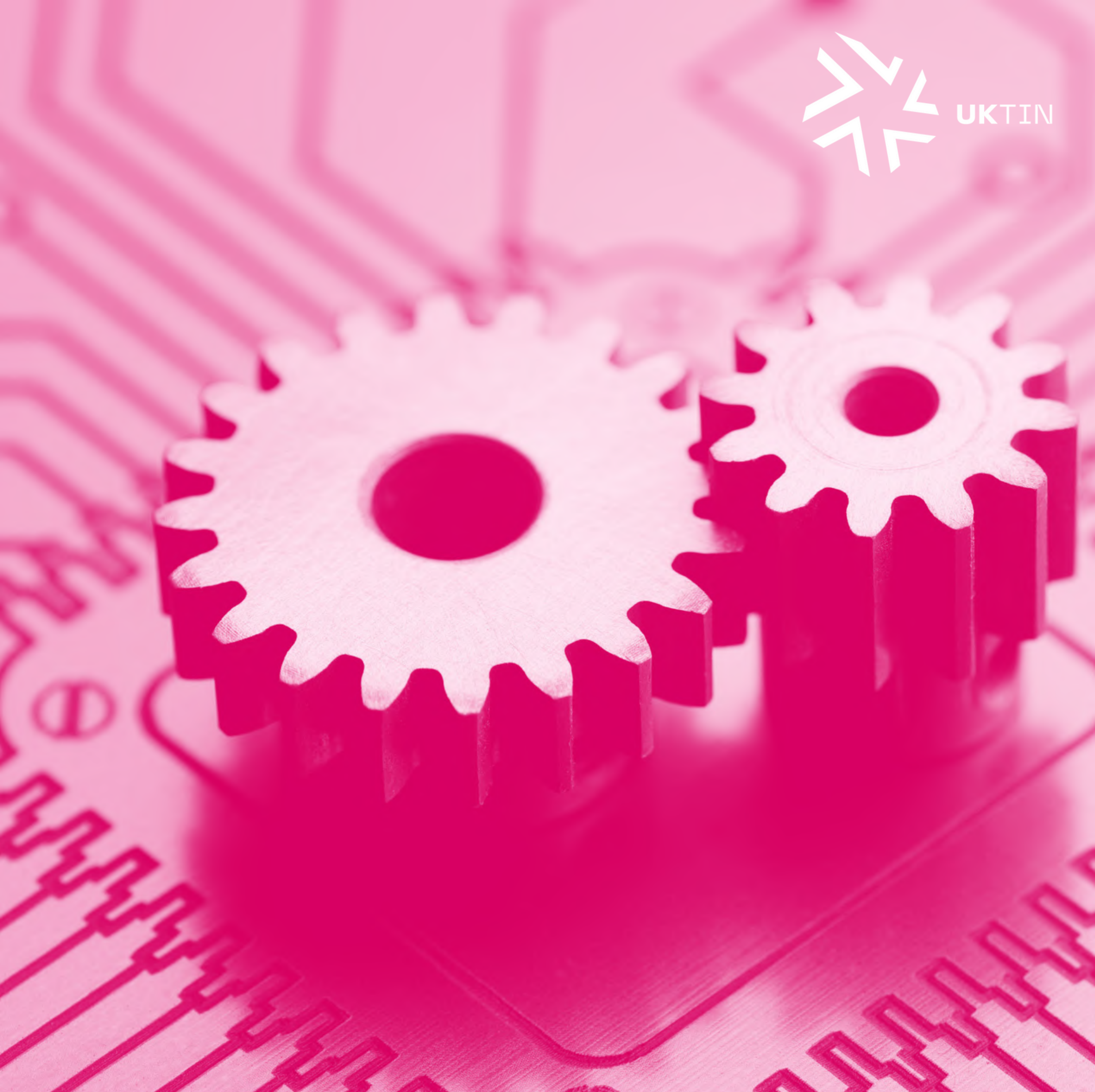
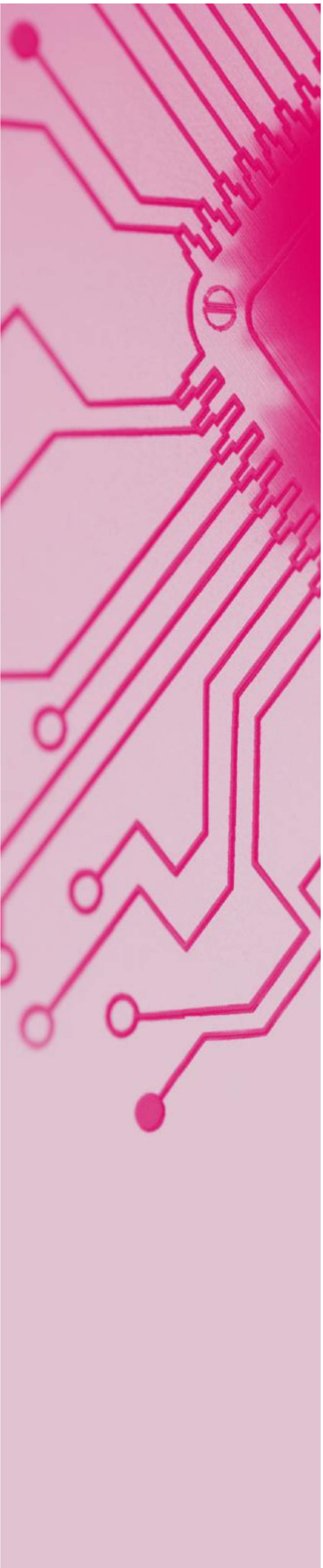


UK'S STRENGTHS IN FUTURE NETWORKS ACADEMIC RESEARCH

Strategic Report

This is a deliverable from the UKTIN Academic Strategy Group



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Introduction

The UK Telecoms Innovation Network (UKTIN) Future Networks Academic Strategy Group plays a pivotal role in shaping the future of telecommunications research in the UK. As the digital landscape evolves, the UK is poised to strengthen its leadership in next-generation communication technologies, fostering innovation and economic growth while ensuring resilience and security in digital infrastructure. This document serves as a strategic guide to identifying and prioritising promising research areas that will enable the UK to maintain and expand its global influence in telecommunications.

In our first whitepaper[1] the 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 compared this with the global R&I&D landscape, focusing primarily on Research and Innovation (R&I) aspects.

1.1/ Objectives

Building on our first paper, the primary aim of this second White Paper is to address the DSIT requirements/questions for the Group which focused around the following areas:

1. Identifying specific technologies and techniques within future networks where the UK has strong capabilities, including both government-funded and organically developing areas.
2. Strengthening links between adjacent fields, such as quantum and classical communications, to enhance the UK's competitive edge in the global research landscape.
3. Examining how business and innovation skills are being fostered within research communities, ensuring commercial viability alongside technical advancements.

Consequently, this White Paper aims to provide a structured and detailed analysis of the UK's strengths in future networks' academic research. It prioritises key areas where the UK has the potential to lead globally, with dedicated sections exploring the most promising research fields. Each research domain is further broken down to highlight specific technologies.

[1] Future Networks Academic Strategic Working Group First Report

The inclusion of adjacent research areas like Artificial Intelligence, Quantum Technologies, Semiconductor Technologies, and Edge-to-Cloud Computing recognises the necessity of cross-disciplinary collaboration, aligning with DSIT's emphasis on linking research communities to strengthen the UK's competitive position. The UK's telecom research community drives future network technologies, but commercial success requires business and entrepreneurial skills. Equipping researchers to commercialise innovations, forge industry partnerships, and stay competitive is essential. This white paper also explores some of the key initiatives supporting these capabilities.

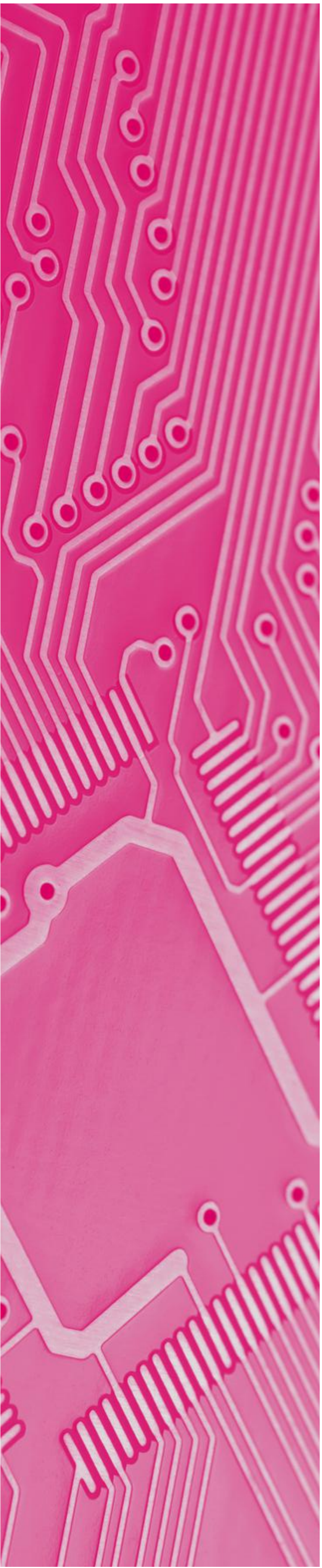
Finally, the summary and recommendations section provide a mechanism for prioritisation, helping to identify the most promising strands of research and emerging strengths.

