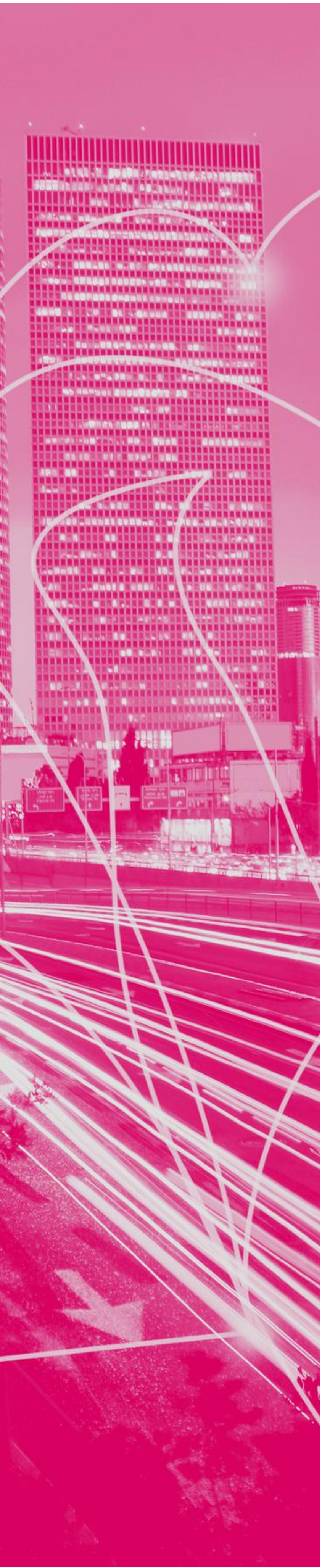
UKTIN

Strategic Working Group Report

Future Networks

This is a deliverable from UKTIN Academic Future Networks Strategy Group

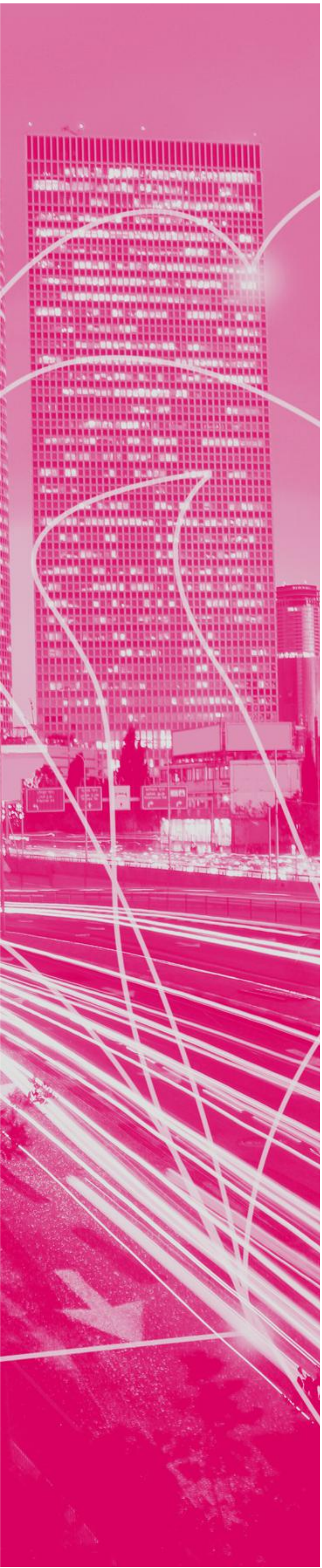


Executive Summary

The UKTIN Academic Future Networks Strategy Working Group (which can be referred to as the Academic Strategic Working Group[1]) is one of the UKTIN groups which is tasked with developing a long-term strategy that will ensure world-leading academic research into future networks well into 2040. A key focus of the group is to create a forward-looking vision for research and innovation (R&I) in future networks, driven by UK academia, and provide recommendations on how this can be achieved.

In this first whitepaper, aligned with the above mission, the UKTIN Academic Strategy Working Group set out an overview and initial inventory of the UK's current academic-led Research, Innovation, and Development (R&I&D) landscape and ecosystem in future networks. We also compare this with the global R&I&D landscape. The paper focuses primarily on Research and Innovation (R&I) aspects. This allows us to examine, compare, and understand the strengths and gaps in the UK's current academic-led R&I programmes. Building on this, we offer strategic recommendations aimed at capitalising on existing strengths while promoting new growth in areas with gaps, with the potential to secure a future leadership position for the UK.

[1] UKTIN Academic Strategic Working Group



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Introduction

1.1/ Setting the Scene

The Integrated Review 2023, and the UK Science and Technology (S&T) Framework[2] identified artificial intelligence (AI), quantum technologies, engineering biology, semiconductors, and future telecoms as priority areas of focus for UK S&T and data as a crucial enabler. The UK should position itself at the forefront of future telecoms, recognising its potential to address pressing challenges like sustainability and connectivity gaps. To build the UK's capability to shape the next generation of communications networks, the government should make a long-term commitment to foster next-generation connectivity solutions in the UK.

With a commitment to shaping the global agenda for Future Networks, including 6G, the UK can leverage its expertise and historical influence in telecoms. Key objectives include ensuring that 6G aligns with UK operators' needs and broader policy goals, fostering domestic telecoms capability, and supporting the smooth transition from 5G to 6G. The strategy should emphasise collaboration in international forums to advocate for UK priorities and secure access to essential patents. Additionally, it should underscore the importance of large-scale investments, international partnerships, and export markets to sustain R&D and economic growth in the telecoms sector.

The UKTIN Academic Future Networks Strategy Working Group (or Academics Strategy WG for short), working in collaboration with other UKTIN WGs, is mainly tasked with developing a long-term strategy that will ensure world-leading academic research into future networks well into the next decade (i.e., towards 2040). A key focus of the group is to create a forward-looking vision for research and innovation (R&I) in future networks, driven by UK academia, and provide recommendations on how this can be achieved.

[2] UK Government Science & Technology Framework

Consequently, this working group takes a holistic, end-to-end, and converged perspective of future networks, encompassing both wireless (including 6G and beyond-6G) and wired future networks, including high-capacity optical fibre networks, operating on different time- and distance scales, which underpin the internet and the digital infrastructure, as well as their convergence and key enablers and new drivers, including spectrum, energy, security and resilience, AI, Cloud and Edge Computing. In addition to various resources, this paper incorporates inputs from several White Papers by the UKTIN Expert Working Groups, which focus on essential building blocks and enabling technologies for future networks. We plan to further integrate additional insights and contributions from these Working Groups into our forthcoming papers. Below we briefly describe the key building blocks of future networks.

1.1.1/ 5G evolution to 6G

The International Telecommunication Union (ITU) and the wireless industry are in the process of defining the 6G requirements of IMT-20303. Below shows some of the key characteristics that are expected in 6G
evolution:

- High Data Rate: The peak downlink data rate will exceed 100 Gbps, enabling ultra-fast transmission of large amounts of data. The uplink peak data will also be enhanced to larger than 10 Gbps.
- High Capacity: The network capacity will be 100 times higher than 5G, supporting massive data traffic and concurrent users.
- Gbps Coverage Everywhere: The network coverage will extend to three-dimensional spaces, including the skies, space, and underwater, ensuring seamless connectivity in any environment.
- Extreme Low Latency: The air interface latency will be less than 1ms, enabling real-time and interactive applications that require high responsiveness and accuracy.
- High Reliability: The network reliability will reach five nines (99.999%) or above, ensuring minimal errors and failures in critical scenarios.
- Always Secured: The network will provide trust, security, and resilience for all users and devices, protecting them from cyberattacks and privacy breaches.
- Sensing Capability and High Precision Positioning: The network will have the ability to sense the physical environment and provide high precision positioning for users and devices, in the resolution of 1 to 10cm, enabling new applications such as augmented reality and autonomous driving.
- Massive Connected Devices: The network will support up to 100 million connected devices per square kilometre, enabling the Internet of Things and smart city applications.

- Low Energy and Cost: The network and devices will consume low energy and cost, making them more sustainable and affordable.
- AI-native: AI is expected to be both a key service and a native feature in 6G communication networks. 6G RAN and Core design will leverage E2E AI and ML to implement customised optimisation and automated operation, administration, and management.

6G evolution will serve various sectors and domains, such as consumer, business, industry, and government, and enable new possibilities and opportunities for innovation and development. Furthermore, the governments of the United States, Australia, Canada, the Czech Republic, Finland, France, Japan, the Republic of Korea, Sweden, and the United Kingdom have agreed on shared principles for the research and development of 6G wireless communication systems[3]. They emphasise the importance of open, global, secure, and resilient connectivity to build a more inclusive, sustainable, and peaceful future. The key principles include Trusted Technology and National Security; Security, Resilience, and Privacy; 6G systems; Global Standards and Collaboration; Open and Interoperable Innovation; Affordability, Sustainability, and Global Connectivity; Secure Supply Chains; Spectrum Efficiently.

1.1.2/ Open RAN

In the last decade, several research and standardisation efforts, which were usually led by telecom operators, have promoted the Open RAN as the new paradigm for the RAN of the future. Open RAN deployments are based on disaggregated, virtualised and software-based components, connected through open and standardised interfaces, and interoperable across different vendors.

Disaggregation and virtualisation enable flexible deployments, based on cloud-native principles. This increases the resiliency and reconfigurability of the RAN. Open and standardised interfaces also allow operators to onboard different equipment vendors, which opens the RAN ecosystem to new players.

Finally, open interfaces and software-defined protocol stacks enable the integration of intelligent, data-driven closed-loop control for the RAN. The O-RAN Alliance is a consortium of operators, vendors, research institutions, and industry partners that focuses on reshaping the RAN ecosystem toward an intelligent, open, virtualised and programable architecture.

[3] US State Department, Joint Statement Endorsing Principles for 6G: Secure, Open, and Resilient by Design

1.1.3/ Evolution of fixed and optical networks

Future fixed network innovations are the key to enabling a wide range of new applications and services that require high-speed, low-latency, secure, and reliable connectivity, offering deterministic connectivity experience that is more difficult to achieve in a mobile network. While 5G is moving on to 5G Advanced and 6G, the evolution of fixed network is also progressing. The European Telecommunications Standards Institute (ETSI) is studying the evolution of the fixed network needed to match and further enhance the benefits that 5G has brought to mobile networks and to communications. ETSI is currently defining improvements with respect to previous solutions and the new characteristics of what represents the 5th generation fixed network, and work is currently evolving towards F5.5G and F6G[4].

The demand for higher transmission capacity, lower per-bit transmission costs, and power consumption has always driven optical modules towards higher transmission rates. With the explosion of fixed and mobile Internet traffic and new service requirements, both the core optical network as well as intra- and inter-datacentre networks, also require development to provide ubiquitous high capacity with low delays and guaranteed security and resilience, as well as reduced energy needs. Currently the backbone can handle traffic at 100G and 200G line rates. However, the increasing traffic growth will made 100G and 200G insufficient to meet bandwidth requirement. 800G/1.2Tbit/s are expected to replace 100G and 200G deployments soon, with laboratory demonstrations significantly ahead. A shift towards 400G/800G/1.2Tbit/s backbone is underway, which is driven by the following factors[5]:

- Emerging applications and services: 400G backbone Internet will significantly improve bandwidth to support data-hungry future applications such as digital twins, holographic communications, and 8K resolution video streaming
- AI and Cloud computing: with the massive adoption of AI and cloud computing technologies, and cloud-based service with demand for increasing bandwidth capacity and low latency, 400G is essential to provide high speed connections between data centres as well as data centres and users.
- 6G network and edge computing: edge computing is a crucial part of 5G to bring cloud capability closer to the end users. The extension of 400G fibre connection to edge nodes provides the foundation to support 6G service demand, such as digital twins and holographic communications and metaverse.

[4] ETSI, Fifth Generation Fixed Network (F5G)
[5] ETSI White paper, All-optical network facilitates the Carbon Shift.

It should be noted that to ensure both existing and future applications, high-capacity digital infrastructure underpinned by optical fibre networks is a must and significant efforts must be devoted to maintaining and enhancing UK R&D leadership in this area, even in the absence of an indigenous manufacturing capability. Optical fibre networks represent UK's critical infrastructure and must be world-leading in their capabilities: speed, throughput, low delay and high-security and resilience, capable of delivering high capacity when and where it is needed.

