapid introduction of non-GEO's operating globally has produced challenges. The authorisations of non-GEOs via a single National Regulator can potentially have unintended global implications. For example, a number of non-GEO constellations use the same frequency bands e.g., either Ku or Ka bands, and the satellite operators are left to coordinate their networks between themselves, as there are no International Regulatory processes in place to deal with this situation. This may result in poor spectrum efficiency. In this respect, there is a need for further work internationally, to adjust the Regulatory filing procedures and the satellite coordination process to the new challenges.

The increased complexity of satellite systems for delivery of communications services, as extensions to terrestrial networks, will entail the use of LEO constellations with changing geometry and geostationary satellites and terminals with dynamic beamforming, link adaptation and multi-user interference mitigation techniques. These transient behaviours will present significant challenges to spectrum regulators in all jurisdictions, who are tasked with ensuring conformance against standards, compliance with operational constraints, determination of anomalous equipment behaviour, and detection and enforcement activity regarding of malignant or unlicensed activity. Ofcom should be supported in becoming a world leader in spectrum monitoring and regulatory enforcement to ensure maximum benefits to UK citizens as well as UK industry players innovating in NTN services.

4.5.3/ Impact on Business

The availability of NR and NB-IoT standards provides an opportunity for new services. However, there is an issue with the availability of the spectrum, which is slowing down their uptake. In the IoT area a number of small constellations are looking to exploit the new standard in the FR1 bands around S band at 2GHz. Such services only require a low bandwidth of circa 5MHz, but in Europe the 30MHz of MSS band is currently shared between Inmarsat and Echostar (until 2027) for integrated satellite/terrestrial services and this is causing challenges for new entrants. There is great pressure on these lower frequency bands and the Regulators need to come up with solutions that would enable a wider spectrum utilisation from new services. In the case of NR-NTN more bandwidth is required (10-20MHz) and the problem is even more challenging. To allow early demonstrations of these new systems more flexible Test & Development licenses could accelerate developments.

4.5.4/ R&D Needs

There is a need for more R&D in the coexistence area to evaluate the interference issues and to propose mitigation methods. As mentioned, coexistence simulation activities within 3GPP are taking place for adjacent channel interference but there is little work on co-channel interference and how it affects co-existence across different frequency bands. It will be important to have real-life measurements e.g., with experimental payloads, in addition to interferences emulations, to shape a more robust picture of the coexistence. In addition, although there are processes for regulating interference from LEO to GEO, there are no Regulatory processes for LEO-to-LEO interference control. Research into mitigation techniques is urgently required to address those issues.

There is some R&D supported by ESA in the coexistence area but nothing in the UK and thus it is a gap that needs filling.

4.5.5/ Recommendations

As the various regulatory discussions around spectrum for NTN are still at a proposal level and currently ongoing at the WRC-23 conference, there is no clear picture on the frequency bands that may be agreed to be studied at a global or regional level for NTN. However, we provide below a list of policy and standardisation recommendations to be taken into account with respect to the coexistence between TN and NTN:

- **Study the identification of suitable frequency bands for NTN, acknowledging that in-band TN and NTN coexistence may be significantly more challenging to achieve.**
- **Study the development of suitable technical conditions for the out-of-band emissions of both TN and NTN to eliminate the potential adjacent band interference to NTN and TN, respectively.**
- **Study and define the required conditions for efficient cross-border coordination of NTN services to prevent interference being caused to TN services in neighbouring countries.**
- **Harmonisation of the NTN technical conditions to avoid market fragmentation and allow NTN operators to deploy services more efficiently at a global scale.**
- **Ensure that clear guidance is in place for national administrations, for the coordination of ITU filings and the operation under ITU-R No. 4.4 of Radio Regulations.**
- **It is recommended that Ofcom should be provisioned with a budget to create monitoring infrastructure suitable for ensuring compliance with future NTN systems.**

4.6/ Skilled Workforce

4.6.1/ Topic Description

With a rapidly growing ecosystem in the area of NTN, skills at all levels are required to ensure business sustainability. This means ensuring skills at all levels: those delivering and leading groundbreaking R&D through to those delivering and leading established products and services, covering commercial as well as technical skills.