We believe that this structured approach—supported by UK-specific research contributions, case studies and examples, ensures that the document serves as a strategic tool for guiding future investments in UK networks research.
We acknowledge that the list of research initiatives, universities and principal investigators that are mentioned in this report are a reflection of the current landscape which may evolve over time, and is by no means exhaustive.

1.2/ Organisation

This paper is organised as follows.

- Section 1 introduces the objectives and scope of the report, outlining the rationale behind identifying and prioritising research areas where the UK has the potential to lead globally.
- Section 2 focuses on the most promising research areas in future networks, covering specific technological domains such as Optical Wireless Communications (OWC), Spectrum Technologies, Wireless Communication, Non-Terrestrial Networks (NTN), and Optical Fibre Technologies. Each subsection provides an overview of the field, followed by an assessment of UK research strengths.
- Section 3 examines adjacent research areas that are crucial for strengthening the UK's position in future networks, including Artificial Intelligence, Formal Methods, Edge-to-Cloud Computing, Quantum Technologies, Semiconductor Technologies, and New Computing Paradigms. These areas are assessed for their contributions and linkages to future network advancements.
- Section 4 explores the role of business and entrepreneurial skills within research communities, emphasising the importance of fostering commercial acumen to translate research into market impact.
- Section 5 provides a summary of key findings and strategic recommendations, helping to prioritise areas for investment and collaboration.



Promising Research Areas in Future Networks for UK Leadership

2.1/ Optical Wireless Technologies

Optical Wireless Communications (OWC) utilise the optical spectrum, ranging from 100 nm Ultraviolet C (UVC) to 30 µm (far infrared), to transmit data wirelessly. This spectrum is three orders of magnitude larger than the entire radio frequency (RF) spectrum and remains unregulated. The recent Institute of Electrical and Electronical Engineers (IEEE) 802.11bb standard defines the near-infrared spectrum (800 nm to 1000 nm) for Light Fidelity (LiFi) systems. Despite over four decades of research, OWC remains an emerging technology with immense potential, requiring a well-defined taxonomy to highlight its capabilities and applications.

OWC can be categorised into three primary technologies: Free-Space Optical (FSO) Communications, Light Fidelity (LiFi), and Optical Camera Communications (OCC) (Figure 1). While RF-based wireless technologies have well-established markets (e.g., WiFi, Bluetooth, and Zigbee), OWC is still developing its market differentiation.

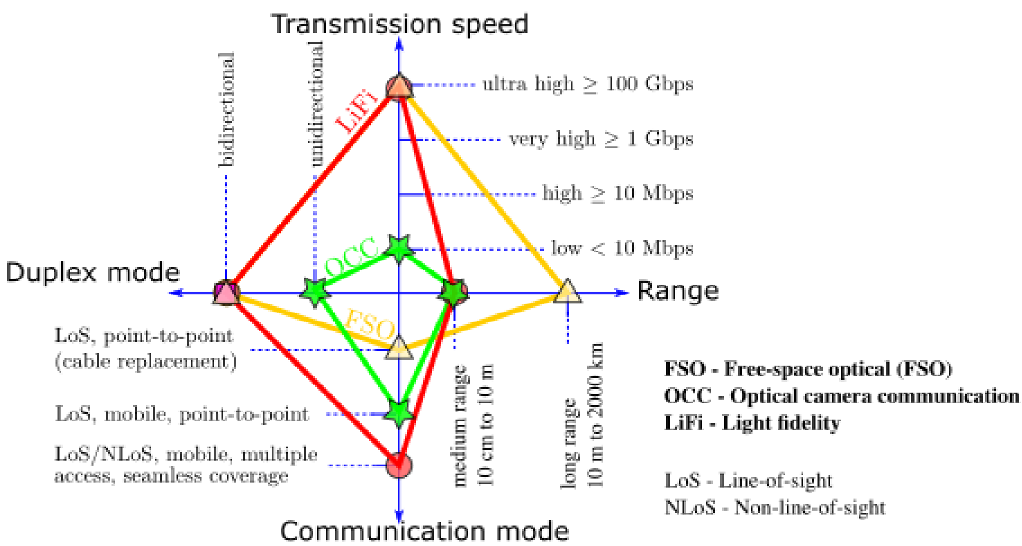


Figure 1: A taxonomy of optical wireless communication technologies and use cases.

2.1.1/ Free-space Optical Communication (FSO)

FSO is an outdoor, point-to-point, bi-directional communication technology that strictly requires line-of-sight (LoS) conditions. It is used primarily for connecting static or quasi-static endpoints and is categorised into terrestrial FSO (covering distances of tens of kilometres) and non-terrestrial FSO (operating over distances up to 35,000 km including GEO-LEO links). Applications include low Earth orbit (LEO) satellite-ground communications and inter-satellite links, such as those deployed in the Starlink network. FSO offers low size, weight and power (SWaP) transceiver technology which is important of satellite applications.

Key UK companies working on FSO technologies include QinetiQ, Astrolight, Cablefree, and Archangel Lightworks. Research focuses on:

- Developing reliable channel models supported by extensive testbeds.
- Enhancing FSO modems for improved range and data rates.
- Advancing pointing, acquisition, and tracking (PAT) systems for mobile platforms.
- Advancing new data encoding principles such, as orbital angular momentum (OAM)
- Exploring ultraviolet (UV) FSO for improved robustness against background radiation and misalignment (University of Cambridge and University of Strathclyde).
- Investigating quantum FSO systems.
- Developing underwater FSO technologies.

Institutions such as the University of Cambridge, University of Oxford, Fraunhofer UK, University of Strathclyde, Aston University, University of Glasgow, University College London, University of Southampton, Heriot-Watt University, University of Edinburgh, and Durham University are actively contributing to FSO research.

2.1.2/ Optical Camera Communication (OCC)

OCC leverages camera sensors, typically embedded in smartphones, to decode information from flickering light sources. This one-way communication technology does not require LoS and supports mobility. OCC functions similarly to electronic, location-specific barcodes emitted from visible light communication (VLC) sources such as LED bulbs. Applications include indoor navigation and advertising.

Companies such as IST Ltd (UK) have developed OCC products. UK research groups at University of Cambridge, University of Oxford, University of St. Andrews and Northumbria University are pioneering OCC advancements. Notable research contributions include:

- Exploiting the rolling shutter effect of CMOS cameras as a fundamental principle to achieve data rates with CMOS cameras that are substantially higher than the frame-rate of the camera (pureLiFi Ltd patent: EP2774287B1).
- Using OLED displays for high-speed device-to-device communication (University of St Andrews and University of Cambridge), achieving data rates of 4 Gbps.
- The Universities of Strathclyde and Edinburgh have demonstrated ultra-high framerate (>100 kfps) micro-light-emitting diode arrays suitable for both micro-display and high-speed data communication.

2.1.3/ Light Fidelity (LiFi)

LiFi is a wireless access technology designed for point-to-multipoint and multipoint-to-point communications, enabling high-speed, high-security indoor coverage. Unlike RF-based systems, LiFi does not penetrate walls, reducing interception risks and enhancing physical-layer security.

Key developments in LiFi include:

- Achieving user data rates exceeding 100 Gbps, enabling applications such as holographic 3D displays.
- Advancements in array of arrays (AoAs) for large coverage while maintaining high-speed connectivity (>10 Gbps)[2], developed under the EPSRC-funded Terabit Optical Wireless System (TOWS) program (King's College London, University of Cambridge, University of Edinburgh, and University of Bath).
- Oxford has developed beamsteering techniques that enable a direct interface between indoor fibre systems, such as passive optical networks, and short optical wireless links. Tb/s transmission combined with quantum key distribution (QKD) has been demonstrated.
- Industry leadership by pureLiFi, which chaired the IEEE 802.11bb research task group and spearheaded early LiFi adoption, generating multi-million-dollar revenues and job creation.
- Government and private sector investments positioning the UK as a global LiFi innovation hub.

[2] M. D. Soltani et al., "Terabit Indoor Laser-Based Wireless Communications: LiFi 2.0 For 6G," in IEEE Wireless Communications, vol. 30, no. 5, pp. 36-43, October 2023, doi: 10.1109/MWC.007.2300121.