1.1.4/ Non-terrestrial networks

Non-terrestrial networks (NTNs), which encompass unmanned aerial vehicles (UAVs), high altitude platforms (HAPS), and satellite networks (GEO, LEO, MEO), have seen significant advancements due to recent developments in aerial and space technologies, combined with the reduced costs of manufacturing and launching these systems. This progress has enabled more sophisticated applications of NTNs, particularly when integrated with terrestrial communication networks[6].

Various new use cases and applications have emerged, focusing on providing continuous, ubiquitous, and high-capacity connectivity worldwide. The inherent limitations of ground infrastructure and economic considerations often restrict the deployment of terrestrial networks (TNs) in remote or inaccessible regions, such as rural areas, deserts, and oceans. Consequently, user equipment (UEs) in these underserved or unserved areas cannot access terrestrial services. Integrating NTNs with existing terrestrial infrastructure offers a feasible and cost-effective solution for achieving continuous and ubiquitous wireless coverage.

NTNs can enhance network scalability by acting as access nodes that improve the capacity, coverage, and latency of terrestrial networks. They can also address the shortcomings of terrestrial infrastructure in meeting the required levels of reliability and widespread availability for future wireless applications. Use cases of NTN include but are not limited to: (i) Disaster Recovery and Emergency Response; (ii) Rural and Remote Area Connectivity; (iii) Maritime and Aeronautical Connectivity; (iv) Agricultural Monitoring and Management; (v) Smart City Infrastructure, complimenting terrestrial networks.

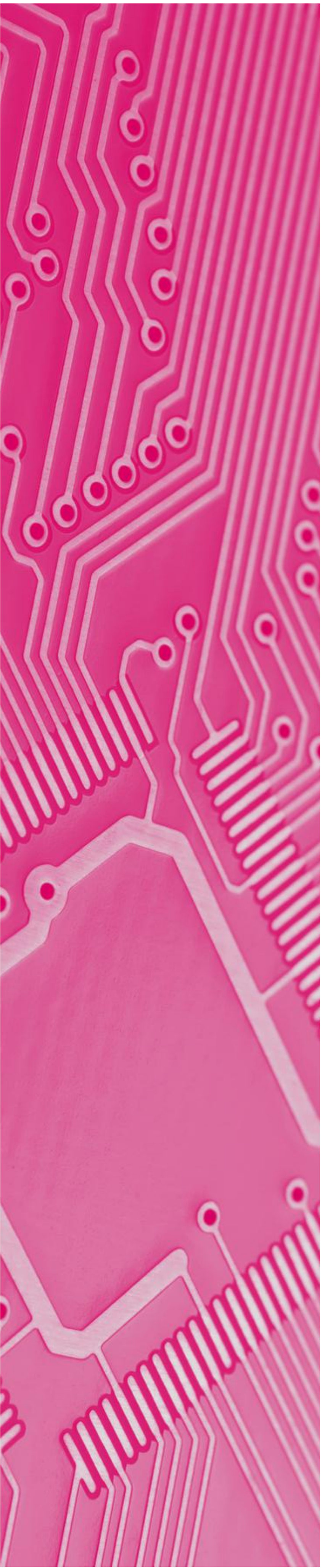
Following the benefits offered by NTNs and to capitalise on the economies of scale, 3GPP is working on integrating NTN as an additional access technology into 5G[7]. In 5G the focus of 3GPP NTN work has been on satellite communications networks (LEO, MEO and GEO) but in 6G this is expected to be expanded to support High altitude platform stations as 5G base stations systems and air-to-ground networks.

[6] UKTIN, Future Capability Paper: Non-Terrestrial Networks
[7] 3GPP, Non-Terrestrial Networks Overview

1.2/ Objectives & Organisation

In this first white paper, we set out a view and initial inventory of the UK's current academic-led R&I landscape and ecosystem in future networks, as well as providing a view of the same in global R&I landscape for comparison. Following this we will examine, compare, and contrast the strengths versus gaps in UK's current academic-led R&I programmes. We then offer strategic recommendations aimed at capitalising on UK's R&I leadership in areas of strengths, while enabling new growth in R&I in areas where there are gaps and on the other hand there is great potential to secure a leadership position for UK.

The rest of this report is organised as follows. Section 2 provides an overview of the major UK R&I programmes in future networks, including the Future Communications Systems Early Stage Federated Hubs (which focus on lower TRL research) and the Future Network Challenge Projects (with focus on higher TRL research), as well as other significant programmes. In Section 3 we describe key regional and national R&I initiatives in future networks, in the EU, the United States, and elsewhere. In Section 4 we will provide an initial Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the UK's current R&I position in the development of 6G and offer several recommendations aimed at further strengthening UK's position as a leader in future networks.



R&I Programmes

2/ Major R&I Programmes in Future Network (UK)

To deliver the UK's ambitions in future telecoms, progress had been made by the previous UK Government in the Future Telecoms Mission Fund programme, consisting of £70m funding, aims to further the goal of UK as a global leader in Future Telecoms.

A key element of this mission is a series of Future Telecoms Research Hubs[8], where early stage and applied research has been funded and coordinated through UKRI and EPSRC via the Technology Missions Fund (TMF), which will use similar models to fund other priority areas including Quantum and Artificial Intelligence. The Hubs will build on the springboard provided by EPSRC's £6 million investment for 3 federated and connected platforms in the communications technologies space. Supported by the UK Telecoms Innovation Network (UKTIN), these platforms will engage with the telecoms industry, catapults and internationally around 3 broad themes: (1) a network of networks; (2) wireless and wired systems and spectrum; (3) cloud and distributed computing. The platforms will draw together the existing portfolio of EPSRC investments in telecoms-related areas into a coordinated approach and will inform any future investment in mission-focussed research hubs.

Additionally, the Future Open Networks Research Challenge (FONRC)[9] is a £25 million challenge that will is enabling universities to work with large RAN vendors, and other telecoms organisations, to conduct R&I to drive the openness and interoperability of future network architectures. These technologies will need to be commercially attractive to large vendors, MNOs, and Venture Capitalists, and promote diversification in future network architectures. The challenge runs until the end of March 2025. It is part of the UK government's £250 million Open Networks R&I Fund which is supporting the5G Telecoms Supply Chain Diversification Strategy through a range of telecoms R&I projects, which is funded by the Department of Science, Innovation and Technology (DSIT).

[8] UKRI Announcement: Major future telecoms research boost announced
[9] Gov.uk, Future Open Networks Research Challenge

In addition to the above programmes, the UK Research and Innovation (UKRI) and the Engineering and Physical Sciences Research Council (EPSRC) currently support over 130 live grants (close to £300 million investment) in telecoms-related research.

In the rest of this section, we provide a brief overview of the portfolio of projects supported by TMF and the FONRC programmes, and additionally describe some of the other ongoing UK R&I research in future networks, including in fibre optics.

2.1/ Future Communications Systems Early-Stage Federated Hubs

The three federated telecoms hubs, CHEDDAR, HASC and TITAN, together with the Joint Open Infrastructure for Networks Research (JOINER), are currently being supported by a governance structure that is established to foster impactful translation of research, in alignment with the UK Wireless Infrastructure Strategy published by DSIT. The hubs will support the first UK 6G trials conducted using JOINER. The hub programme is scheduled to run until March 2025. The TITAN hub will establish the operational elements necessary to support this governance structure. The objectives are:

- To provide the skills and resources to create and maintain IPR.
- To provide a 'research interface' to standards development organisations (SDO).
- To contribute to the development of a telecom's standards strategy in partnership with other stakeholders such as UKTIN.

The specific actions to achieve these objectives are organised into four key interventions: 1) standards and international engagement; 2) training and skills development; 3) technology roadmaps, industry scoping, and forecasting; and 4) marketing. Below we provide a short description of each of these hubs.

2.1.1/ CHEDDAR

The CHEDDAR hub aims to drive research and networking across the UK academic community using Synergy Fellows with Project and Platform funding, to facilitate the connection of UK excellence, early career researchers, and brave new ideas in this field. To do this they are examining new emerging computation, key infrastructures, with an end-user focus, through a cohesive research ecosystem nurturing talent and encouraging blue horizon ideas. CHEDDAR will deliver its research framework through the following objectives:

1. Research, design and derive proof-of-concepts of the 6G technologies that will support edge-fog-cloud continuum of computation through three thematic pillars (Figure 2-1): (i) emergence, encompassing network embedded sensing and intelligence, and the support of emerging methods of computation from autonomy to quantum; (ii) sustainability of device, algorithms, data pipelines and service integration, green-by-design; and (iii) human-centric design with trust, security, privacy, resilience, interpretability, transparency, and equitability.
2. Bring about a step change in research community engagement, including early career development, with an open, inclusive way of working, such that we can accelerate national scale innovation for furthering knowledge across these three core pillars making the UK a global communications lighthouse, promoting open research practices and RRI and build a cohesive research ecosystem that nurtures ECRs.
3. Connect distributed pockets of excellence across the UK to form a critical mass in each thematic area, and engage with non-communications platforms; CDTs, institutes, DCIT and UKTIN etc.
4. Develop pathways to enabling new communication network design and connect with the All Spectrum, TITAN, and JOINER platforms to inform them of new application, interoperability and spectrum utilisation requirements and cross-fertilise the co-design while providing mechanisms to transition low TRL research to innovations and inform standardisation and conduct regulatory engagement.
5. Bring computing and communications communities together through cross-disciplinary thematic projects to establish UK leadership in cloud native technologies for telecoms.

CHEDDAR frames its research around core themes that align with DSIT's 6G strategy and roadmap. The work is categorised into three pillars as shown in Figure 2-1.