The UKTIN NTN EWG readily and universally agreed that having a skilled workforce was necessary and that there is a shortage of such workers in this area. This assertion was made by all the industrial members of the group and endorsed by the academic members citing inputs from their various industrial advisory boards. At this point, it is a limited sample and there should be a wider investigation to provide more evidence. Degree and higher degree courses do not seem to provide the skills or people needed and are not considered an economically attractive option in terms of course funding options and career prospects on the part of the graduates. More broadly, there is a lack of incentive for industry and businesses to engage with universities. Furthermore, satellite communications and NTN are not widely covered in UK universities, whilst computer science is booming but electrical & electronic engineering is declining. There is more interest in space science and technology but not communications engineering. Whilst there is a dearth of courses and UK graduates, there are also restrictions on recruiting overseas workers, further exasperating the problem. We will examine this gap in the areas of undergraduate recruitment, post graduate training and in research degrees.

4.6.2/ State of the Art

Traditionally, satellite communications skills have been supplied through transfer from adjacent and well supported areas such as electronics and communications engineering, computer science and physics undergraduate courses. These courses are quite general and no course currently on offer at this level covers satellite communications in depth. Indeed, one of the issues is the growing breadth of the subject area. Generally, computer science graduates lack a background in radio and physical levels, whereas electronic engineers lack coding and programming skills. The growing breadth of satellite communications and NTN requires a much broader set of skills cutting across computing and radio and including networks as well as business and transferrable skills. Hence, a postgraduate masters or shorter and dedicated conversion courses are needed to top up general undergraduate degrees. It is clear that the majority of UK students have little appetite for such further education due to the economic pressures imposed on them. Until recently there was only one master's course dedicated to satellite communication engineering in the UK offered by the University of Surrey. This has now been joined by a similar course from the University of Bradford. Heriot-Watt University has some satellite content, whilst York has expertise in HAPS and Cranfield in aerial vehicles. Short conversion courses are offered by the IET and the Universities of Surrey and Southampton and via an ESA sponsored course at Oxford University. Attracting UK students to courses on communications engineering, both at undergraduate and postgraduate level has been difficult and the majority of students are from outside of the UK. In contrast, courses on space have proved attractive to UK students which tends to suggest that there is an awareness issue in schools of the importance of the communications and networking areas that are an essential part of any space mission.

The UK houses some key infrastructure and facilities for satellite and space developments, as follows:

Satellite Applications Catapult: One of the nine catapults in the UK, it collaborates with academia and industry in satellite technology, earth resources and navigation applications. It also has a test and demo site nearby Westcott.

Harwell space cluster: This cluster houses world leading space companies such as Airbus, the UKSA and ESA facility. The facilities include clean rooms, integration rooms, and specialised laboratories as well as an administrative hub.

Rutherford Appleton Laboratory (RAL) Space: A part of Science and Technology Facilities Council (STFC), it is a research institute located at Harwell with state-of-the-art facilities including clean rooms and test beds contributing to space systems development.

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ECSAT: The European Space Agency as a major funder of R&D in the NTN domain has its main European Telecommunications Centre located at Harwell with a 5G and 6G hub for experimentation.

National Satellite Test Facility (NSTF) and the National Space Propulsion Test Facility (NSPTF) are also located at Harwell.

Also, the UK is home to satellite manufacturers Airbus in Portsmouth and Stevenage as well as smaller manufacturers Surrey Satellite Technology ltd, Clyde Space, InSpace and several cubesat companies. Satellite operators Inmarsat-Viasat, Eutelsat-OneWeb and Avanti plus several associated equipment manufacturers and network suppliers also have significant operations based out of the UK. The UK has a significant number of consultancy companies that specialise on satellite technology such as PA, CGI, e2e group, TTP and Cambridge consultants. The UK is one of the largest contributors to ESA's budget.