2.1.4/ UK Research strengths in OWC

OWC plays a critical role in TITAN, the UK Telecoms Hub on the Network of Networks[3]. One of TITAN's six lighthouse areas focuses on integrating optical wireless technologies with traditional RF networks to enhance resilience and enable ubiquitous connectivity across terrestrial, aerial, and underwater domains. Ongoing UKRI-funded research projects include:

1. Integrated Sensing and Communications (University of Edinburgh) - Developing new techniques for sensing and communications integration in OWC networks.
2. Underwater Communications (University of Edinburgh) – Innovating new waveforms for optical wireless underwater communication.
3. Optical Reconfigurable Intelligent Surfaces (RIS) (University of Strathclyde, University of Edinburgh, University of Cambridge) – Advancing RIS applications in OWC.
4. Turbulence Mitigation in FSO (University of Southampton) – Utilising photonic lanterns for atmospheric turbulence mitigation.
5. Modelling and Network Slicing (King's College London) – Developing intelligent optical wireless network slicing and modelling tools.
6. Digital Modulation and Optical Metasurfaces (University of Cambridge with partners in Finland and Turkey) - Harnessing Orbital Angular Momentum (OAM) for high-speed data transmission.
7. High-Speed OWC Receivers with Energy Harvesting (University of Cambridge, Fraunhofer Institute for Solar Energy Systems) – Developing photovoltaic-based high-speed receivers.
8. Low-Cost OWC Receivers for Sensor Integration (University of Cambridge, University of St Andrews) - Exploring organic photovoltaics for cost-efficient sensor applications.
9. Low-Latency and High-Precision Positioning (University of Cambridge) – Aiming for 100 µs latency and 1 cm positioning accuracy for industrial applications.
10. Optical Wireless Networking (Brunel University) – Advancing optical wireless networking technologies.

These research initiatives underscore the transformative potential of the OWC technologies developed in the UK in shaping the future of global telecommunications, enhancing security, scalability, and high-speed connectivity across diverse environments.

[3] A. Krishnamoorthy, H. Safi, O. Younus, H. Kazemi, I. N. O. Osahon, M. Liu, Y. Liu, S. Babadi, R. Ahmad, A. Ihsan, B. Majlesein, Y. Huang, J. Herrnsdorf, S. Rajbhandari, J. McKendry, I. Tavakkolnia, H. Caglayan, H. Helmers, G. Turnbull, I. D. W. Samuel, M. Dawson, R. Schober and H. Haas, "Optical Wireless Communications: Enabling the Next Generation Network of Networks", arXiv, https://arxiv.org/abs/2412.16798

2.2/ Spectrum Technologies

The ever-increasing demand for wireless communications and the resulting 'spectrum crunch' derives the need for research into spectrum-related technologies. higher frequencies for wireless. Broadly, these fall into:

- Technologies to access new spectral regions. These include higher millimetre-wave and THz, which are being considered for 6G and optical frequency bands.
- Technologies for efficient use of spectrum. These includes efficient use of WiFi, cellular and other bands. It encompasses cognitive radio, spectrum sharing, dynamic spectrum access, interference management, schemes to enhance and exploit spectrum efficiency.
- Techniques to modify the electromagnetic propagation environment, such as Reconfigurable Intelligent Surfaces (RIS).

2.2.1/ UK research strengths in spectrum-related research

The UK has a range of strengths in spectrum related research (spectrum as considered here is concerned with free-space communications, as a separate section covers spectrum in the context of fibre-based communications). This section aims to summarise the activity and trends[4].

More research is required to raise the Technology Readiness Levels (TRL) of the technology, and to provide data for standards- underpinning activities required to lead to their widespread adoption.

Technologies for new spectrum

The UK has significant research strength in both the RF and optical regions of the spectrum. Wireless systems operating in the optical spectrum are detailed in Section 2.1 of this report. In the RF domain, the UK has strength in depth associated with the technologies required for systems operating in the mm and THz (broadly defined as >100GHz) bands. Centres of expertise include UCL, Cambridge, Durham, Lancaster, Leeds, Glasgow and Sheffield, with a range of current UKRI investments including programme grants and a 6G National testbed in Sheffield. In addition to applications in communications the underlying technologies and expertise supports areas such as medical imaging and chemical sensing.

The quest for higher bandwidth and data rates is driving exploration into new frequency bands and transmission technologies. Terahertz (THz) communication (0.1-10 THz) is a major area of focus, offering the potential for ultra-high bandwidth and specialised applications, while also incorporating sensing capabilities to create environment-aware systems.

[4] The UKTIN Discovery tool is used to help identify funded projects relevant to each broad area, which started within the last 5 years (i.e. from 01/01/2020)

Research at University College London, University of Leeds, University of Oxford, University of Cambridge, University of Birmingham, and Queen's University Belfast includes channel modelling, antenna and device design, signal processing, and security in the THz band. Underlying work on channel modelling and measurement is required for standardisation and deployment in the higher frequency bands. Belfast, Sheffield, Durham and others have extensive measurement and test infrastructure. This validates modelling and simulation activities, both at the channel level, and as inputs to network-oriented simulations.

Development of the necessary transmitter and receiver subsystems is an area of strength. The UK has expertise in photonic approaches to signal generation (including work at Cambridge, Southampton, UCL, Kings, and Glasgow), high speed electronics and semiconductors (see Section 3.5,) antenna design (with a broad range of expertise and funded work, including centres in Surrey, York, Glasgow, Queen Mary, Sheffield, Lancaster, Durham, see Section 2.3.1).

University of Strathclyde is engaged in developing techniques for measuring and monitoring the use of spectrum, particularly for identifying unallocated spectrum bands. This data is essential for building accurate models and training AI systems for dynamic spectrum sharing, a crucial aspect of ensuring efficient spectrum use in the future.

Efficient use of spectrum
The efficient use of spectrum encompasses work on dynamic spectrum sharing technologies, latterly using AI based techniques as well as design of spectrally efficient modulation, multiple access schemes, and interference management strategies with significant work at Imperial, Surrey, Southampton, and others. These are further discussed in Section 2.3. Dynamic spectrum sharing, latterly using AI based techniques, is being advanced at Bristol, Imperial, Sussex and others. Funding under the REASON project and the Future Telecommunications Hubs has enabled the development of an AI driven RIC (mATRIC), which controls access to spectrum using multiple interfaces. This has an associated digital twin, to enable training. Research on use of unallocated bands, including work on non 3GPP bands and sharing techniques are undertaken at the University of Strathclyde. Furthermore, measurement and monitoring of current spectrum use is of particular importance given the need for data to train AI models.

Techniques to modify the propagation environment
There is a range of work on modification of the RF, THz, and Optical environments, notably using Reflective Intelligent Surfaces (RIS) and Reconfigurable Intelligent Edges (RIE). RIS are large, ideally passive but can also be made active, surfaces that are embedded in the electromagnetic environment and reconfigured dynamically to shape or engineer the radio propagation and boost the performance of wireless systems (communications, sensing, power transfer, localisation, security, etc). They can also be embedded in transceiver architecture to enable advanced multi-antenna-like processing in the analogue domain, which is promising for next generation of ultra-massive MIMO. They are also envisaged as an underpinning technology to performance computation directly in the analogue domain, which presents a number of advantages over conventional digital signal processing in terms of energy efficiency and energy consumption. The primary function of a RIE is to overcome shadowing in radio environments. This can include mitigating the impact of high-rise buildings in cellular environments or reducing diffraction losses caused by wall corners within indoor environments. Like RIS, they are ideally passive structures, harnessing diffraction, or refraction to help 'bend' radio signals around obstacles to enhance network coverage. Active reconfigurability can be obtained by adjusting the refractive index of the constituent material for refractive RIEs or using tuneable electronics implemented on the diffractive RIE surface to dynamically steer the radio signal around the edge.

Work encompasses theory and demonstration, with early prototypes demonstrated at a number of frequencies. There is significant effort at several UK institutions including Queen's University Belfast, Glasgow, Imperial College, Surrey, and Sussex.

Industry involvement
Much of the work discussed above has been undertaken in collaboration with industry. Operators and end-users such as the Vodafone, BT, BBC and Meta support spectrum related activities, including both the research itself and its adoption into spectrum policy and standardisation. There are also a large number of collaborating companies researching and developing different aspects of the access technologies, including applications which extend outside of the civilian telecommunications domain (e.g. defence). These include companies such as Leonardo, BAE Systems, Airbus and QinetiQ, manufacturers such as Samsung, Ericsson, Nokia and Keysight and a large number of other vendors with interest in spectrum, including Real Wireless, Neutral wireless, Plextek, Toshiba, RALspace, Ran Semi and Viavi.

2.3/ Wireless Communication technologies

6G has set out to accomplish a broad range of goals, requiring novel architecture and broad range of wireless communication technologies. As with 5G, no single wireless technology will define 6G. The groundwork laid out in 5G will serve as a starting point for 6G. But because 6G will be a distinct new generation, there is also an opportunity to break with previous revisions and introduce new concepts. This section outlines some of the key research activities being undertaken within UK universities that are pushing the boundaries of wireless technology and helping to shape the future of wireless communication networks, including 6G and beyond. Time will tell which of these technologies become part of the standards and proceed to commercialisation.

2.3.1/ UK research strengths in wireless communication

Next generation radio network architectures
To meet the demands of future applications, researchers at several universities, including Queen's University Belfast, University of York, University of Edinburgh are rethinking traditional RAN network architectures. Cell-free massive Multiple Input, Multiple Output MIMO (Cell-Free MIMO) is emerging as a potential technology for 6G, eliminating cell boundaries by employing numerous distributed access points (APs) to serve users cooperatively. This paradigm shift promises significant improvements in spectrum efficiency and user experience (with potential user throughput exceeding 1 Gbps). Research in this area includes resource allocation, advanced transmission protocols and integration with technologies like RIS. In addition, the concept of Integrated Satellite-Terrestrial Networks (ISTN) is gaining traction, with work at Queen's University Belfast and University of Surrey aiming to provide seamless connectivity by integrating satellite, aerial, and terrestrial networks.