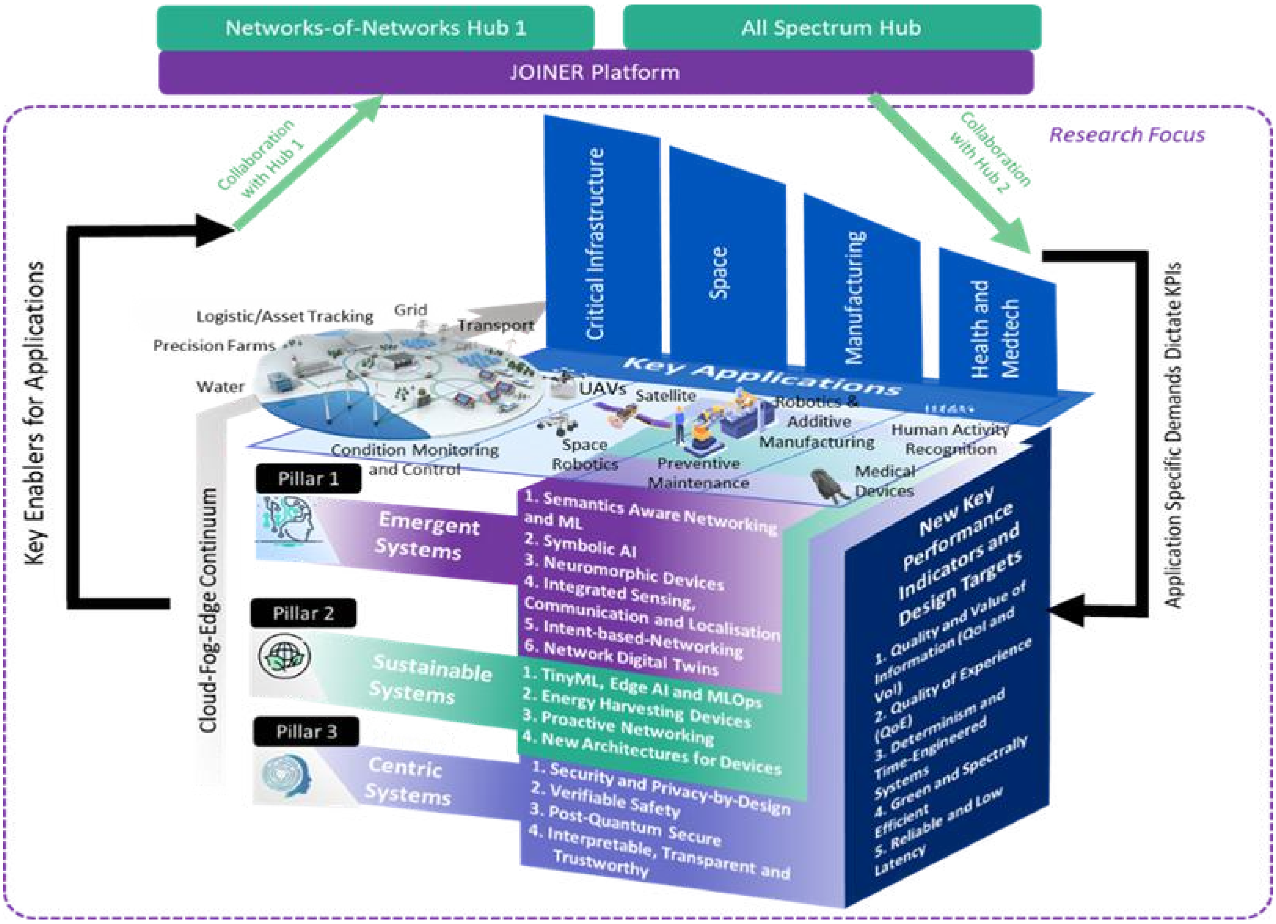


Figure 2-1 Cheddar's research pillars

Furthermore, the CHEDDAR challenge domains are categorised as:
(1). Critical Infrastructure (including Grid, Transport, Water, Tracking/Logistics, Precision Agri, etc.) that bring safety and security requirements but also new demands due to high-interaction control/feedback loops and growing autonomy. There are new challenges to provide a compute continuum that network together; ground, maritime, air, and space computing capabilities providing on-demand edge computing.
(2). Increasing usage of robotics and the need for continuous monitoring of next generation manufacturing systems requires new ways of integrating different communications systems and time-engineered networks where determinism is a key requirement.
(3). Health and Medical technologies add the conflicting requirements of mobility, safety, security, and privacy as well as increasing demands for bandwidth, edge processing and flow management. The three domains are complemented by blue-sky and pilot research funded as part of the hub. These projects are designed such that multiple partners contribute towards a single project to create critical mass around each of these research topics delivering true impact.

2.1.2/ HASC

The primary objectives of the Future Communications Hub in All-spectrum Connectivity (HASC) are as follows:

1. Integration of Spectrum Bands: The aim is to devise strategies that seamlessly merge various bands across wired and wireless spectrums, facilitating ultra-high-speed and energy-efficient access.
2. Dynamic Spectrum Allocation: The hub strives to develop techniques for the dynamic allocation and optimisation of spectrum resources across wired and wireless domains.
3. Enhanced Security Measures: Employing a blend of RF and optical technologies, including classical and quantum techniques, the hub endeavour to fortify wireless networks against potential vulnerabilities.

Their approach entails active engagement with academia and industry to cultivate a diverse research community.

The hub addresses the following set of challenges.

C0. Modelling: This initiative aims to integrate existing modelling frameworks for wired and wireless systems, facilitating end-to-end modelling capabilities. Emphasis will be placed on key performance indicators (KPIs) such as throughput, efficiency, error, reliability, and resilience across various environments and wireless channels.

C1. Connectivity: Focused on achieving Tbps-class connectivity with high energy efficiency, this challenge explores new spectral regions, interfaces, and technologies to optimise wired and wireless propagation channels.

C2. Reliability and Adaptivity: Addressing holistic spectrum management, this challenge aims to leverage "All Spectrum" capabilities by incorporating intelligent spectrum resource scheduling, interference management, mobility management, and cross-layer designs.

C3. Security: Investigating the utilisation of optical and RF channels to fortify wireless networks, this challenge explores quantum communications, physical layer security techniques, and position-based security measures.

The hub contributes to a range of demonstrator capabilities, including beam steering terminals, quantum communications, advanced measurement labs, 5G networks, quantum networking, LiFi testbeds, and optical wireless demonstrators. These resources collectively form a cutting-edge research infrastructure poised to drive innovation and advancement in communications technology.

2.1.3/ TITAN

TITAN is the UK telecoms hub on Network of Networks (NoN). TITAN will conduct unique and highly transformative research on the interfaces of classic and emerging communication network elements (e.g. quantum) to achieve the seamless, open and fully integrated NoN. To this end, the ambition is to create the ultimate secure, self-configurable, self-optimising, self-healing, energy efficient, resilient NoN that achieves pervasive coverage across the globe. While bringing all the necessary network elements together, it is envisaged that TITAN will uncover many unsolved research challenges across the interfaces.

TITAN's vision can only be realised by co-creation enabled by an environment that allows active and meaningful cross-disciplinary collaboration. Therefore, TITAN has brought together 16 universities that individually lead research in crucial segments of communication networks. TITAN will provide strong consolidated inputs to global activities in telecommunications in partnership with the companion EPSRC platforms. TITAN will engage with industry to translate market-ready research into future products by creating a pipeline of new intellectual property. It will provide crucial input for the development of new policies, including assessments of socio-technical aspects, through engagement with bodies such as UK Telecommunication Network (UKTIN). The TITAN research collaboration programme is structured in six strongly inter-connected lighthouse projects (LPs) focusing on key network elements required for end-to-end connectivity under emerging key value and key performance indicators. The research topics in the LPs are summarised in Figure 2-2.

LP 1	LP 2	LP 3	LP 4	LP 5	LP 6
• New open architectures for end-to-end services • Intelligent Multi-access controller • AI-native networks • Network optimisation using AI/ML	• Cell-free, high-density wireless networks • Energy-efficient wireless networks • Massive MIMO • Holographic MIMO • Sub-THz • Reflective Intelligent Surfaces (RIS)	• Net-zero data links • New device technologies • Terabit/s optical wireless networks • Free-space optical for satellite, arial platforms and underwater • Communication and sensing – LiFi-LIDAR	• Hollow-core and multi-core fibre for low latency data links • Dynamic spectrum management • Integration of sensing techniques for network monitoring	• Optimum resource allocation for low latency links • Satellite data link optimisation using AI/ML • Aerial platforms / HAPS integration • Reliable high-speed link from ground to satellite	• New architectural solutions for combining quantum and classic communications • E2E physical layer security / crypto • Quantum router • Distributed computing and sensing

Figure 2-2 Titan's Lighthouse projects, LP1: 'Network Intelligence and End-to-End Integration', LP2: 'User-Centric Service-Aware Radio Access Control, Integration and Optimisation', LP3: 'Optical wireless networks integration', LP4: 'Fibre enabled connectivity integration'; LP5: 'Non-Terrestrial network design and optimisation', LP6: 'Quantum Networks Integration'

Each LP targets specific research objectives across multiple partners, aiming to solve impactful challenges and drive innovation. To this end, TITAN has defined 33 closely interconnected mini-projects (MPs) distributed across the six (LPs). TITAN, like all the other hubs, has adopted an inclusive approach by providing mechanisms for onboarding new partners through dedicated calls.

Moreover, TITAN coordinates a governance function (see Figure 2-3) for all hubs and JOINER as part of the Federated Telecoms Hubs to meaningfully establish effective frameworks and processes to facilitate translation of research though new and established approaches such as IPR pools, standards development engagement, partnerships with SMEs and industrial partners, technology roadmap creation and skills & training. TITAN aims to build dedicated teams to support these interventions and will closely coordinate these with UKTIN.

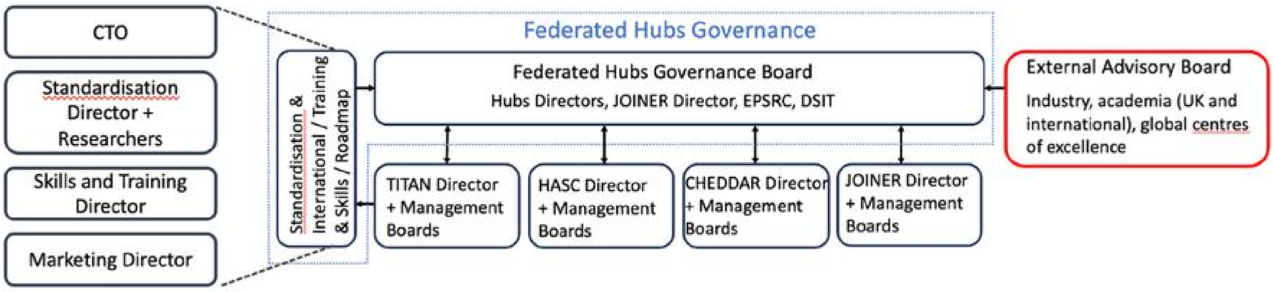


Figure 2-3 Federated Hubs Governance

2.1.4/ JOINER

JOINER is a national-scale experimentation platform aimed at supporting research and development initiatives in future communications networks. Initially focusing on serving the needs of EPSRC Future Communications Federated Hubs and other R&D programs, JOINER aims to eventually support the broader telecommunications ecosystem in the UK, including academia and industry. It will achieve this by providing an open and federated experimental platform for collaborative research and testing, facilitating the evaluation of telecoms R&D under representative conditions.

The platform will address the complexity and heterogeneity inherent in telecommunications networks by offering scale, heterogeneity, and reach, simulating real-world networks. This approach aims to increase the credibility and impact of experiments, accelerating the translation and commercialisation of academic research. JOINER will also generate large datasets to enable innovation in data-driven services and AI/ML tools.

Key objectives of JOINER include:
1. Providing a large-scale host for experimental research, development, and testing.
2. Offering a federated testbed for research on the full breadth of solutions in a telecom ecosystem.
3. Facilitating research collaboration across academia, industry, and government.
4. Accelerating the translation of early-stage research into commercial products.
5. Showcasing outcomes and capabilities of future networks through impactful demonstrations.
6. Contributing to national skills development in telecom systems.
7. Championing UK capabilities in future network concepts internationally.

JOINER's high-level system design includes nodes interconnected through a fabric consisting of managed physical and virtual infrastructure. The nodes, spread across the UK, will house a range of experimental facilities and testbeds, offering complementary capabilities across various technological domains. The fabric will provide managed physical connectivity, including dark fibre and high-speed links, as well as virtual infrastructure hosted in hybrid public-private clouds.

Overall, JOINER aims to address the critical challenges of future telecommunications through collaborative research, testing, and experimentation, ultimately driving innovation and advancing the UK's position in future network technologies.

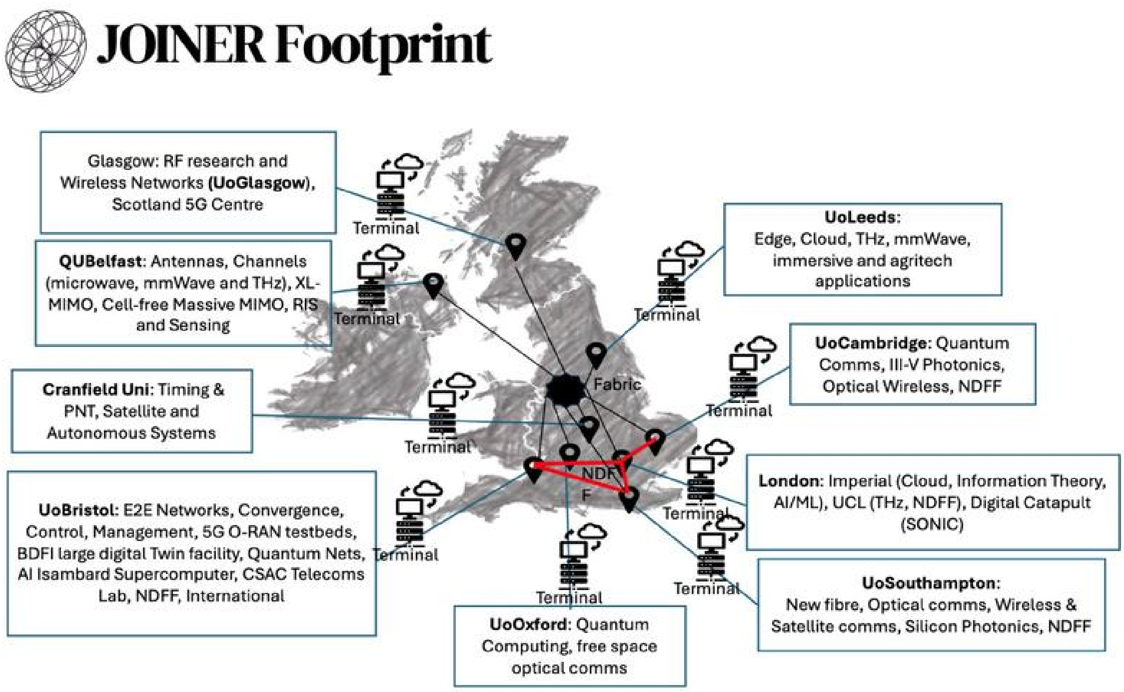


Figure 2-4 JOINER Project's footprint map

2.2 The Future Open Networks Research Challenge

The Future Open Networks Research Challenge (FONRC) is a £25 million challenge that will enable universities to work with large RAN vendors, and other telecoms organisations, to conduct R&I to drive the openness and interoperability of future network architectures. These technologies will need to be commercially attractive to large vendors, MNOs and Venture Capitalists, and promote diversification in future network architectures. The challenge runs until the end of March 2025. It is part of the UK government's Open Networks R&I Fund which will deliver on the £250 million 5G Telecoms Supply Chain Diversification Strategy through a range of telecoms R&I projects, which is funded by the Department of Science, Innovation and Technology (DSIT).