The status quo of skilled workforce provision has, in the past, been adequate for serving the UK ecosystem, but is now considered inadequate as the ecosystem rapidly grows in size and depth. Examining the gaps in current skills provision.

What skills are missing?

The following key skills are considered lacking and would benefit from a rich supply of skilled workers.

- SatComs/NTN network design, antennas and antenna arrays, radiation hardened ASIC design, signal processing and algorithm design and implementation including software & firmware, especially in the area of 5GNR.
- Satellite, HAPS and UAV and payload design, constellation design, aerospace and launch options.
- Ground network design, including fixed networks, ground stations, 'cloud', network core & interfaces, network operations, administration, and management.
- AI/ML, cyber-security is likely to be embedded and many areas of the system design process as well as integral to system deployments.
- Power management, solar and batteries for the space and ground segments
- Design for manufacture, systems engineering skills and technical sales.

Note that many of the above are borne from a range of technical pathways such as communications, electronics, computer science, physics, aerospace etc, but rarely converge on current courses.

What level should be targeted?

A balanced approach that addresses the skills gap at all levels is suggested. That includes apprentices, graduates, postgraduates, and experienced practitioners. Hence, this requires pathways encompassing apprenticeships, degrees, masters, and PhDs, as well as up-skilling of experienced practitioners through dedicated short courses. It is noted that training does not replace experience and hence gaining hands-on experience is essential at all levels. This can be facilitated through joint ventures which include apprenticeships, gap years, internships, and industry-based doctoral studies. In addition, opportunities through established schemes offered by the Royal Society (e.g., Industry Fellowship and others), Royal Academy of Engineering (e.g., post-doctoral funding schemes) and support through institutions such as the Institute of Engineering and Technology (IET), the Institute of Telecommunications Professionals (ITP) and others is considered an essential ingredient to ensure a motivated and informed workforce. All these institutions also offer schemes to enthuse school pupils, and the wider public, and to increase awareness. A great further example are the schemes offered by the Royal Institution which includes the televised Christmas lectures. As well as in-depth technical skills, communications and education of new directions and concepts for commercial roles should also be provided. This could be through short courses, or work shadowing as possibilities.

One of the blockers for attracting talent is funding, where it is not considered attractive from a financial perspective. Hence it is suggested that special funding schemes dedicated to NTN are set up, as well as part-employment for post-graduate studies that attracts government sponsorship.

Research training-PhD/Eng D's:

There is a need for a workforce of highly skilled researchers to drive the innovation needed in future systems but here again there is a supply gap evidenced from the NTN EWG industrial and academic members. The difficulty in recruiting UK candidates maps that above in post graduate training and is amplified by the extra duration. Most research groups in UK universities today are populated by overseas students and these have been the main source of flow to industry for some years but are now drying up. Whilst the high standing of UK universities attracts talent worldwide to UK Engineering research groups, the pool from which this talent is drawn is limited by several factors. These include the high cost of visas and tuition fees for international students in comparison, for example, with Europe where in some cases full sponsorship is available. Brexit and the UK status in Horizon Europe has affected European recruitment and ATAS (Academic Technology Approval Scheme) has hampered recruitment from abroad, especially China that was the main supply.

Academic research in NTN areas of satellites, HAPS and UAVs in the UK is at a low level and below that in Europe. It is noted that in the Horizon Europe Smart Networks and Services (SNS) programme there are several projects covering NTN but there is no UK involvement. R&D in this area is dispersed among a number of groups in which it is a minority component. A helpful innovation was the three DSIT funded academic/industry consortia on 'networks-of-networks' which to some extent addressed this problem.

Bringing industry together with academia to tackle major problems maps the EU model and should be extended in the UK.

The DSIT TUDOR project is focused on the integration of NTN into TN under the 3D open networking RAN ecosystem and is the only major project in this area in the UK at the moment.

Currently, university research groups are suffering from an inability to fill research posts both from UK and overseas, which is endangering their continuation and the flow of skilled workers to industry. There is a need to seek a more viable model for recruitment and funding of this key seed for future innovation. For UK students, the motivation would be a funded pathway to employment and a salary commensurate with new graduates in industry. For overseas students it would be full sponsorship to complete their PhD.