Advanced antenna systems
A cornerstone of future wireless systems lies in the development of sophisticated antenna technologies and innovative methods for manipulating the propagation of electromagnetic waves. Research at universities within the UK such as Queen's University Belfast, Imperial College London, University of Southampton, Queen Mary University of London, University of Surrey, University of Glasgow, and University of Sussex is focused on advanced antenna systems, including reconfigurable antennas, massive MIMO, holographic antennas, and extra-large massive MIMO (XL-MIMO).

These advancements are being coupled with novel propagation manipulating tools like reconfigurable intelligent surfaces (RIS), reconfigurable intelligent edges (RIE), and spatio-temporal modulated meta-media, including metamaterials, metasurfaces and metalines being developed at many of the same universities.

The goal is to achieve unprecedented control over wave propagation, eliminating deleterious channel effects, enhancing coverage, capacity, spectrum efficiency (targeting improvements of 5-10x compared to 5G) and energy efficiency (aiming for 10-100x improvement), and enabling functionalities such as precise beamforming and dynamic wavefront shaping.

New waveforms

New physical-layer waveforms are a topic of intense research in the development of each new generation of mobile communication standards. Orthogonal frequency-division multiplexing (OFDM) is the waveform used in 4G and 5G, but 6G may look to change that. While OFDM has advantages, the required signal flatness is hard to achieve in RF amplifiers for wider bandwidth signals, even with advanced digital predistortion (DPD) techniques. Developers have proposed wider bandwidth signals for frequencies above 50 GHz, and amplifier design at those frequencies is already a challenge without the flatness requirements of OFDM.

Aside from challenges with RF components, there are other reasons to believe that 6G will use new waveforms. Joint communications and sensing, for example, requires waveform modifications to accommodate communications signals and the signals required for sensing. Advances in AI and ML present an interesting opportunity to reconsider what a physical-layer waveform is at a fundamental level. Previous generations have been bound to use fixed waveforms and have focused on quadrature modulation schemes. AI- and ML-based physical layers could use an adaptive PHY with adaptive modulation that looks nothing like the quadrature modulation schemes communications engineers are familiar with, as is shown, e.g. in research at the University of Sussex’s 6G Lab[5] conducted in collaboration with Samsung[6].

Orthogonal Time Frequency Space (OTFS) modulation is being investigated at Queen’s University Belfast and the University of Southampton as a more reliable alternative to OFDM, particularly in high-mobility scenarios, with potential for integrated sensing and communications.

However, breaking away from OFDM waveforms will be a significant challenge in an industry that has perfected an OFDM-based supply chain capable of squeezing out high-performing components with high yields and minimal research and development investment required to implement new features. Therefore, it is more likely that new beyond-OFDM waveforms will be introduced in 6G evolution, alongside evolved versions of OFDM.

[5] 6g-lab.org
[6]D. Wu, M. Nekovee, Y. Wang, “Deep learning based autoencoder for m-user wireless interference channel physical layer design”, IEEE Access , 5 Oct 2020, 8:174679-174691.

Multiple access technologies
Candidate techniques such as Orthogonal Multiple Access (OMA), Spatial Division Multiple Access (SDMA), Non-Orthogonal Multiple Access (NOMA) and Rate-Splitting Multiple Access (RSMA) hold great promise in enhancing the transmission efficiency of next generation wireless networks across parameters such as spectrum efficiency, power consumption, latency, and user fairness.

New Multiple Access schemes, such as RSMA and NOMA, are being developed at Imperial College and used by Queen's University Belfast and others to allow for more users and functionalities to be served by a single resource. These technologies are also the focus of the newly established ETSI Industry Specification Group (ISG) on Multiple Access Techniques (MAT) for 6G, where UK academic and industry partners play a leading role[7].

Integrated sensing and communication (ISAC) and imaging
The convergence of communication and sensing is a defining trend in future wireless systems and is currently being investigated at several UK universities including University College London, Queen's University Belfast, University of Bristol, University of Sheffield, and Imperial College London, Sussex. Integrated Sensing and Communication (ISAC), also known as Joint Sensing and Communication (JSAC), aims to unify these functionalities. It will be a core part of 6G and beyond systems, enabling applications such as environmental monitoring, localisation, activity recognition, and vital sign monitoring through shared hardware and spectrum. This area also encompasses advanced electromagnetic imaging techniques, including computational imaging, compressive metasurfaces, and real-time algorithms for applications like through-wall imaging and direction-of-arrival estimation.

We note that ISAC technologies are the focus of an ETSI Industry Specification Group (ISG), where UK-based industry and academic institute have leadership roles[8].

Other enabling technologies
Advances in enabling technologies will be crucial for realising the vision of future wireless systems. Novel approaches to Wireless Power Transfer (WPT) are being developed at Queen's University Belfast and Imperial College London, and University of Sussex to provide convenient and efficient charging solutions, particularly for Internet of Things (IoT) devices and wireless charging of Electric Vehicles, drones and other mobile platforms, with research targeting power transfer efficiencies of 50% or more over distances of up to several metres.

[7] "ETSI Launches New Group on Multiple Access Techniques for 6G Networks", ETSI Press Release, Sophia Antipolis, France, 28 January 2025, https://www.etsi.org/newsroom/press-releases/2484-etsi-launches-new-group-on-multiple-access-techniques-for-6g-networks
[8] ETSI.org

2.4/ Non-terrestrial Networks (NTN)

The UK has established itself as a global leader in the research, development, and deployment of non-terrestrial networks (NTNs), reinforcing its position in the global communications ecosystem[9]. NTNs utilise satellite constellations, high-altitude platforms (HAPs), and airborne infrastructure to expand connectivity in underserved regions. The UK's investment in this sector underscores its commitment to addressing digital connectivity gaps and fostering global inclusivity.
Key industry players, including Starlink in the United States and leading UK-based firms Inmarsat (now part of Viasat), OneWeb (now part of Eutelsat), have contributed to advancing low Earth orbit (LEO) satellite constellations. These networks provide high-speed broadband in areas where terrestrial infrastructure is impractical or uneconomical. The UK's space sector is a major contributor to the national economy, accounting for 17.7% of GDP in 2020 and employing over 45,000 people, with projected revenues of £40 billion by 2030.[10,11]

2.4.1/ UK research strength in NTN

The UK enjoys a rich eco-system of academic engagement in NTN. In particular, high-profile EPSRC projects are and have been hosted at the University of Leeds on Terahertz frequency devices and systems, at Heriot-Watt University on satellite ground stations, at the University of Bath studying the ionospheric impacts on future satellite communications, and at the University of Kent on beam-steerable array antennas. This has been underpinned by the federated telecoms hubs, JOINER led by the University of Bristol, TITAN led by the University of Cambridge and CHEDDAR led by Imperial College London, which have supported a wide variety of NTN projects. These include the development of Doppler-resilient physical and upper-layer solutions, such as OTFS. Another cutting-edge TITAN solution is based on Affine Frequency Division Multiplexing referred to as AFDM, just to name a few. They require bespoke channel estimators, error correction codes and networking solutions.

UK universities—including Imperial College London, University of Surrey, the University of Leeds, and the University of Glasgow, University of Cranfield, as well as the TUDOR project—are engaged in NTN-related projects ranging from terahertz frequency systems and beam-steerable antennas to quantum-secure NTN-aided networks. The UK's ambition to develop a quantum internet, spearheaded by Heriot-Watt University, could revolutionise secure communications and national security infrastructure. The University of York has been applying wireless communications to HAPs since 1999, coordinating or being partners in numerous collaborative academic and industrial projects, worth around £3M, and is home. The university is home to the interdisciplinary Centre for High Altitude Platform Applications (CHAPA), which is pioneering technologies for wireless communications, environmental monitoring, and atmospheric science applications.

[9] UKTIN Future Capability Paper - Non-Terrestrial Networks, February 2024, available here.
[10] Health of the UK Space Industry Report 2022
[11] Unlocking Space for Investment - Business and Investor Pathway Programme Information

There are a number of successful spin-out companies from the NTN technology area in the UK. As an example, AccelerComm[12] was spun-out of the University of Southampton in 2016, based on its underpinning research on the practical implementation of high-performance error correction codes. Over the years, AccelerComm grew its portfolio of FPGA, ASIC and software IP solutions for wireless physical layer signal processing, which it licensed to various base station manufacturers, including satellite customers. Recognising the growing NTN opportunity, AccelerComm developed a complete physical layer for 5G New Radio NTN base stations. Uniquely, this solution is targeted at low-power, radiation tolerant FPGAs and embedded CPUs, which are suitable for deployment on a satellite. In 2023, Lockheed Martin integrated the AccelerComm physical layer IP into its TacSat LEO satellite. It is anticipated that when it launches later in 2025, TacSat will provide the world's first demonstration of a 5G New Radio base station in orbit, connecting to user devices on the ground. Since completing the integration with Lockheed Martin, AccelerComm has engaged widely across the NTN industry and is now developing physical layer IP for commercial scale deployments of direct to device and broadband 5G services.