2.2.1/ TUDOR

The TUDOR Project is a pioneering £12 million initiative funded by the UK's Department of Science, Innovation, and Technology (DSIT). Its primary objective is to spearhead research targeted at addressing key technical challenges in the development of future 6G technology. This project focuses on low Technology Readiness Level (TRL) research and aims to integrate satellite, airborne, and terrestrial network capabilities into a seamless 3D architecture, crucial for the evolution of 6G. The TUDOR consortium comprises 25 partners, including universities, research institutions, and industry leaders. Each partner contributes expertise and resources towards the project's objectives, ensuring a collaborative and multidisciplinary approach to advancing 6G technology.

The key technical objectives of TUDOR are:

1. Open Networking and Universal Connectivity: Designing a novel 3D architecture based on open networking principles to provide seamless, reliable, and secure connectivity across diverse geographic environments.
2. Maximising Spectrum Openness and RAN Efficiency: Delivering capacity-assured 6G wireless connectivity through the integration of terrestrial and non-terrestrial network capabilities.
3. Automation and Agility: Addressing research challenges related to the automation of network operations in complex multi-tenant and multi-provider 6G ecosystems.
4. Enabling 6G-Era Services: Researching innovative technologies such as Integrated Sensing and Communication (ISAC) and Semantic Communications to enhance future network capabilities.
5. Validation and Testing: Rigorously testing the TUDOR solution against emerging use cases in large-scale, real-life environments.

The TUDOR project advocates for end-to-end openness across radio access network (RAN), transport, and core network segments. It extends Open RAN principles to other network segments, enabling a fully end-to-end open network architecture. The project emphasises flexible network function disaggregation, enabling seamless integration of new functions from different stakeholders. Container-based solutions with unified APIs and cloud-native support are developed to facilitate deployment and management. The project also investigates technologies like Integrated Sensing and Communication (ISAC) and Semantic Communications to enhance 6G capabilities. ISAC aims to reuse common hardware platforms for radar and communication systems, while Semantic Communications seeks to reduce bandwidth requirements by transmitting semantic information.

2.2.2/ REASON

The Realising Enabling Architectures and Solutions for Open Networks (REASON) project brings together a consortium comprising five leading universities (University of Bristol, King's College London, Queen's University Belfast, University of Southampton, and University of Strathclyde), major equipment vendors (Ericsson, Nokia, Samsung), an O-RAN vendor (Parallel Wireless), a network service provider (British Telecom), BBC as a content service provider, system integrator Thales, Digital Catapult, and two SMEs (Weaver Labs and Real Wireless). Additionally, contributions from CS Connected (CSC) cluster semiconductor expertise for unique RF and optical wireless technology advancements.

REASON aims to innovate, develop, and industrialise technologies and solutions for future open end-to-end communication networks. It proposes a roadmap for future network architectures to integrate multi-technology access networks effectively and advance their performance in line with the growing demand for mobile data. The project focuses on delivering advanced device technologies, enabling terabit per second transmission speeds, supporting network densification, and leveraging smart technologies for sensing and supporting 6G use cases. Additionally, REASON develops solutions for network-edge automation and end-to-end service optimisation through cognitive orchestration tools. REASON addresses challenges in delivering end-to-end open network solutions, focusing on interoperability, agility, sustainability, and security. It considers next-generation multi-technology access, spectrum resource utilisation, multi-access control, intelligent edge computing, and AI/ML for network operations and service delivery. The project aims to define an architecture blueprint for open networks, positioning UK-native technologies and ensuring compliance with openness and interoperability principles.

The key technological objectives of REASON are:

1. Define a reference architecture for autonomous open networks.
2. Deliver multi-technology access network solutions, including new intelligent multi-technology access control.
3. Create a framework for embedded, trustworthy, and verified AI across the network.
4. Produce an intelligent edge solution incorporating distributed monitoring, offloading management, and joint optimisation of communication and computational resources.
5. Develop an end-to-end multi-domain autonomous and predictive service orchestration enabled by ML.
6. Implement a cybersecurity by design framework for open architectures.
7. Propose native energy consumption optimisation at the system level.

Driven by its ambitious KPIs and emerging standards, REASON targets aggregate data rates, network densification, ultra-low latency, and energy efficiency. It introduces advanced network sensing, security, resilience, and energy efficiency across all architectural elements. The project's major technological components are addressed through closely interrelated work packages. The REASON architecture is validated using simulation tools and testbeds such as JOINER, Adastral Park/BT, and SONIC Labs. The End-to-End open network architecture of REASON is shown in Figure 2-3.

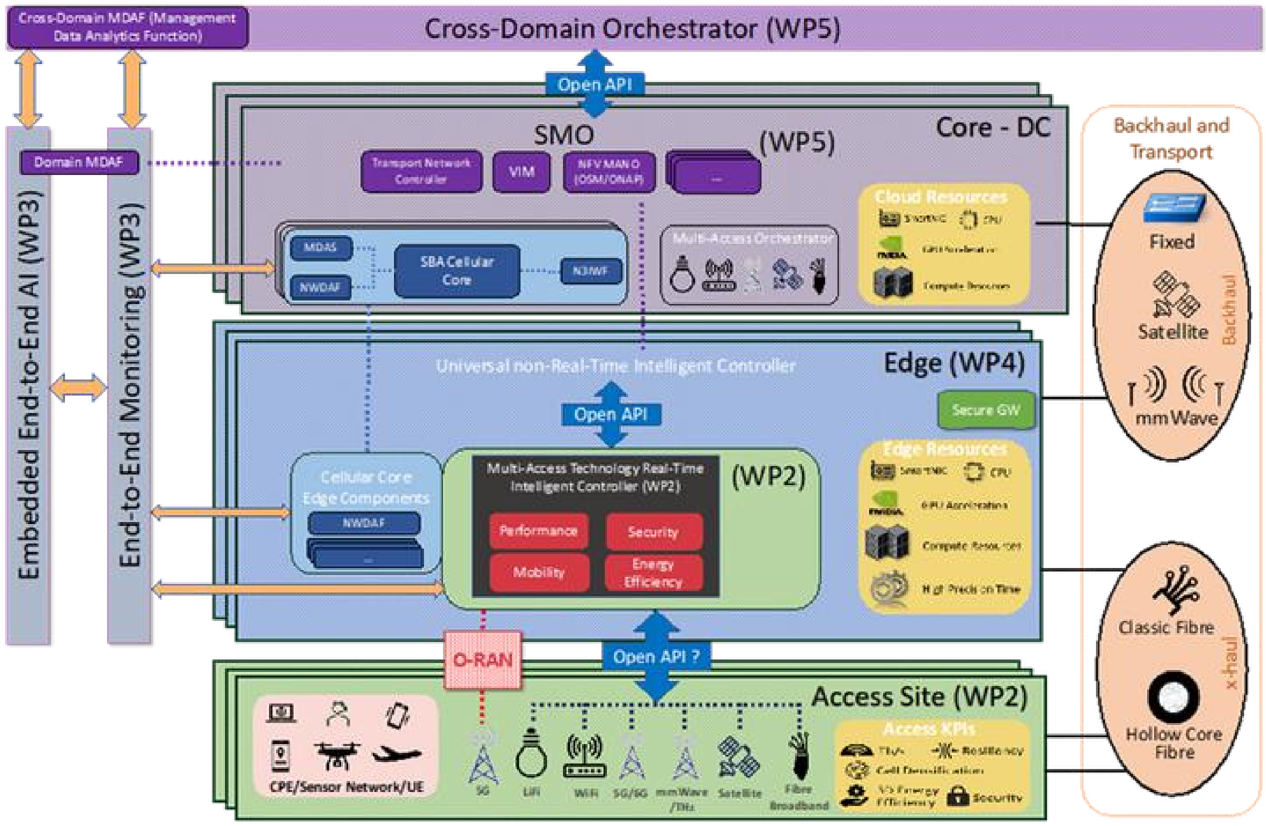


Figure 2-5 REASON Project's open network architecture

2.2.3/ YO-RAN

YO-RAN addresses the development of Neutral Host Networks (NHNs) utilising Open RAN technology across the entire protocol stack. Its primary focus is on deploying 5G standalone network infrastructure in both urban and rural areas, each presenting unique challenges. Urban areas require dense network infrastructure to meet capacity and latency needs, while rural areas demand infrastructure to serve limited users.

NHNs offer a solution by allowing operators to utilise necessary infrastructure from a neutral host while maintaining visibility and control over user experience. Open RAN's open interfaces facilitate this requirement, enabling neutral hosts to manage multiple RAN components virtually, catering to various operators. However, the lack of commercially available low-cost, configurable O-RUs and efficient fronthaul interfaces poses challenges.

The key technology objectives include:

1. Development of O-RUs (Open Radio Units), O-DUs (Open Distributed Units), O-CUs (Open Centralised Units), and the RAN Intelligent Controller (RIC).
2. Creation of configurable, low-cost, multiband O-RUs capable of operating in N78 (public) and N77 (private) bands. These O-RUs should have flexible, wide/multi-band capabilities.
3. Optimisation of the fronthaul transport, focusing on eCPRI (enhanced Common Public Radio Interface) for efficient data transport between O-RU and O-DU.
4. Implementation of AI and ML capabilities in the RIC for intelligent resource allocation and network slice management in NHNs.
5. Addressing security and integrity challenges in open and disaggregated networks, developing guidelines and practices for secure NHN operations.

The YO-RAN consortium, led by the University of York, comprises universities, vendors, and network operators with expertise in Open RAN technologies. Partners contribute to various aspects such as fronthaul development, RIC, security solutions, and network operator roles. YO-RAN focuses on developing Open RAN network architectures including O-RUs, O-DUs, O-CUs, RICs, and core networks, along with fronthaul connectivity. It aims to develop flexible O-RUs capable of operating in diverse frequency bands, with prototypes evaluated on field trial testbeds. Fronthaul transport utilises eCPRI for efficient data transmission, with optimisations for NHNs.

The project comprises six work packages (WPs), covering areas like O-RU development, fronthaul connectivity, RIC development, security, integration, and field trials. These WPs address key aspects of Open RAN technology, aiming to develop viable solutions for commercialisation and standardisation. Looking ahead to 6G, YO-RAN explores opportunities for Open RAN technology. With 6G's focus on multiple frequency bands, including higher bands, smaller cell radio and increased indoor deployments are anticipated. Cell-free RAN architectures based on CFmMIMO are investigated for improved system capacity and efficiency. Additionally, extending Open RAN concepts to non-terrestrial networks and advancing RIC functionalities are areas of interest for 6G deployment.

2.3/ Other Major R&I Programmes Future Networks

Fibre optics research has seen significant advancements in recent years, largely originating from work in the UK. The Airguide Photonics Programme Grant[10], led by the Optoelectronics Research Centre at the University of Southampton, has focused on exploring hollow-core optical fibres and their applications. The project has made strides in improving antiresonant nodeless fibres, enabling light to travel across a wide optical bandwidth with losses comparable to conventional solid-core silica fibres. This advancement offers benefits such as reduced latency during signal transmission and the elimination of optical nonlinear effects, which can impede optical transmission. In addition to hollow-core fibre technology, the programme has developed optical fibre amplifiers, taking advantage of broadband transmission mediums. Furthermore, it has showcased new system applications, demonstrating the potential of these technologies. This progress has led to the emergence of Lumenisity Ltd., a start-up at the University of Southampton, subsequently acquired by Microsoft Azure in 2022.