Industrial involvement in the PhD research is both attractive to the student and beneficial to industry and should be encouraged. In the past we have seen in the mobile communications area successes via the Mobile Virtual Centre of Excellence (MVCE) in the early 2000's and more recently the 5G Innovation Centre at the University of Surrey. Both of these involved companies to collectively engage in pre-competitive research with universities in which the graduate students work alongside practicing engineers on key research topics. They resulted in a high degree of mobility of graduates into the participating industries. Neither of these was satellite nor NTN involved. We would recommend that such a model is considered for the NTN area.

Apprenticeships

Nationally, apprenticeships are gaining momentum across a wide range of industries, including the space and telecommunications sector, with the latter being championed by the Institute of Telecommunications Professionals. Apprentices form an attractive route to employment whilst being underpinned by education, including degree level. Those that have completed apprenticeships often go on to perform key technical and commercial roles in the chosen industry whilst circumventing the financial challenges of the traditional university route. They attain key hands-on skills and acquire real-world experience ready to apply upon completion. As such, they complement the traditional route and would fill a critical skills gap in the world on satellite communications and NTN. We would recommend that apprenticeships opportunities are created and championed in the satellite and NTN sector.

4.6.3/ Impact on Business

The current limitation in satellite and NTN technology skillset is one of the key risks for any company seeking to invest in emerging NTN opportunities.
If we do not address the emerging need for skills that is resulting from the rapid growth in the ecosystem, it will not enable businesses to flourish and may even fail as a result, hence failing the economy. It will also increase the price tag on those with the skills and hence making the cost of employment potentially challenging and unsustainable.

Conversely, having a rich supply of skilled workers will enable businesses to flourish, deliver on their obligations and innovate further to remain competitive on the global stage.

4.6.4/ Recommendations

- **Whilst the above assessment is based on the views of a range of experts, it could be considered as anecdotal. Hence, evidence gathering in support of the above is recommended along with a breakdown and careful assessment of the findings and emerging needs.**
- **Test beds to assist in training are recommended. This would include bench testing capability for low level hardware as well as for NTN communications networking, and would consist of simulation & modelling, laboratory 'device in the loop' tests with test equipment and extend to a 'in-orbit' test.**
- **The commissioning of a rich research environment that brings together industry and academia in a cost-effective way with the dual aims of undertaking strategic pre-competitive research; and attracting and developing highly skilled PhD candidates with the means to segway into industry and become industry leaders in the area of NTN and satellite communications.**
- **It is recommended to develop rich opportunities for apprentices at all levels, with the required dual support of study and industry work, where apprentices would work along-side experienced practitioners with a pathway to such roles in the future.**

5/ Recommendations

In each of the topic areas discussed in this paper, we have made initial recommendations appropriate to the specific topics. It is to be noted that in the area of user equipment there is work in progress and we will make recommendations in the second issue of the Future Capability Paper to cover this area. Here we summarise the most important recommendations at this stage of the process. They are to be read as interim and will be reviewed in v2 of the Future Capability Paper, as more data and views are collected.

Recommendations to UK industry

R1. UK industry should work with 3GPP and other relevant standards entities to ensure that end-to-end management plane capabilities, including trans-TN-NTN boundary continuity, are included in future standards.

R2. UK industry should work to identify any gaps and limitations in the current standards that would slow down the mass adoption of NTN technology. The UK industry should take lead to lobby with the relevant standard and regulatory bodies on the urgency to fix these issues in order to keep up with the pace of business trends.

Recommendations to Government R&D

R3. It is recommended that the Government set up a Centre of Excellence in NTN for knowledge sharing between academia and industry and preparations for inputs to standards. In addition, that Government seeks ways to raise the profile of NTN within the National Space Strategy.

R4. UK government should run collaborative programmes for developing, launching, and validating in-orbit/flight, the end-to-end service management capabilities required by the evolving market to enable UK industry to develop world-leading insight and operational solutions.