2.5/ Optical Fibre Technologies and Optical Communication Systems

Optical fibre communications form the backbone of the internet’s remarkable growth and its transformative impact on society. Optical fibre systems and networks underpin the digital communications infrastructure and enable 5G/6G. The availability of ubiquitous, high-capacity, secure and resilient digital communications infrastructures is essential to the economic growth of all nations and represents a critical national infrastructure for the UK as well as underpinning virtually all services and other infrastructure such as NHS, transport, finance, energy and judiciary. Broadband infrastructure is considered of strategic priority to the UK, with significant investments driving network upgrades and initiatives, such as Project Gigabit, a £5 billion UK Government programme aiming at delivering fast, reliable gigabit-capable broadband to hard-to-reach communities. This complements the £15 billion investment from Openreach, predicted to help grow the UK economy with a £72bn productivity boost[13].

[12] Accelercomm.com
[13] Openreach News “We've reached our first 10 million homes and business with ultrafast, ultra-reliable Full Fibre broadband” March 2023

2.5.1/ UK's research strengths in optical fibre and optical communication systems

The UK has played a significant role in the development of optical fibres for communications. Nobel laureate Sir Charles Kao, through his pioneering work at STL in Harlow during the 1960s, established the use of fibre optics for communications with STL and the Post Office subsequently trialling the world's first fully deployed fibre optic link between Hitchin and Stevenage in 1977. From 1970s to early 2000s, UK led the world in the optical fibre fabrication and especially optical fibre communications systems research with research in industrial laboratories of BT in Martlesham, STL in Harlow, GEC Hirst Research Centre and Plessey developing key optical communications components, sub-systems and systems concepts, with BT the first operating company in the world to install optical fibre systems into its network! In the 1980s the discovery of erbium doped fibre as an amplification and the development of the erbium doped fibre amplifier (EDFA) medium at the University of Southampton eliminated propagation losses as a key limitation to optical transmission. This opened the wavelength domain in optical fibres to increase the potential bandwidth for transmission.

Whilst seen as an important research area, towards mid 1990s, financial pressures to key industry players led to a reduction to research investment in optical communications and key researchers and research activity moved to universities. Key researchers from BT moved to Aston University and focused on soliton transmission, building world leading research in this area, starting a company called Marconi Soltis. Polina Bayvel moved to UCL starting the Optical Networks Group, starting the first academic optical fibre systems group focusing on multiwavelength transmission, setting up the first multiwavelength systems and networks test-bed and developing the area of wavelength selective components, leading the world thinking on high-speed multiwavelength networks. In mid-2000s, many UK industrial labs closed down but the university groups developed into world leading forces to define the development of future optical communications and networks. While loss was no longer an issue, data rates were limited to channel distortions, but it was demonstrated a new receiver based on DSP and coherent detection could mitigate this with the first transatlantic distance reported by UCL in 2007. Subsequent developments allowed UCL achieve a record fibre capacity of 178 Tbit/s in 2020.

Throughout this period, the UK has led the world in research on novel fibre technologies, with pioneering early work on microstructured optical fibres carried out, both at Bath and Southampton. Research in fibre optics has seen significant advancement in recent years, driven by the ever-growing demand for increased communication network capacity.

This renewed focus has given rise to radically new fibre types, and highlights a shift that is taking place in the technologies underpinning network infrastructure. Research in fibres and amplifiers for space-division multiplexed (SDM) systems at Southampton led to the EU Horizon 2020 €0.5M Prize for high-speed optical transmission (2016), and the development of the lowest loss fibres ever made based on hollow-core fibre technology (also from Southampton, 2024). Subsequent breakthroughs, such as the deployment of multi-core fibre cables in undersea links and the integration of hollow-core fibres in data centre infrastructure mark transformative milestones and represent a departure from the long-standing reliance on standard silica single-mode fibres, which have been the industry standard for decades.

The legacy of research and innovation continues today and the UK remains a global leader in optical communication technologies and their integration into advanced systems. Fibre optic research is predominantly experimental and has flourished thanks to sustained investments both from UKRI and EU-funded projects. This support has enabled groups in UK universities, including Southampton, UCL, Cambridge, Aston, Bristol, Bath and Bangor to remain at the forefront of developments in fibre optic communications research. Major investments in state-of-the-art fabrication facilities, as well as major infrastructure projects, including NDFF and JOINER, present opportunities for exploiting novel technologies in systems research. Examples where UK research is leading developments at the world stage include:

- World record results by UCL and Aston through the UKRI/ESPRC funded TRANSNET & UNLOC programme grants demonstrating record ultrawideband transmission over laboratory-test bed and installed fibre links over the National Dark Fibre Facility – approximately 100 Tbit/s over 1000km – only NTT in Japan has matched these results.
- Systems-based developments in ultrawideband transmission are enabled by the development of advanced technologies, including fibre amplifiers operating in new spectral regions. The UK is at the forefront of research in optical amplification technologies, which include doped-fibre (such as bismuth-doped amplifiers – developed in the UKRI/EPSRC funded Airguide Photonics Programme Grant), Raman, parametric amplifiers as well as amplifiers built in specialty fibres for SDM systems.
- The UK leads research and commercialisation in hollow-core optical fibres, achieving the development of the lowest loss optical fibres ever made. UKRI-funded research in this area at the University of Southampton (Airguide Photonics Programme Grant) has led to the first commercialisation efforts that have brought these fibres to the market. As a result, fibre cables produced at the Lumenisity factory at Southampton now power Microsoft Azure's fibre network. The new fibres offer opportunities for radically new communication systems and the UK is best placed to study and exploit them.

- Research in other novel fibre types, including multi-core fibres and their associated devices also flourishes in the UK. These fibres significantly enhance the capacity of fibre cables in a space-efficient manner. Meanwhile, research in few-mode optical fibres uncovers fascinating optical phenomena, particularly nonlinear effects that offer potential for controlling the properties of light.
- World leading results in digital signal processing to develop intelligent transceivers which are able to adapt signals to minimise transmission distortions at UCL under the UKRI/ESPRC funded TRANSNET & UNLOC programme grants at UCL.
- Next generation optical communication paradigms benefiting from optical techniques, machine learning and advanced DSP. The growing complexity of dynamic optical networks presents significant challenges in maintaining the quality of signals over a broad and often heterogeneous spectrum. Artificial intelligence and machine learning techniques are penetrating transmission systems, enhancing their performance and enabling substantial capacity scaling to meet future demands.
- Coherent Passive Optical Networks which are a likely contender for the next generation FTTx targeting 200 Gbit/s data rates (50 Gbit/s was standardised in 2023). In 2024, University of Cambridge was the first to demonstrate 200 Gbit/s over 19 km installed fibre under the UKRI/ESPRC funded TRANSNET & UNLOC programme grants.
- Fibre-wireless convergence – For implementing NG-RANs supporting services/applications in the beyond-5G (B5G) era, seamless fibre-wireless network convergence is vital for enabling heterogeneous signals of various characteristics to continuously flow between the optical and electrical domains, without optical-electrical-optical (O-E-O) conversions or DSPs at any intermediate nodes. Initiatives in EPSRC-led consortia (including the COALESCE project and the HASC Telecoms Hub), as well as research at Bangor University bring forward optics-based solutions for establishing dynamic connections at the wavelength, sub-wavelength and sub-band levels.
- Optically-assisted high performance computing systems – Technologies developed for communications also contribute to the health of adjacent fields. The proliferation of integrated photonic systems has made optical implementations of neuromorphic computing possible. Such implementations rely either on linear or nonlinear applications of optical waveguides and have the potential to revolutionise future generations of computing systems by offering ultra-high speed, parallelised data processing solutions.

- Physical layer security and distributed sensing – Techniques that utilise the physical properties of the transmission medium in conjunction with either components that exhibit chaotic characteristics or neural network structures are becoming increasingly important for providing physical layer security in heterogeneously converged RF/fibre/OW networks. Sensing of infrastructures (lending itself also to geo-sensing) is becoming an increasingly important industrial topic, and the integration of sensing and security systems offers opportunities in triple-locked security including data transmission, data network infrastructures and other civil infrastructures in the vicinity of installed fibres. Experimental verifications of such techniques have been conducted at Bangor University, exploiting installed experimental infrastructures, such as installed fibres along the A55 North Wales Expressway, and confirming their unique advantages including “security-by-design”, “openness-by-design” and “dynamic security at traffic level”.

In conclusion, research is focused on one of society’s greatest technical challenges and economic drivers, and one underpinning critical infrastructure, has placed the UK at the forefront of international research in this rapidly-evolving and competitive, yet economically and socially vital area. It has helped transform the area of communications and the aim is that it will help revitalise the industrial communications sector, given the UK Government’s telecoms equipment diversification strategy, with the goal to re-establish UK indigenous industrial capability in this critical area[14]. This research is also at the core of the UK Government Science & Technology Strategy which advocates a systems approach[15]. In addition to the above, next steps will be focused on exploring innovative architectures for next-generation optical networks aimed to meet the demands of AI-driven applications by pushing bandwidth boundaries, increasing network resilience whilst reducing complexity and energy consumption.