Another significant development is the QUDOS Programme Grant[11], which demonstrated the integration of telecommunications wavelength lasers directly onto silicon substrates. This initiative, involving teams from multiple universities and industrial partners, aims to achieve the integration of all photonic circuit functions on silicon, reducing costs and enabling miniaturisation in communication systems. Supporting these efforts are the Innovation and Knowledge Centres (IKCs)[12] established under the UK Government's National Semiconductor Strategy. These centres, located at the Universities of Bristol and Southampton, foster collaboration between research and entrepreneurial activities in compound semiconductors and silicon photonics.

The TeraCom Programme Grant[13], led by the University of Leeds, focuses on developing wireless communication systems operating at higher carrier frequencies, significantly increasing data rates. Meanwhile, the TRANSNET Programme Grant[14] aims to introduce intelligence in optical communication systems, developing adaptable optical transceivers and applying machine learning techniques to generate new network architectures. The Programme Grant TRANSNET (2018-2024) and its predecessor, UNLOC (2012-2018), are major research programmes devoted to transforming optical networks for the cloud and unlocking the capacity of optical communications. Led by UCL, and in collaboration with Aston University and Cambridge University, as well as some 28 industrial and academic partners, EPSRC-funded TRANSNET is focused on the use of AI/machine learning to develop adaptive optical networks for the cloud.

[10] UKRI AirGuide Photonics
[11] UKRI, QUantum Dot On Silicon systems for communications, information processing and sensing (QUDOS)
[12] Gov.uk, Press Release: UK research investment to boost UK semiconductor industry
[13] UKRI, Terahertz frequency devices and systems for ultrahigh capacity wireless communications
[14] UKRI, Transforming networks - building an intelligent optical infrastructure (TRANSNET)

This programme has been essential in producing a new generation of research engineers with skills to develop next-generation optical networks as well as numerous innovations and world-records in optical networks and systems research.

The programme has led to a spin out, Oriole Networks amongst its many outputs. These endeavours are supported by the National Dark Fibre Facility[15], a network linking leading academic institutions and telecommunications hubs worldwide. This infrastructure enables research in real-world conditions, fostering collaboration and innovation within the research community.

The National 6G Radio Systems Facility (N6GRSF)[16], hosted by the University of Sheffield, provides a comprehensive suite of test and measurement equipment and software configured as an instrumented software-defined-radio platform to enable research into sub-THz radio systems for 6G networks. The facility consists of advanced signal generation and capture instruments with multiple over-the-air radio paths covering from DC to 220 GHz. The facility is ideal for researching and developing waveforms, baseband signal processing, RF signal processing, RF circuits and antennas for 6G radio systems. As a small research facility founded by an EPSRC Strategic Equipment grant, both universities and industry can use the facility as a service to carryout research and development work.

[15] National Dark Fibre Facility
[16] UKRI, 6G Sub-Terahertz Software Defined Radio Testbed

Global R&I Programmes

3/ Global R&I Programs in Future Networks

3.1/ The European Union

The EU vision is that 6G will be a significant step beyond the 5G development. From 2030 onwards, 6G networks aim to support billions of things (e.g., vehicles, robots, drones, sensors, etc.) and humans. These end users will generate Zettabytes of digital data.

More challenging applications than today, such as holographic telepresence and immersive communications are envisaged, which result in far more stringent requirements. 6G will be a self-contained ecosystem of artificial intelligence, progressively evolving from being human-centric to human and machine-centric. With the connectivity continuum, 6G will bring near instant and unrestricted complete wireless connectivity. The convergence of connectivity, robotics, cloud, and secure and trustworthy commerce enables enterprises to change radically their operation.

In November 2021, in response to this vision, a huge collaborative research program called Smart Networks and Services Joint Undertaking (SNS JU) was launched to address all relevant research areas towards developing 6G systems[17]. The SNS JU[18] is a Partnership of the European Commission (public side) and the 6G Smart Networks and Services Industry Association (6G-IA). 6G-IA is the voice of the European Industry and research for next-generation networks and services and has 310 members. The SNS JU provides a long-term commitment of the public and private sides for 2021-27. The SNS JU is jointly funded by the European Union (EU) and the private sector (the 6G-IA members) with a total budget of at least € 1.8 billion. The EU contribution is € 900 million and will be matched by at least the same amount by the private side. Public and private side are closely cooperating. In the SNS JU Governing Board, decisions on strategic roadmap and orientation are taken jointly. The SNS JU provides financial support through research and innovation grants to participants in open and competitive calls for proposals.

[17] European Union: Council Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU) No 561/2014 and (EU) No 642/2014
[18] SNS JU

EU Member States are contributing to the JU in a consultancy role in a States Representatives Group to identify synergies with national programmes on piloting and deployment programs, consultation and to provide strategic guidance.

In addition, a Stakeholders Group[19] as an advisory body is established for cooperation with vertical industry sectors as target application domains for 6G systems. International partnerships in mutually relevant domains with counterparts in all global regions for long-term collaborative cross-roadmaps are an essential means for international consensus building in the research phase to contribute to globally accepted standards.

Figure 3-1 shows the strategic objectives, which are based on the three pillars:

- Ensure European leadership for 6G Smart Networks and Services
- Improve digital industries' operation
- Address societal needs and policy objectives.

Figure 3-1 SNS JU strategic objectives

These objectives are following societal, policy, and business drivers for 6G (Figure 3-2) in a human-centric approach[20], and meeting relevant UN Sustainable Development Goals[21].

The research agenda and the work program of the SNS JU are based on a 6G vision, which was developed by 6G-IA and the Strategic Research and Innovation Agenda (SRIA) of NetworldEurope Technology Platform[22], which get updated bi-annually. The EU 6G vision follows overall goals and "stretched technical KPIs (as compared with 5G) shown in Figure 3-4[23], and these have contributed on the globally agreed set of 6G KPIs by the ITU-R (International Telecommunication Union – Radio Sector).

[20] 6G-IA: European Vision for the 6G Network Ecosystem. 2021, DOI: 10.5281/zenodo.5007671.-IA: European Vision for the 6G Network Ecosystem. 2021, DOI: 10.5281/zenodo.5007671
[21] United Nations: Sustainable Development Goals
[22] NetworldEurope Technology Platform
[23] Ömer Bulakçı (ed.), Xi Li (ed.), Marco Gramaglia (ed.), Anastasius Gavras (ed.), Mikko Uusitalo (ed.), Patrik Rugeland (ed.), Mauro Boldi (ed.) (2023), "Towards Sustainable and Trustworthy 6G: Challenges, Enablers, and Architectural Design", Boston-Delft: now publishers

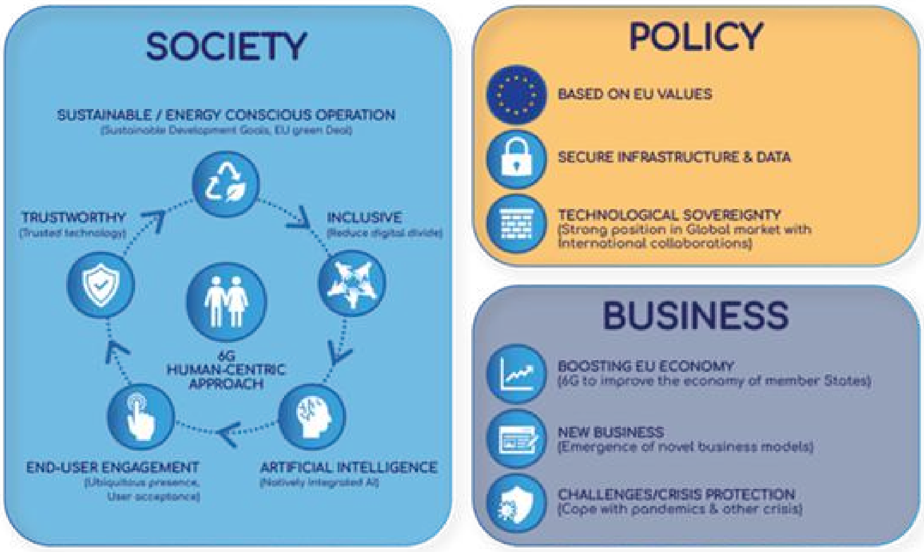


Figure 3-2 Societal, policy and business drivers for 6G according to SNS JU

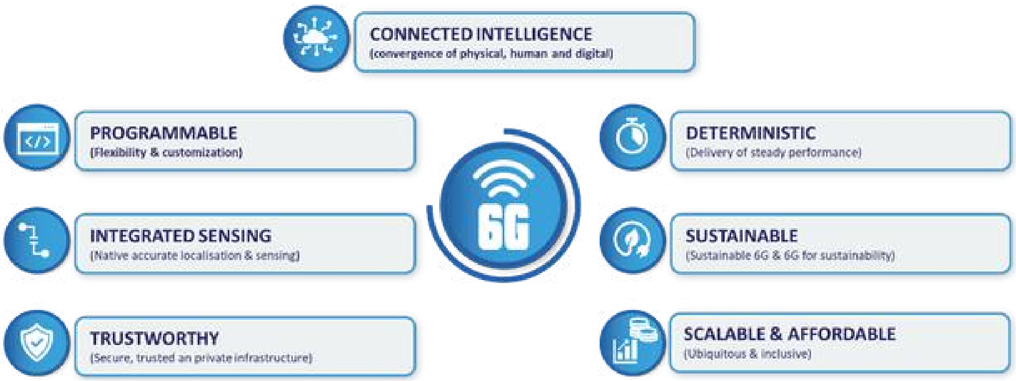


Figure 3-3 Main Goals of 6G according to SNS JU

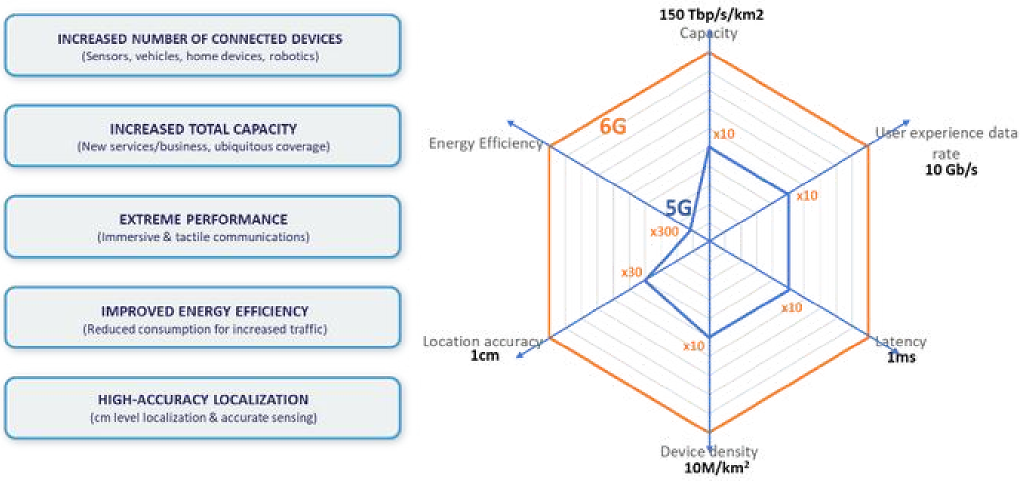


Figure 3-4 Stretching 5G KPIs towards 6G in SNS JU

The overall research program is addressing 12 main areas and is structured in three phases, as shown in Figure 3-6 SNS JU roadmap, 63 projects have already been launched, with a funding budget of about € 400 M. 16 Additional projects will start in 2025 with a funding budget of around € 130 M.