R5. It is recommended that future R&D on 6G technologies be focussed on open networking between NTN and TN and coordinated across DSIT and UKRI being facilitated by larger consortia of industry and academic partners. Additional coverage should be extended to interference management/spectrum sharing, optical communications, AI/ML and on-board processing algorithms and semiconductors for on board processing.

Recommendations

Recommendation to UKRI

R6. A detailed comparison of the LCA for a variety of directly comparable scenarios (terrestrial and non-terrestrial; direct-to-device and backhaul) that sets good precedents for comparing differing telecommunications services is required.

Recommendations to Government – Training & Skills

R7. It is recommended that a wider evidence base on skills shortages in the telecommunications and NTN sector be commissioned in order to validate initial findings in this paper.

R8. It is recommended that Test beds to assist in the training of skilled workforce be established. This would include bench testing capability for low level hardware as well as for NTN communications networking and would consist of simulation & modelling, laboratory 'device in the loop' tests with test equipment and extend to a 'in-orbit' test.

R9. It is recommended to commission a rich research environment that brings together industry and academia in a cost-effective way with the dual aims of undertaking strategic pre-competitive research; and attracting and developing highly skilled PhD candidates with the means to facilitate entry into industry and become industry leaders in the area of NTN and satellite communications.

R10. It is recommended to develop rich opportunities for apprentices at all levels, with the required dual support of study and industry work, where apprentices would work along-side experienced practitioners with a pathway to such roles in the future.

Recommendations to Regulators

R11. It is recommended that Ofcom engages in any future international discussions for the identification of suitable frequency bands and the development of appropriate technical conditions for NTN, supporting their broader harmonisation. That would avoid the risk of market fragmentation and allow NTN operators to deploy services more efficiently at a global scale. An early identification of frequency bands for NTN, would ensure speedy access to spectrum from the operators, encouraging an early uptake of systems using the new NTN standards.

R12. It is recommended that Ofcom should be provisioned with a budget to create monitoring infrastructure suitable for ensuring compliance with future NTN systems.

6/ Conclusions

The task of this EWG was to review a broad range of non-terrestrial telecommunications network architectures and applications including satellite systems, understanding how new emerging trends and techniques would lead to new ways of operating. This Future Capability Paper is the group's first deliverable and a building block towards delivering on its remit at the end of 2024 and thus is to read as work in progress.

The Future Capability Paper commences by outlining the context in terms of the socio-economic considerations and the use cases. This covers new services made possible by NTN and how it can play a part improving people's lifestyles in the areas of; healthcare, transportation, digital inclusion, transforming energy systems, defence, security, and public safety.

Following on we provide a market analysis outlining the structure of existing satellite communications and its value chain between operators, manufacturers, and service providers. We outline the changes taking place in the industry from traditional GEO satellites to the new mega constellation LEO's and a future which is connected multi-orbits. We outline the convergence which is taking place between the satellite and mobile worlds, and the challenges that this brings about to the stakeholders as we move to a unified 6G system. We briefly provide an international comparison of how the UK sits in terms of R&D activities in NTN. A SWOT analysis of NTN in the UK demonstrates in particular the R&D strengths as well as some of the overall gaps. Following discussions within the EWG and the production of a long list, this was reduced to six topics which were considered the most critical for future NTN.

- Value chain, business model and convergence
- Sustainability
- Future architectures and equipment
- 6G Technologies
- Spectrum and Regulation
- Skilled Workforce

In each of these topics we describe the landscape, state of the art, impact to business, R&D gaps and needs and then provide initial recommendations.
The EWG's overall conclusion is that Non-Terrestrial Networks represent a key element in the pathway towards a fully unified 6G network. As such, the opportunity for innovation is arguably much greater in this area than in purely terrestrial networks. The UK has considerable strengths in terrestrial networks, and these now need to be harnessed towards R&D in NTN.

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The Chair, Co-Chair and all members of the NTN EWG are on the group in a personal capacity and not as representatives of their company.

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