By way of final comments, one of the most significant contributions of the UK research has been the training of researchers to enable the critical national infrastructure to be sustained, consolidated and enhanced – these researchers will be critical to the growth of UK industrial base in communications systems, networks and AI.

[14] Government response to the telecoms diversification task force
[15] The UK Science and Technology Framework

Promising Adjacent Research Areas

The UK is world leading in many adjacent research areas that can be brought to communications to enhance their operation in terms of performance, extendibility or indeed safety. We highlight some of the key areas below.

3.1/ Artificial Intelligence

Artificial Intelligence (AI) is transforming the management and design of communication networks, enhancing efficiency, reliability, and adaptability across various domains, including wireless networks, core networks, and emerging technologies. As networks become increasingly complex, AI-driven solutions play a crucial role in optimising performance, predicting failures, and enabling autonomous operations. The future telecommunication networks are set to embrace AI-native[16] design as one of the core tenets. Integration of AI into communication network eco-system can tame the increasing complexity due to continuous disaggregation, virtualisation, and distribution of networks.

Wireless communication networks, including future 6G systems, rely on AI to enhance spectrum efficiency, manage interference, and optimise resource allocation. AI-powered algorithms enable dynamic spectrum sharing, allowing different users and services to coexist without significant performance degradation. Additionally, Machine Learning (ML) models can predict network congestion and proactively adjust parameters to maintain seamless connectivity. AI is also crucial in managing massive Multiple Input Multiple Output (MIMO) systems, beamforming, and energy-efficient transmission techniques, ensuring robust and sustainable wireless communication.

[16] Ericsson Report: Approaching AI Native RANS through generalisation and scalability of learning

Core networks form the backbone of mobile communication systems, where AI is deployed to improve routing, security, and traffic management. AI-driven analytics enable predictive maintenance by identifying potential failures before they occur, reducing downtime and improving network reliability. Software-Defined Networking (SDN) and Network Function Virtualisation (NFV) are heavily reliant on AI for automating traffic routing and load balancing, ensuring optimal utilisation of network resources. Furthermore, AI enhances cybersecurity in core networks by detecting anomalies and mitigating threats in real time, thereby strengthening the overall resilience of communication infrastructures.

Finally, network automation is a key area where AI is making significant strides. Self-organising Networks (SONs) leverage AI to configure and optimise themselves without human intervention, reducing operational costs and improving service quality. AI-driven automation is particularly valuable in network slicing, where virtualised network segments are dynamically allocated to different use cases, such as autonomous vehicles, smart cities, and industrial automation. By continuously analysing network performance metrics, AI ensures that resources are allocated efficiently, and Service Level Agreements (SLAs) are met.

3.1.1/ Example of UK research contributions

The academic community in the UK is at the forefront of integrating artificial intelligence (AI) into communication networks, leveraging its strong research capabilities and collaborative initiatives between academia and industry. For example, The REASON Open Networks Project received the AI Award for High Tech & Telecom at the National AI Awards 2024, highlighting the UK's leading role in AI-driven communication network research.

Research efforts at UK universities such as Queen’s University Belfast, Kings College London, Imperial College London, University College London, University of Bristol are focused on AI for wireless networks. These include developing AI/ML algorithms for physical layer control, resource allocation, and network optimisation. Deep learning (DL) is being applied to create intelligent network architectures for advanced imaging, sensing, target detection (e.g., identifying objects with classification accuracy exceeding 95%), and antenna array configuration.

Promising Adjacent Research Areas

The 6G Lab at the University of Sussex conducts research in AI-based physical layer design for next-generation wireless networks[3], focusing on developing deep learning-based autoencoders to optimise the entire physical layer processing chain, enabling data-driven, end-to-end learning solutions that adapt to varying applications and deployment environments. Finally, the potential of Quantum Machine Learning (QML) for enhancing security in 6G networks (including Integrated Satellite Terrestrial Networks (ISTN)) is being explored at Queen's University Belfast. The University of Glasgow focuses on AI-driven methodologies for electronic circuit and system design, addressing challenges in design complexity and time-to-market. Their research encompasses AI-driven design of microwave devices, RF and analogue integrated circuits, and micro-electromechanical systems.

Several international alliances have been formed to accelerate the development of AI-native networks. AI-RAN alliance[17] was established in 2024 by NVIDIA, Ericsson, Samsung and several other industrial stakeholders to drive pre-standardisation and promote best-practice approaches within these three areas. Several UK universities (University of Leeds, University of York and University of Bristol) have joined the Alliance since its formation to contribute towards pre-standard specification.

One of the core issues as identified by the UKTIN's AI working group report[18] is availability of data at scale. The report solicited "creation of cohesive 'Open6G' testbed that facilitates the seamless integration and assessment of multivendor interoperability solutions for native AI network elements and testbeds". The development of Engineering and Physical Sciences Research Council (EPSRC) funded JOINER platform sets out foundation for development of such open testbed. The JOINER platform is set to host some of the innovative research across three UK future telecoms hub, CHEDDAR, TITAN and HASC. Furthermore, the Centre for Doctoral Training in Future Open SecuRe NeTworks (CDT-FORT) is funded by EPSRC, brings together expertise of the University of Surrey and Queen's University Belfast to address the national need for open, secure, and resilient communication systems, looking across wireless communications, cybersecurity, networking, and AI[19].

[17] AI-RAN Alliance
[18] Available from UKTIN here
[19] FORT-CDT.ac.uk

3.2/ Formal Methods

Since the middle of the last century the UK has lead research in formal methods or the mathematics to allow us to reason about computer systems, software, and hardware. Indeed, Alan Turing's 1949 work on formal methods and program proving is considered the first in in the field, quickly followed by Tony Hoare's 1969 article[20] on the axiomatic basis of programming languages that is considered its cornerstone. Formal methods permit the verification or safety checking of a system in a robust way. Rather than conducting substantial number of tests on a system to check that it is working correctly, formal approaches bring a process to prove the correctness of a system's behaviours, for all paths that the code can take. It is especially important where a system is composed of, or evolves from, dynamic components (software libraries or hardware units) as one can evaluate if these components will compromise the larger system or have unwanted cascading effects.

One notable application area that benefited from such methods is that of Operating Systems, specifically regarding drivers. Drivers are code that allow the operating system to talk to devices that are plugged into it – a keyboard, disk drive etc. These may be plugged in dynamically and new driver code uploaded to enable the connection. This was one of the top causes of operating system failures (aka Blue Screen of Death)[21]. Verification techniques were used to check the device drivers in advance and could be seen as where formal methods moved from an academic topic to being used throughout the industry, for example in Microsoft[22].

Today's telecoms are dynamic and composable, and increasingly defined by software. Programmable networking is a key enabler for 6G technology, helping provide increased scalability and flexibility at a lower cost. The ability to program the network fabric both vertically (control and data plane) and horizontally (end to end), supports extreme performance requirements and service-specific operations. Likewise with the advent of the use of AI, next generation networking will be a highly dynamical system, to the extent not seen thus far. These dynamics bring many advantages, but also vulnerabilities around being able to be sure the new code components will integrate correctly or newly learned protocols and waveforms do what they are supposed to, without unintended consequences.

[20] C. A. R. Hoare. 1969. An axiomatic basis for computer programming. Communications of the ACM 12, 10 (1969), 576–580.
[21] Herder, J. N., Bos, H., Gras, B., Homburg, P., & Tanenbaum, A. S. (2006). MINIX 3: A highly reliable, self-repairing operating system. ACM SIGOPS Operating Systems Review, 40(3), 80-89.
[22] Ball, T., Cook, B., Levin, V., & Rajamani, S. K. (2004). SLAM and Static Driver Verifier: Technology transfer of formal methods inside Microsoft. In Integrated Formal Methods: 4th International Conference, IFM 2004, Cnaterbury, UK, April 4-7, 2004. Proceedings 4 (pp. 1-20). Springer Berlin Heidelberg.

Essential components of Open Radio Access Networks (RAN) automation take the form of xApps and rApps that reside in the RAN Intelligent Controller (RIC). As specialised microservices, they provide essential control and management functions that can optimise radio spectrum efficiency, for example. This architecture has the advantage in that a larger number of players can provide these services tailored to applications like controlling drones. However, like device drivers, they could have severe impacts if their behaviours go unchecked, and this is where formal verification can have a key role in next generation communication networks.

3.2.1/ Examples of UK research contributions

The CHEDDAR Hub purposefully brought a team of the UK's top formal methods people together for the first time to explore this problem. CHEDDAR is examining how AI can help specify the requirements of an xApp or rAPP so that AI can generate their code to those specifications therefore minimising the chance that code will display unwanted behaviours. Emanating from Glasgow University with Imperial with others, the resulting code is then automatically formally verified to ensure that it is safe to run with the other ORAN components. This work is unique to the UK and world leading.

In addition to making the systems safe in terms of their behaviour; further research can examine this from a security and trustworthiness perspective. This is an important feature of trusted AI, while CHEDDAR project is working with the Safe and Trusted AI CDT.