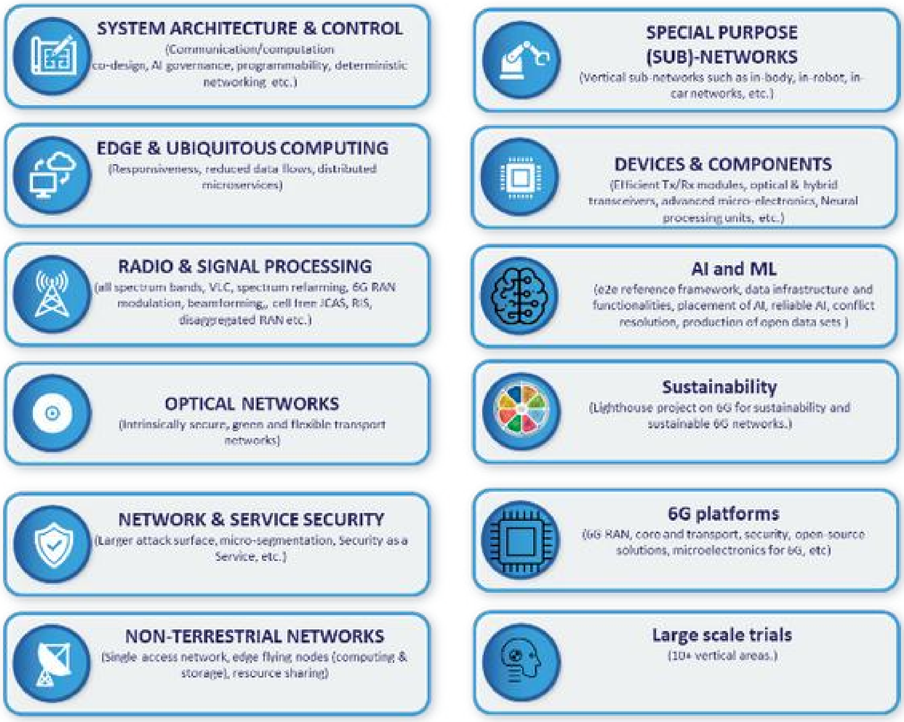


Figure 3-5 Main 6G research areas in SNS JU

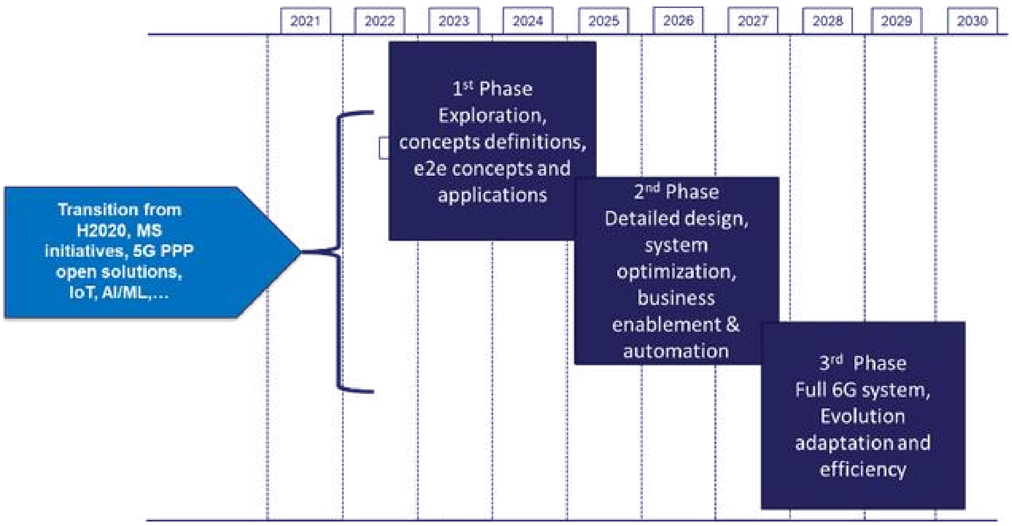


Figure 3-6 SNS JU roadmap

The SNS JU mobilised the research community with several hundred involved organisations in launched, and upcoming, projects. The SNS JU is supporting an extensive research agenda in collaborative research projects, which are contributing to global developments in international standardisation and other international industry fora.

The UK agreed a deal to associate to Horizon Europe on 7 September 2023. UK researchers can now apply for Horizon Europe funding including 6G SNS calls, a successful UK applicants will be covered through the UK's association (or through the guarantee) for the remainder of the programme. Furthermore, several UK universities and research entities are member of the 6GIA and NetWorld Europe, and through their membership, can influence future orientation of the programme.

3.2/ The United States

The US government is building its position in the 6G race by making strategic alliances with other countries and regions (e.g. Europe, India, South Korea, Japan and the United Kingdom). However, a considerable part of the US 6G debate and its roadmap development relies heavily on a private sector-led effort. The Next G Alliance, a private sector partnership to advance North American 6G technology, comprises organisations and experts from industry, government and academia dealing with 6G. The alliance issues publications and reports on 6G, and among its goals is to 'develop a roadmap that will promote a vibrant marketplace for 6G introduction, adoption, and commercialisation with North American innovation in mind.

The RINGS (Resilient and Intelligent NextG Systems) Program is a major initiative by the National Science Foundation (NSF) to engage government, academic, and industry partners in a joint research program. This program seeks to accelerate research, drive innovation, and increase the competitiveness of the United States in NextG networking and computing technologies. The Innovate Beyond 5G (IB5G) program in the Office of the Under Secretary of Defence for Research and Engineering contributed $6 million toward the total of over $37 million awarded to 41 research projects.

RINGS seeks to address the growing demand for high-speed, reliable, and secure communication networks that can adapt to dynamic conditions and emerging challenges. This includes advancements in areas such as wireless communication, network architecture, spectrum utilisation, cybersecurity, and machine learning. The program encourages interdisciplinary collaboration among researchers from academia, industry, and government agencies to tackle fundamental research questions and technological barriers in building resilient and intelligent communication systems. It supports projects that explore innovative approaches, algorithms, protocols, and technologies to enhance the performance, efficiency, and robustness of future communication infrastructures. By investing in the RINGS program, NSF aims to accelerate the development and deployment of next-generation communication systems that can meet the evolving needs of society, facilitate economic growth, and support emerging applications such as Internet of Things (IoT), smart cities, connected vehicles, and augmented reality.

FABRIC, which stands for "Facility Architecture and Business Models for Research Infrastructure on Clouds," is a ground-breaking research program in the United States aimed at creating an advanced research infrastructure for networking and cloud computing[24]. The FABRIC project seeks to address the evolving needs of scientific research by providing a flexible and customisable platform for experimentation and innovation. It enables researchers to explore new networking architectures, protocols, and applications in a controlled environment. Key features of FABRIC include:

- Advanced Networking Capabilities: FABRIC offers high-speed, programmable networking infrastructure that allows researchers to create custom network topologies and experiment with novel networking protocols.
- Cloud Integration: The platform integrates with cloud computing resources, enabling researchers to seamlessly deploy and manage their experiments across distributed computing environments.
- Customisable Experimentation: Researchers have full control over their experiments, allowing them to configure the network, deploy applications, and collect data according to their specific requirements.
- Scalability and Performance: FABRIC is designed to scale to support large-scale experiments and accommodate the growing demands of scientific research.
- Open Architecture: The FABRIC platform is built on open standards and encourages collaboration among researchers, enabling the development of new technologies and solutions.

[24] Portal Fabric Testbed

3.3/ China

China's 14th Five-Year Plan (2021-2025) aims at strengthening research on new 6G network infrastructure as well as clarifying its technology requirements. In addition, the government selected 6G as a 2023 top priority in its annual state-of-the-year work conference and will speed up the R&D for this technology. Some sources claim that China accounts for nearly half of 6G-related patent applications in the world. In the recently published 'Three-Year Action Plan for the Industrial Innovation and Development of the Metaverse (2023-2025)', 6G is mentioned as one of the key technologies needed for the creation of a Chinese metaverse. China's IMT-2030 (6G) Promotion Group[25], representing the flagship platform in China promoting 6G and international cooperation, published a report according to which 6G will also provide efficient support for AI services as well as for large-scale AI deployments in various industries. China began research on 6G as early as 2018 and formed the IMT-2030 (6G) Promotion Group anticipating that 6G would be commercialised around 2030. This was the basis for a two-stage plan that seeks commercial use of 6G by 2030. The first phase of the plan (2018-2025), underway now, launched research on the need for a 6G vision, research on and verification of potential key 6G technologies, and design and verification of a 6G system concept. The second phase of the plan (2026-2030) will formulate 6G standards, launch product development and industry promotion, and cultivate commercial use of 6G and the development of 6G applications.

3.4/ India

The Bharat 6G Vision[26], initiated by the Prime Minister Modi on March 23, 2023, articulates India's aspiration to lead in the design, development, and deployment of 6G technology by 2030. Anchored in the principles of Affordability, Sustainability, and Ubiquity, this vision positions India as a global frontrunner in delivering advanced yet economically viable telecom solutions that contribute to broader global welfare. India's commitment to 6G transcends mere contributions to global standards.

The government aims to secure at least 10% of global Intellectual Property Rights (IPR) in 6G technology, with active involvement from Indian researchers in shaping the 6G vision within ITU, 3GPP, and TSDSI. Government initiatives, including support for research and development (R&D), promotion of domestic manufacturing, and the launch of programs such as the Production-Linked Incentive (PLI) and the India Semiconductor Mission, underscore India's dedication to fostering innovation and bolstering self-reliance in the telecom sector. ITU Timelines and R&D Priorities

[25] The IMT-2030 Introduction
[26] The Bharat 6G Vision Statement

The endorsement of the draft recommendation during the June 2023 meeting sets the stage for the development of IMT-2030. Subsequently, the Radiocommunication Assembly 2023 (RA-23) ratified revisions and established the nomenclature "IMT-2030," along with pertinent principles. The forthcoming phase (2024-2027) will concentrate on delineating requirements and assessment criteria for potential radio interface technologies (RIT) for IMT-2030.

India released its 'Bharat 6G Vision' in March 2023. The government envisages India as a front-line contributor in design, development, and deployment of 6G technology by 2030. The proposal aims to 'design, develop and deploy 6G network technologies that provide ubiquitous, intelligent and secure connectivity for high quality living experience for the world'. According to the proposal, a total pool of INR10 000 crore (£0.94 billion) – raised through instruments such as loans, grants and venture capital funds) is expected to be invested over the next 10 years in R&D projects developing India's 6G ecosystem. India has already secured around 200 patents on 6G technology through industrial and academic collaboration with the support of the Department of Telecommunications. Wireless communications R&D in India receives funding from three agencies: the Ministry of Electronics and Information Technology (Meity), the Department of Telecommunications (DOT), including its R&D arm CDOT, and the Department of Science and Technology (DST). These agencies sponsor both public and private entities to conduct wireless R&D across various domains, including next generation analogue and digital electronics, communication systems, and standards development. The following elucidates the details of existing R&D funding programs in India:

- Meity: The cCCBT R&D group of Meity is tasked with:
  - Conducting R&D in Convergence, Communications & Broadband Technologies, and Strategic Electronics. These domains are pivotal for economic growth and infrastructure development, fostering innovation and indigenous technology advancement.
  - Fostering R&D initiatives in emerging areas such as Next Generation Networks (NGN), Massive MIMO, Software Defined Radio (SDR), Software Defined Networks (SDN), Network Function Virtualisation (NFV), Cognitive Radio, Heterogeneous Wireless Networks, 5G and beyond, 6G, among others.
  - Encouraging the creation of intellectual property (IP) leading to patents, innovative algorithm design, and prototype development aligned with the 'Make in India' and 'Digital India' initiatives.
  - Inviting project proposals in the thrust areas with a focus on innovation and indigenous technology development for potential commercialisation.

- TTDF by DOT: The Telecom Technology Development Fund (TTDF) Scheme targets domestic companies and institutions engaged in telecommunication product and solution design, development, and commercialisation to foster affordable broadband and mobile services in India. Allocation of 5% of annual collections from the Universal Service Obligation Fund (USOF) is earmarked for funding R&D in the telecom sector, prioritising commercialisation and adoption of developed technologies and solutions. The scheme aims to induce new technology developments in the Indian telecom sector through pilots, trials, and technology demonstrations, particularly in rural and remote areas. The scheme endeavours to bridge the digital divide by:
  - Promoting technology ownership and indigenous manufacturing.
  - Reducing import dependency and facilitating export opportunities.
  - Facilitating proliferation of next-generation telecom technologies in rural and remote areas.
  - Fostering a culture of technology co-creation and co-innovation.
  - Promoting the ecosystem for research, design, prototyping, development, and commercialisation of telecom products, end-to-end solutions, use cases, pilots, among others.
  - Establishing relevant standards to meet national requirements and enabling their standardisation in international bodies.
  - Creating synergies among academia, research institutes, start-ups, and industry for capacity building and telecom ecosystem development.
  - Bridging the gap between R&D and commercialisation of products and solutions.
  - Enabling proliferation of affordable broadband and mobile services through technology demonstration, product integration, pilots, and field trials.

3.5/ Japan

Japan issued its roadmap to 6G in June 2020, aiming to ensure its future international competitiveness in the sector. The 'Beyond 5G Promotion Strategy'[27] provides funding for 6G research through three programmes for a total budget of around £445 million. Furthermore, Japan and the US agreed to jointly invest US$4.5 billion (£3.6 billion) for the development of 6G technology. The Beyond 5G Promotion Consortium brings together representatives of Japanese industries and academic institutions to carry out research and development initiatives as well as advocating for 6G.

[27] The 'Beyond 5G Promotion Strategy'

The Innovative Optical and Wireless Network (IOWN) initiative in Japan was founded by Nippon Telegraph and Telephone Corporation (NTT) and is a major beyond- 5G initiative in Japan. Sony and Intel have been early supporters and contributors to the IOWN Global Forum, an organisation established to promote and advance the goals of the IOWN initiative. The forum aims to bring together a wide range of stakeholders from industry, academia, and government to collaborate on the development of new technologies and standards that will underpin the future digital infrastructure envisioned by IOWN. NTT announced IOWN as part of its vision for the next generation of network infrastructure, aiming to leverage advanced photonics and computing. The initiative seeks to address the growing demands for data communication capacity, speed, and energy efficiency, setting the stage for the development and deployment of 6G technologies.

The primary goal of IOWN is to create a highly flexible, efficient, and sustainable network infrastructure that can support the exponential growth of data traffic anticipated with the advent of 6G technologies. IOWN focuses on three main components:

1. All-Photonics Network (APN): APN seeks to leverage photonics technology to enhance data transmission speeds and capacity while reducing energy consumption. The approach is to replace electronic-based data transmission and processing with photonics.
2. Digital Twin Computing (DTC): DTC aim to enable advanced simulations, predictions, and decision-making processes by mirroring the physical world in real-time.
3. Cognitive Foundation (CF): CF proposes a flexible and intelligent infrastructure that can dynamically allocate and optimise resources based on demand, context, and application requirements.

IOWN's vision is underpinned by several key technological innovations:

- Photonics-based communication: Leveraging light for data transmission and processing, offering potentially limitless bandwidth and lower latency compared to current electronic systems.
- Edge computing: Distributing computing resources closer to the data sources to reduce latency and bandwidth needs, enhancing the performance of real-time applications.
- Artificial Intelligence (AI) and Machine Learning (ML): Integrating AI and ML for intelligent network management, resource allocation, and predictive maintenance, ensuring optimal network performance and reliability.

3.6/ Korea

Having been a key contributor to the development of 5G technology, South Korea is striving to position itself as a global leader in 6G technology by gaining dominance in international standards and patents. In February 2023, South Korea's Ministry of Science and ICT announced its K-Network 2030 strategy, with the goal to secure the best 6G technology in the world. Under this plan, the ministry will invest KRW625.3 billion (around £ 376 million) in R&D projects. South Korea will host the 'Pre-6G Vision Fest' in 2026, aiming to demonstrate the outcomes of the country's research in 6G and become a model country for global cooperation on 6G.

3.7/ Singapore

As part of the Research, Innovation and Enterprise plan, the Infocomm Media Development Authority (IMDA) and the National Research Foundation (NRF) in Singapore invested close to S$70M (£40.64M) in the Future Communications Research & Development Programme (FCP) to support "cutting-edge" communications and connectivity research. Comms & Connectivity (C2) is a critical technology that supports digital services. Four Autonomous Universities (AUs); namely the Singapore University of Technology and Design (SUTD), Singapore Institute of Technology (SIT), National University of Singapore (NUS), and Nanyang Technological University (NTU) are involved in the collaborative research and development by integrating existing technologies, leveraging them, and synergising all efforts to achieve the programme objectives.

SUTD is primed to accelerate the development of innovative technologies through the Future Communications Connectivity Lab (FCCLab) at SUTD. The software-defined, modular, reconfigurable R&D testbed will facilitate targeted research on future generations of communications technologies, as well as validate technologies and IPs developed in this programme.

The FCCLab facilitates research on future generations of communications technologies. It is an 5G-enabled open Radio Access Network (RAN) testbed that can provide a platform for testing and optimising performance of different functional blocks (including both hardware and software modules that follow open interface specifications). The testbed leverages open-source software and tools from the OpenAirInterface™ (OAI) Software Alliance (OSA) and uses cloud-native software-defined radio access network (RAN) to support scalability, flexibility, reliability/resiliency, and cost-effectiveness. The testbed takes reference to the O-RAN reference architecture to enable support of RAN virtualisation, and application of machine learning and artificial intelligence in RAN optimisation. The modular design of the testbed also provides flexibility of reconfiguring the RAN to different architectures.

Leveraging infrastructure of the FCCLab, SUTD has also established the Asia & Pacific Open Testing and Integration Centre (OTIC) in Singapore, which is the first OTIC in the Southeast Asia region. With the Asia & Pacific OTIC in Singapore, the FCP will look to advance Singapore's digital infrastructure capabilities and enable the next level of innovation in future communications and capabilities. It will establish a centre of excellence on the security, sustainability, and Artificial Intelligence/Machine Learning (AI/ML) aspects of Open RAN. It will also support holistic testing and integration activities for mobile networks and applications with both indoors and outdoors test environments. The Asia & Pacific OTIC in Singapore will serve as part of the global OTIC networks and establish itself as the Southeast Asia hub and gateway to the global Open RAN ecosystem.

SIT facilitates industry adoption of nascent technologies in 5G and future communications through the Future Communications Translation Lab (FCTLab). The FCTLab is set up to facilitate innovation and technology translation by providing the necessary testbed platforms and tools to industries. This will enable open innovation, learning, testing, and validating of technologies and use cases with industries and agencies.

3.8/ Elsewhere

6G Finland[28] is a coalition of Finnish 6G R&D organisations to advance the impact of Finnish 6G expertise globally, build new international partnerships, and intensify national 6G development efforts.

The German "Platform for Future Communication Technologies and 6G (6G Platform)" [29] project aims to contribute scientifically to 6G development and support the organisational processes necessary for implementing the German-European 6G program. This includes harmonising with international regulations, creating opportunities for societal and industrial participation, and ensuring broad input into 6G application and requirement identification.

The Kingdom of Saudi Arabia has recently announced the formation of a major technological and industrial alliance, including key players such as the Ministry of Communications and Information Technology, the Saudi Authority for Industrial Development and Innovation, Saudi Aramco, and the Saudi Telecommunications Company (STC). The alliance is focused on advancing research and development in 5G, 6G and ORAN[30].

[28] 6G Finland
[29] 6G-Platform.com
[30] Saudi Technical Alliance

The Brazil 6G Project[31] – an initiative supported by the National Institute of Telecommunications (INATEL), the Ministry of Technology and Innovation (MCTI), and the Rede Nacional de Ensino e Pesquisa (RNP), also known as the National Education and Research Network issued an action plan for Brazil's future 6G network development. In May 2023, Brazil announced investment of BRL60 million (£9.8 million) in the competence centre responsible for the development of 5G and 6G (INATEL).

Started in 2023 and funded by a consortium of telecom companies in Australia, the Telecom Research Unit at the University of Technology Sydney has a remit to uplift the telecommunications applied R&D capability for Australia and international companies. It drives innovation, applied research, and industry collaboration to benefit society and empower graduates with cutting-edge, industry-relevant skills and knowledge. The team together with industry are currently in the process of setting up a national centre for telecom resilience testing and capability enhancement in conjunction with industry partners to address national needs for emergency services calling / telecom connectivity during resilience events.

3.9/ Summary

The UK has historically played a significant role in shaping telecom advancements, though countries like Japan, South Korea, China, and the US dominate currently. Yet, there is an opportunity for the UK to contribute to early-stage research in the development of 6G networks. As 6G standards-setting begins, coordination and consolidation of research programs becomes vital. Coordinated research should go together with the protection of intellectual property, large-scale investments in telecom R&D in industry and SMEs, and collaboration on an international scale.

A key element of the UK's coordinated research on future networks, including 6G, is the Future Telecoms Research Hubs. These hubs receive funding and coordination through UKRI and EPSRC TMF for early-stage and applied research. They will engage with the telecoms industry, catapults, and international partners around three broad themes: (1) a network of networks; (2) wireless and wired systems and spectrum; (3) cloud and distributed computing. The platforms will draw together the existing portfolio of EPSRC investments in telecoms-related areas into a coordinated approach and will inform any future investment in mission-focussed research hubs. Additionally, FONRC has enabled universities to work with large RAN vendors, and other telecoms organisations, to conduct R&I to drive the openness and interoperability of future network architectures.

[31] Inatel: Brazil 6G

Global R&I Programmes

Across the globe consolidated regional and national research efforts in future networks are being funded, in support of underlying regional/national ambitions and strategies, including influencing the development of 6G standards, fostering national/regional telecom capability, ensuring smooth transitions from 5G to 6G, and in alignment with broader objectives, including technology sovereignty, sustainability, and economic growth.

However, there are significant variations across different regions and countries in the scope, priority areas, and funding models of these programs. The EU model, for example, promotes industry-led collaborative research through its 6G SNS JU, where large and (typically) industry-led consortia get funded, and strong industry participation is strongly promoted by offering up to 90% EU funding to involved companies. On the other hand, in the US model, the NSF funds academic research but do not directly fund industrial R&D.

There are also important variations in the timelines and longevity of funding research. In the EU model EURO 900m public funding for research and innovation in 6G technologies was secured upfront for the entire duration of Horizon Europe programme, covering the entire cycle of pre-standardisation research, contribution to development of standards, trials, and initial deployment. In other countries the focus, and hence duration of fundings has a focus on the pre-standardisation research.

To foster a robust and thriving UK ecosystem for the next and future generations of telecommunication networks, it's imperative to synchronise research efforts with the safeguarding of intellectual property rights, substantial investments in telecom R&D within industry, and fostering collaboration on a global scale. This integrated approach serves as the cornerstone for innovation, ensuring that breakthroughs in telecommunications technology are not only achieved but also effectively protected and shared. By harmonising these elements, we lay the groundwork for a flourishing environment wherein advancements propel the UK to the forefront of telecommunication innovation, benefiting generations to come.

SWOT

4/ SWOT Analysis & Recommendations

4.1/ SWOT Analysis

The SWOT analysis for the UK leadership in future networks is summarised in Figure 41 and elaborated as follows.

Figure 4-1 SWOT Analysis

Strengths

1/ Current Forefront Position: A study by Uswitch mobiles reveal that UK globally ranks fourth in readiness for 6G based on 6G patent filings and the median and maximum 5G download speeds[32]. Also, optical fibre networks in the UK are world-leading in their speed, throughput, low delay and high-security and resilience and are capable of delivering high capacity thereby meeting 6G requirements.

[32] Advanced-Television.com, Study: UK 4th most 6G ready country, Nov, 2023

2/ Government Funding: Progress has been made by the previous UK Government in the £70m Future Telecoms Mission Fund programme, which aims to further the goal of UK as a global leader in Future Telecoms, including 6G. This included £40m for Future Telecoms Research Hubs and JOINER and £28m for the SBRI Future Telecommunications Challenge.

3/ Strategic Objectives: The strategic objectives of UK's major R&I programmes in future networks, including skills development, environmental sustainability and aligning the interests with key stakeholders in telecommunications industry, clearly focus on ensuring that the UK remains at the forefront of global telecommunications innovation and competitiveness.

Weaknesses

1/ Fragmented R&I: Despite various initiatives, the UK's R&I efforts in 6G networks are currently fragmented.

2/ Lack of long-term commitment and an up-to-date strategic vision: The continuation of the committed funding for coordinated R&I in Future Networks is dependent on the Spending Review and finish in March 2025. Looking at timelines for 6G standards development, which are expected to kick off in 2025 and continue until 2028, and the longer-term commitments by, e.g. the EU[33] to support R&I in Future Networks, there is a danger that without guaranteeing long-term strategic funding beyond 2025, UK will be unable to leverage on its current investment to achieve a leadership position in Future Networks, including 6G. Coupled with this is that there has been little update on the 6G vision since the publication of UK Wireless Infrastructure Strategy in 2023.

3/ Limited contributions towards international standardisation: The UK's influence on 6G international standardisation is relatively limited compared to other countries at the forefront of 6G innovation. For example, the UK has filed a low number of patents for 6G technology in comparison to US and China[34]. This scenario highlights a very competitive and challenging situation for the UK to maintain relevance and influence in a rapidly evolving sector.