Furthermore, the REASON Project is investigating Formal Verification of AI models for telecoms, with examples in Service Orchestration and mATRIC

3.3/ Edge to cloud computing continuum

The continuum from the edge to cloud computation is supported by, and a key enabler for, the next generation telecoms architectures. This topic, sometimes referred to as Fog Computing, is an adjacent technological focus. It is described as an architecture that places processing either closer to end users or at data sources. Originating from Content Delivery Networks of the 1990s, the former facilitates faster data delivery to the users (e.g. videos). More recently, with the proliferation of the Internet of Things (IoT) systems, it means that processing is close to the data sources (IoT systems are strong data generators via sensors or human interactions) which means that the outputs from the processing are communicated rather than the more voluminous raw data. Given that many IoT systems are battery powered, and communicating data is one of the more energy consuming tasks, this impacts the duration that the IoT device is active (i.e., powered) which has sustainability advantages even if it is not battery powered. An added advantage of Edge compute is that it can be seen as more secure and privacy preserving as less, potentially personal, data is sent over networks. It also facilitates autonomy for systems such as self-driving cars or drones and smart manufacturing.

AI has long considered to be a computationally heavy technology, typically run in data centres hosting cloud services. More recently there is a movement towards pushing the AI to the edge for the advantages listed above. This brings many challenges, the first of which is being able to carry out processing like Machine Learning trained on small data rather than big data as before, or indeed not being trained at all on past data, but learning as it processes, like in Reinforcement learning. Data from a given device or from a given locality, or other dimension, only represents the world at that point, therefore answers from the AI only pertain to that, i.e., it is heavily biased on that domain. An added challenge is being able to interpret a more macro phenomenon based on the various locally biased outputs, key information that sit on the boundaries of a domain may be missing but important at a higher level of abstraction.

3.3.1/ Examples of UK research contributions

The areas of research in this field that the UK has contributed to are around the partitioning of problems and task offloading, and privacy and security. Examples of UK leadership in the latter are from the PETRAS centre of excellence in IoT cyber security[23], Cyber Security Research and Networking Environment NetworkPlus, RITICS Research Institute in Trustworthy Industrial Control Systems[24], as well as numerous specific research projects. Specifically for Edge AI, the National Edge AI Hub for Real Data: Edge Intelligence for Cyber-disturbances and Data Quality, involves eleven universities examining on the effect of cyber disturbances on Edge AI systems[25]. Examples of UK impact leadership is around securing edge computation through the ARM Morello designs and the CHERI prototype.[26,27]

We note that with important applications in "Telco Edge" a number of projects, such as REASON and JOINER are investigating the adoption NFV and cloud-native principles, which makes the use of cloud/edge imperative for telecom workloads.

3.4/ Quantum technologies and quantum communications

The UK has a globally leading National Quantum Technologies Programme, which is currently entering its second decade. This encompasses academically led research hubs, public-private partnership funding through Innovate UK, national centres such as National Physics Laboratory (NPL) and the National Quantum Computing Centre[28], and a thriving start-up sector. The impact of 'Quantum 2.0' on telecommunications is likely to be through (i) investment in devices and subsystems that can be used for both classical and quantum communications (ii) development of quantum computers that can play a part in the optimisation of future networks and systems and their operation and (iii) through the development of large-scale entanglement-based quantum networks.

[23] EPSRC Grant reference EP/S035362/1 and EP/N02334X/1
[24] EPSRC Grant Reference EP/L021013/1
[25] Edge AI Hub
[26] ARM Morello CPU
[27] BusinessWeekly.co.uk, New cohort given access to arm morello board to trial cyber security solutions
[28] NQCC.ac.uk

Quantum networking is (by far) the largest element of these. Within the UK there has been a Quantum Communications Hub[29] since 2014, with a focus on QKD at all length scales. This has implemented a trusted node Quantum Key Distribution (QKD) network, short-range handheld QKD, and developed satellite QKD (with a CubeSat launch expected in 2025), along with associated work on architectures and protocols. The expertise and infrastructure this has helped create, together with other funded work (for instance on quantum data centres), is now focused on entanglement-based networking, with an Integrated Quantum Networking Hub funded from 2025-2030. There is also a National Mission to create an at-scale network secured by entanglement by the early 2030s. Such a network will require single photon sources, quantum repeaters, and low-loss 'amplifier-free' switches, wavelength converters, and a range of other components. Work to develop these leverages UK wide expertise in photonics.

Quantum Computing (QC) is maturing rapidly as a field, and there are an increasing number of proofs of principle applications in telecommunications. There have been operational logistics optimisation and network planning applications demonstrations with several operators, both in the UK and elsewhere. The utility of these is likely to grow, as is the complexity of the cases chosen. QC 'at-scale' also provides a threat to the underlying encryption used in internet and other applications, and in this regard, operators are beginning to consider post-quantum techniques. Post-quantum, combined with QKD is therefore an area of growing interest.

3.4.1/ Examples of UK research contribution

A highly promising new era is emerging in the development of NTN-aided, ultra-secure quantum networks, with the ambitious goal of realising the quantum Internet[30]. This transformative technology is expected to enable a suite of innovative services and drive significant economic opportunities. Quantum networks utilising optical wireless NTN links can seamlessly bridge vast distances without the need for amplification—unlike terrestrial, fibre-based quantum networks, which require quantum-to-classical signal conversion and amplification approximately every few dozen kilometres. In Edinburgh, a research hub led by Heriot-Watt University is dedicated to pioneering solutions for a quantum Internet capable of interconnecting multiple quantum computers. Meanwhile, a research hub at the University of Glasgow is focused on developing quantum technologies essential for resilient positioning, navigation, and timing systems. These advancements are crucial for national security and the establishment of a robust national quantum infrastructure.

[29] QuantumCommsHub.net
[30] L. Hanzo et al. , "Quantum Information Processing, Sensing and Communications: Their Myths, Realities and Futures". In Proceedings of the IEEE

3.5/ Semiconductor technologies

Semiconductors underpin many telecoms technologies and while the UK has strengths in digital design, there were some concerns around the lack of industrial-scale silicon fabrication capabilities[31]. To address this, the UK has taken important steps to develop a sovereign semiconductor strategy that will enable its industries to lead future communication networks. Two key developments have significantly enhanced the UK's capabilities, namely the South Wales Semiconductor Cluster[32] and the CORNERSTONE silicon photonics foundry[33].

3.5.1/ Examples of UK research contribution

The South Wales Semiconductor Cluster is focussed on the development of Indium Phosphide based active components such as O and C band lasers, Detectors and Semiconductor Optical Amplifiers for fibre optic transmission applications. The Cluster has the capability to deliver low TRL research, including design to chip-level solutions, pilot scale manufacturing through to volume manufacturing via the Institute for Compound Semiconductors at Cardiff University, The Centre for Integrated Semiconductor Materials at Swansea University, The Compound Semiconductor Centre and IQE Plc.

Chip-scale and packaged device testbeds are in place at the Optoelectronics Research Centre at Southampton University, the Digital Signal Processing Centre at Bangor University, and the National Physical Laboratory. Current collaborative R&D&I activities cover custom specification demonstrations to deliver system advantage, novel semiconductor device architectures and manufacturing scale up research. These activities include the projects REASON[34], CHIPIN6, CSconnected and SECURE-Comm.

CORNERSTONE is a silicon photonics rapid prototyping service hosted by the Universities of Southampton and Glasgow. To date, it has supplied more than five hundred orders for photonic integrated circuits (PICs) to over one hundred institutions in twenty-three countries. CORNERSTONE is recognised as the national centre for silicon photonics prototyping and is complemented by the Innovation and Knowledge Centre (IKC) called the CORNERSTONE Photonics Innovation Centre, an £11.7M EPSRC + Innovate UK investment.

[31] UKTIN Future Capability Paper “Semiconductors for Telecoms,” 17 July 2024
[32] Tradeandinvest.wales Key Sectors, Compound Semiconductors Case Studies
[33] www.cornerstone.sotonfab.co.uk
[34] REASON-open-networks.ac.uk

3.6/ New computing paradigms

Today's computers and communication systems rely on digital electronic circuits that operate using discrete values, typically binary (0 and 1), to encode and process data. However, advances in neuromorphic computing, analogue computing, in-memory computing devices, and accelerating neural-network interfaces can be expected to have a strong impact on the design and performance of future communications systems and networks.

3.6.1/ Examples of UK research contributions

Researchers at Imperial College London design new transceiver architectures based on analogue computing to make the network faster and much more energy efficient, reducing the computational complexity by multiple orders of magnitude compared to conventional digital processing.

Convergence in Future Networks

4/ Convergence in Future Networks

This section explores key trends and research directions related to convergence in future networks[35]. Many of these concepts are still under development or in early research stages, yet they collectively indicate how future 6G systems might seamlessly integrate various communication, computing, and sensing technologies. The overarching goal of convergence in future networks is to create a unified, intelligent, and sustainable communication framework capable of adapting to emerging applications and global connectivity demands.

While 6G is still in its research and early standardisation phases, these trends highlight the cross-disciplinary nature of next-generation networks and underscore the pivotal role convergence will play in shaping our hyperconnected future. These topics are also widely explored by the UK academic community and align with the broader strategic objectives outlined in this document.