[33] Note that, e.g, The Horizon Europe framework runs until 2027, which means that R&I projects in future networks, including 6G will continue at least until 2029.
{34] Advanced-Television.com, Study: UK 4th most 6G ready country, Nov, 2023

4/ Skills gap: The current educational framework in telecom engineering is falling short in addressing the rapidly evolving technological landscape. There is a significant lack of investment in relevant MSc programs that focus on cutting-edge subjects like energy-efficient AI, quantum computing, and advanced communications. This gap in education is contributing to a broader STEM skills shortage, leaving crucial emerging areas without the necessary expertise to drive innovation and growth. Without targeted efforts to enhance and expand these specialized programs, the industry risks lagging in global technological advancements.

Opportunities

1/ Securing a leadership position: The UK has already established strong collaborative links with international parties involved in 6G research. It has been a significant participant in the EU's Horizon 2020. We now need to re-establish our leading position in Horizon Europe's 6G SNS programme, hence ceasing the which is a major opportunity for the UK to become a leader in future networks and 6G.

2/ Multidisciplinary approach: Promoting collaboration between telecoms and adjacent fields such as power and energy, AI, digital twins, quantum technologies, photonics and optical communications offers significant opportunities for innovation. Additionally, user psychology, futures methodology, financial and regulatory aspects of the technological advancements must also be considered in parallel.

3/ Developing a unified platform: Developing a unified national platform that integrates all research infrastructures can foster cohesive progress and collaboration across the telecoms sector. This platform would help streamline efforts, enhance resource allocation, and accelerate innovation by setting collaborative KPIs and would also avoid duplicated efforts caused by fragmented R&I.

Threats

1/ Economic uncertainty: The existing economic situation in the UK is unpredictable, and potential economic downturns or budgetary constraints could impact the availability of funds for long-term R&I programmes. It may negatively affect the current progress of UK towards future networks. In addition, it may also prevent global industries from research investments and collaborations. The theoretical research and experimental capabilities are required to be updated regularly to ensure world-leadership. Lack of guaranteed funding can result in challenges to maintain current UK's position.

2/ Global competition: Other leading economies such as the US, China, South Korea, and the EU are heavily investing in next-generation telecommunications. These countries have established comprehensive R&I programs. The UK's competitive edge can only be maintained with significant funding and infrastructure, strong collaborations with leading international participants and fast-paced research in both industry and academia.

3/ Talent drain: The UK must retain and attract top talent in telecommunications and related fields. However, economic crisis and competitive opportunities abroad can lead to a talent drain, where skilled researchers and professionals move to other countries for better prospects. Additionally, the UK's ability to attract international talent can be affected by immigration policies and global mobility trends.

4.2/ Recommendations

We recommend the following to strengthen the UK's position as a leader of future networks

1/ Long-term funding models for research in future networks

Long-term and sustained research funding is key for enabling an ambitious R&D agenda that leads to the development of cutting-edge technologies and the ability to both contribute to and influence global standards, ensuring the UK remains competitive on the global stage. Furthermore, long-term funding provides stability for researchers, encourages collaboration between academia and industry, and fosters the training of the next generation of telecommunications experts.

2/ Appropriate Funding Models to strengthen Industry-Academia Collaborations

Establish funding models that incentivise industry to engage in long-term low TRL collaborations with universities. This approach will help create a stronger ecosystem where industry partners adopt solutions jointly developed with universities and promote these solutions in international standardisation bodies as well as influential open networking and open source initiatives. The European Commission's shift in more favourable funding models for industry, which started from Horizon 2020 onwards, has successfully fostered strong long-term partnerships between universities, industry, and SMEs, resulting in a significant increase in standard contributions from the EU R&I projects. Appropriate funding and continuing development of technology exchange with leading industrial partners will allow to consolidate and enhance UK capabilities.

3/ Focus on filling skill gaps, including in non-traditional telecom engineering areas such as Software, AI, cybersecurity and optical networks in Telecom Education

The future of telecom networks and infrastructure will increasingly rely on software, AI, open platforms, and diversification. At the same time this trend leads to new challenges in security, resilience, trustworthiness and explainability (in the case of AI). Traditional telecom engineering education currently lacks a strong focus on these crucial skills, which are already high in demand but short supply in the wider industry. Newly funded multidisciplinary Centres for Doctoral Training (CDTs), new MSc programmes at universities, supported by industry, can offer accelerated routes to address the industry's needs in these areas. In the longer term, there is a need for the telecom engineering degrees and degree apprenticeships across the country to be updated to prepare the future engineers with skills in software engineering, AI, and security. Inclusive scholarships, mentorship programs, and marketing campaigns to raise awareness can attract diverse talent towards telecom research. It is also important to develop industrial sponsorships for home undergraduates to develop a cadre of qualified home students to prevent talent drain and skills gap.

4/ Promote Collaboration in R&I between Telecoms and adjacent disciplines, and specially AI, Quantum and Optical Communications to reflect emerging trends in global Telcom and leverage UK's unique strengths to secure UK's future leadership

Specially designed collaborative initiatives should be created to foster cross-disciplinary research and innovation across Telecoms, AI, Quantum and optical communication technologies. Major vertical sectors should also be considered in cross-disciplinary approaches and initiatives. For example, telemedicine, intelligent healthcare, automation industry and transportation systems can be revolutionised with the synergy of telecom and related technological advancement.

5/ Enhanced support for UK Universities for international collaborations to achieve scale, remain competitive and grow

Increase support for UK universities to achieve higher participation and success rates in Horizon Europe programs. Additionally, develop and promote bi-lateral collaboration opportunities with other key players, including the US, Japan, India, Korea, Canada, Australia, and Singapore as well as with emerging players in the Middle East, Africa and Latin America.

6/ Establish a Future Network Observatory

Create a future network R&I observatory to agree on the UK's ambition, roadmap and set of KPIs for success. This group will regularly review the UK's R&I performance in future networks and benchmark against other advanced economies and provide recommendations and actions.

7/ Federate the entire UK telecom research infrastructure into an end-to-end open platform system of systems to create both physical and digital experimental platform for future networks research

Learn and further expand infrastructures such as JOINER, SONIC, NDFF to create a system of systems platform with the capability to reflect the real-life scale and complexity of production-level telecommunication network and systems, hence providing a unique UK-based facility for academia and industry for large-scale experimentation and innovation, including in energy efficiency, network AI, resiliency, cybersecurity, convergence and interoperability. The federation should also ensure strong alliance with leading countries having shared principles to secure a firm position in the competitive landscape. In terms of physical platforms, optical networks are part of an essential infrastructure which needs development for future networks.

8/Provide stronger and consolidated support to academics for translation of research into patents, standards, start-ups, and university spin-offs

This should complement the “bottom-up” institutional support which is already available at universities, but significantly vary in scale and strength across UK’s Higher Education Sector. Entrepreneurial trainings and incubation programmes can also in help preventing talent drain and encourage researchers in the UK to contribute towards technological advancements as well as local economy.

Appendix A

List of Contributors

Members of the Working Group and International External Experts who have contributed to this White Paper are listed below in the order of the appearance of their first contribution to the paper. In addition to the individual contributors listed below, all other Working Group members have significantly contributed through extensive roundtable discussions and collaborative efforts.

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Appendix A

Version Control

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0.1	First draft ToC	Maziar Nekovee	WG	17/01/2024
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2.0	Second draft	Maziar Nekovee, Major revision to address UKTIN and WG comments	WG, UKTIN	15/05/2024
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4.0	Final report	Maziar Nekovee, Dimitra Simeonidou, Ferheen Ayaz & contributors in table, New Section on SWOT analysis to address DSIT comments		15/07/2024

Appendix B

List of Acronyms

6G Platform	Platform for Future Communication Technologies and 6G
6G-IA	6G Smart Networks and Services Industry Association
AI	Artificial Intelligence
APIs	Application Programming Interfaces
APN	All-Photonics Network
ASWG	Academics Strategy WG, Academic Future Networks Strategy Working Group
BBC	British Broadcasting Corporation
C2	Comms & Connectivity
CDTs	Centres for Doctoral Training
CF	Cognitive Foundation
CFmMIMO	Cell-Free Massive MIMO
CHEDDAR	The Communications Hub for Empowering Distributed Cloud Computing Applications and Research
CSC	CS Connected
DCIT	Centre for Defence Communications & Information Technology (DCIT)
DOT	Department of Telecommunications
DSIT	Department of Science, Innovation and Technology
DST	Department of Science and Technology
DTC	Digital Twin Computing
E2E	End to End
eCPRI	Enhanced Common Public Radio Interface
ECRs	Early Career Researchers
EPSRC	Engineering and Physical Sciences Research Council
ETSI	European Telecommunications Standards Institute
EU	European Union
FABRIC	Facility Architecture and Business Models for Research Infrastructure on Clouds
FCCLab	Future Communications Connectivity Lab
FCP	Future Communications Research & Development Programme
FCTLab	Future Communications Translation Lab
FONRC	Future Open Networks Research Challenge
Gbps	Gigabytes per Second
GEO	Geostationary Equatorial Orbit
HAPS	High Altitude Platforms
HASC	Hub on All-Spectrum connectivity

IB5G	Innovate Beyond 5G
IKCs	Innovation and Knowledge Centres
IMDA	Infocomm Media Development Authority
IMT-2030	IMT-2023 Framework
INATEL	National Institute of Telecommunications
IoT	Internet of Things
IOWN	Innovative Optical and Wireless Network
IPR	Intellectual Property Rights
ISAC	Integrated Sensing and Communication
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radio Sector
JOINER	Joint Open Infrastructure for Networks Research
KPIs	Key Performance Indicators
LEO	Low Earth Orbit
LiFi	Light Fidelity
MCTI	Ministry of Technology and Innovation
Meity	Ministry of Electronics and Information Technology
MEO	Medium Earth Orbit
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MNOs	Mobile Network Operators
MPs	Mini-Projects
N6GRSF	National 6G Radio Systems Facility
NDFF	National Dark Fibre Facility
NFV	Network Function Virtualisation
NGN	Next Generation Networks
NHNs	Neutral Host Networks
NoN	Network of Networks
NRF	National Research Foundation
NSF	National Science Foundation
NTNs	Non-terrestrial networks
NTT	Nippon Telegraph and Telephone Corporation
NTU	Nanyang Technological University
NUS	National University of Singapore
OAI	Open Air Interface TM
O-CUs	Open Centralised Units

O-DUs	Open Distributed Units
O-RAN	Open Radio Access Network
O-RUs	Open Radio Units
OSA	Software Alliance
OTIC	Open Testing and Integration Centre
PLI	Production-Linked Incentive
QUDOS	QUantum Dot On Silicon systems for communications, information processing and sensing
R&I	Research and Innovation
R&I&D	Research, Innovation, and Development
RAN	Radio Access Network
REASON	Realising Enabling Architectures and Solutions for Open Networks
RF	Radio Frequency
RIC	RAN Intelligent Controller
RIC	RAN Intelligent Controller
RINGS	Resilient and Intelligent NextG Systems
RIT	Radio Interface Technologies
RNP	Rede Nacional de Ensino e Pesquisa
RRI	Responsible Research and Innovation
S&T	Science and Technology
SDN	Software Defined Networks
SDO	Standards Development Organisations
SDR	Software Defined Radio
SIT	Singapore Institute of Technology
SMEs	Small Medium Enterprises
SNS JU	Smart Networks and Services Joint Undertaking
SONIC	SmartRAN Open Network Interoperability Centre
SRIA	Strategic Research and Innovation Agenda
STC	Saudi Telecommunications Company
SUTD	Singapore University of Technology and Design
SWOT	Strengths, Weaknesses, Opportunities and Threats
Tbps	Terrabyte Per Second
TMF	Technology Missions Fund
TNs	Terrestrial Networks
TRANSNET	Transforming networks - building an intelligent optical infrastructure
TRL	Technology Readiness Level

TSDSI	Telecommunications Standards Development Society, India
TTDF	Telecom Technology Development Fund
TUDOR	Towards Ubiquitous 3D Open Resilient Network
UAVs	Unmanned Aerial Vehicles
UEs	User Equipment
UK	United Kingdom
UKRI	UK Research and Innovation
UKTIN	UK Telecoms Innovation Network
US	United States
USOF	Universal Service Obligation Fund
WPs	Work Packages
YO-RAN	York Open-RAN