Convergence of Terrestrial and Non-Terrestrial Networks

- Communication-sensing fusion: 6G research envisions systems that simultaneously transmit data and sense the environment (e.g., for object detection, localisation, and imaging). This could enable new services such as high-precision radar-like capabilities for autonomous vehicles and robotics.
- Edge and cloud computing integration: To meet the massive scale and low-latency demands of next-generation applications, 6G will combine edge computing—bringing computation closer to users—with centralised cloud resources. Dynamic orchestration between these layers will be essential.
- Distributed intelligence: AI and machine learning will be central to 6G, enabling real-time network optimisation, resource allocation, and service orchestration. Distributing computing power from core clouds to far-edge nodes will enhance responsiveness and reduce network congestion.

[35] Additionally, see section 2.5.1 for a discussion of fibre-wireless convergence.

Convergence in Future Networks

Convergence of Communication, Computing, and Sensing

- 6G research envisions systems that simultaneously transmit data and sense the environment (e.g. for object detection, localization, imaging). This could open new services such as high-precision radar-like features for autonomous vehicles and robotics.
- Edge and cloud computing convergence: To cope with the massive scale and low-latency demands of next-generation applications, there is a push to bring computing closer to the user (edge computing) while still leveraging centralized cloud resources. 6G will require integrated orchestration across edge and cloud to dynamically allocate workloads.
- Distributed intelligence: As AI and machine learning become integral for 6G (for network optimization, resource allocation, and service orchestration), computing capabilities will be distributed from core clouds to far-edge nodes. This ensures real-time insights and reduces the burden on transport links.

Convergence in network architecture

- Software-defined networking (SDN) and network function virtualisation (NFV): 6G will advance software-defined architectures, autonomously optimising end-to-end network slices and resources.
- Network slicing and slicing-as-a-service: Building on 5G slicing, 6G will offer even more granular and automated network segmentation to support diverse use cases, from ultra-reliable low-latency communications (URLLC) for industrial automation to massive IoT (mIoT) deployments.
- Composable networks: 6G may introduce a paradigm where network components (compute, storage, radio resources) are dynamically assembled based on evolving application needs, requiring deep programmability and AI-driven orchestration.

Convergence of security, trust, privacy and resilience mechanisms

- End-to-end security from ground to non-terrestrial networks: As 6G extends connectivity across satellite links and UAVs, ensuring security and trust in multi-layered environments will be crucial.
- Quantum-safe cryptography: With the anticipated rise of quantum computing, 6G networks may integrate cryptographic algorithms resistant to quantum attacks.
- AI-driven security monitoring: AI-powered anomaly detection, threat prediction, and automated response mechanisms will strengthen cybersecurity in 6G environments.

Convergence of Sustainability and Green Design

- Energy efficiency as a core design principle: 6G will focus on minimising energy consumption through AI-driven power allocation, energy harvesting techniques, and optimised sleep modes for idle network nodes.
- Life cycle approach: Beyond operational efficiency, 6G research explores green manufacturing, sustainable deployment, and environmentally responsible disposal of infrastructure components.

Convergence of New Use Cases and Services

- Haptic and holographic communication: Ultra-high data rates and ultra-low latency in 6G could enable immersive telepresence, extended reality (XR), and the tactile internet, where users interact with remote physical or virtual environments in real time.
- Cyber-physical systems: As the digital and physical worlds become increasingly intertwined, 6G will support vast sensor networks for Industry 5.0, autonomous transportation, and next-generation healthcare applications.

Fostering Innovation

5/ Fostering Innovation, Research Translation and Entrepreneurship in Research Communities

Research in academia and industry explores the impact of commercialisation or value-added services. Academia focuses on knowledge generation and societal benefit, while industry prioritises profit and competitive advantage. Both blue-sky and applied research can lead to commercialisation, but their timelines, paths and impacts differ depending on the origin. The UK's academic research community plays a vital role in advancing future network technologies. However, translating this cutting-edge research into commercial success requires a strong emphasis on business acumen and entrepreneurial skills. Ensuring that researchers are equipped to navigate the commercialisation process, establish industry partnerships, and develop market-ready innovations is critical for maintaining the UK's global competitiveness. This section highlights some of the key initiatives and best practices in fostering business and entrepreneurial capabilities within research communities.

In addition to those highlighted below the Catapult network plays an important role in research translation. At least four catapult centres (Digital, Satellite Applications, Compound Semi-conductor and High Value Manufacturing Catapults) are working directly on Future Telecoms projects and initiatives in partnership with universities, for example, in Programmes such as Innovation Launchpad Network+[36].

5.1/ UKTIN – from Research to Commercialisation

Bridging the gap between research and industry remains a well-known challenge. The UK Telecoms Innovation Network (UKTIN) serves as a key enabler in addressing this issue by fostering collaboration between academia, industry, and government. UKTIN's mission is to transform the UK's telecoms innovation ecosystem, leveraging the country's strengths in technology and research to drive commercialisation and industry growth.

[36]Innovationlaunchpad.group.shef.ac.uk

As a founding partner of UKTIN, Bristol Innovations, a division within the University of Bristol, specialises in research commercialisation. It connects universities, investors, and industry partners to streamline the process of translating research into market-ready solutions. According to Simon Bond, Director of Bristol Innovations, UKTIN's role is to "equip research-savvy entrepreneurs with the skills and ambition to bring their innovations to market, creating successful companies that drive economic growth and national resilience."

UKTIN provides tailored support to researchers and startups, including business plan development, investor engagement, and supply chain integration. Notable UKTIN-supported success stories include:

- Space Villages – A startup pioneering in-orbit servicing and spacecraft repair to enhance sustainability in space operations.
- Praeferre – A leader in data privacy services, offering secure data management solutions for modern networks.
- Finchetto – A company awarded significant funding to develop the world's first fully optical switch for telecoms networks.
- pureLiFi – A trailblazer in LiFi technology, which employs 50 highly skilled workers and has attracted $40 million in investment, including from the USA and Singapore, and is generating multi-million pound revenues annually.

UKTIN collaborates closely with the SETsquared university-business incubator, co-founded by the University of Bristol, to support startups in securing investment and navigating the commercialisation landscape. This partnership strengthens the UK's position as a telecoms innovator and cultivates a robust entrepreneurial ecosystem.

5.2/ Federated Telecoms Hubs (FTH)

The UK has a strong reputation for research in communication technologies, systems, and networks, with numerous internationally recognised research groups. However, despite these strengths, the commercialisation of this research has been limited, and efforts remain fragmented across various institutions. To bridge this gap, four major UK telecoms research hubs—TITAN, CHEDDAR, HASC, and JOINER—have joined forces to establish the FTH. This collaborative initiative brings together 25 leading UK universities and over 100 researchers, serving as a central hub for international collaboration. A key component of the FTH structure is its governance function, which plays a crucial role in translating research into practical applications.
The governance structure of the FTH is designed to facilitate effective research translation and is divided into four main functions, each led by a dedicated Director:

Technology Roadmapping and Commercialisation
This function focuses on developing technology roadmaps and research strategies based on industry needs and standardisation efforts. A major aspect of this initiative is the creation of an Intellectual Property Rights (IPR) pool, fostering a 'think patent first' culture among FTH researchers. Industry panels will help prioritise patents for proof-of-concept (PoC) and minimum viable product (MVP) development. Where feasible, the JOINER platform will be used to showcase PoCs and MVPs. Additionally, support will be provided for business model development and market studies, with strengthened links to investor communities to facilitate early-stage investment. This function also contributes to government telecoms policy development, produces whitepapers on future technologies, and fosters collaboration with industry by facilitating consultancy requests.

Standardisation and International Collaboration
FTH aims to close the gap between cutting-edge research and real-world industry applications. Both standardisation efforts and open software projects are central to this goal. To maximise impact, an exploitation strategy will be developed based on the UK's research strengths. The FTH will engage strategically with standards development organisations (SDOs) in two key ways:

- Introducing key technologies, supported by patents from its IPR pool, into relevant SDOs such as 3GPP.
- Collaborating with industry to support ongoing standardisation efforts.

A team of senior researchers will regularly attend standardisation meetings, providing technical contributions and offering feedback to inform the technology roadmap. This initiative also fosters international collaborations, organises global workshops and symposia, and advises the government on international policy and funding priorities.

Skills and Training
To build the next generation of telecoms professionals, FTH is addressing critical skills gaps in AI, cloud computing, quantum technologies, security, and advanced telecom systems. The telecoms sector faces challenges such as an ageing workforce and declining interest in digital infrastructure careers. Without intervention, the UK risks lagging behind in global telecoms innovation.

FTH is developing training programmes at all levels, from school outreach to lifelong learning initiatives. These efforts will be essential as restrictions on international talent persist. The initiative will also leverage the strengths of UK higher education, support government policies, and collaborate with industry to close existing skills gaps.

Marketing and Outreach

Ensuring that FTH's research outputs gain visibility and impact, this function is responsible for promoting the assets developed across all hubs. By establishing a strong identity for the FTH, it aims to position itself as the UK's central hub for communications research. Marketing efforts will include national and international events, the development of promotional materials, and the broad dissemination of research breakthroughs.

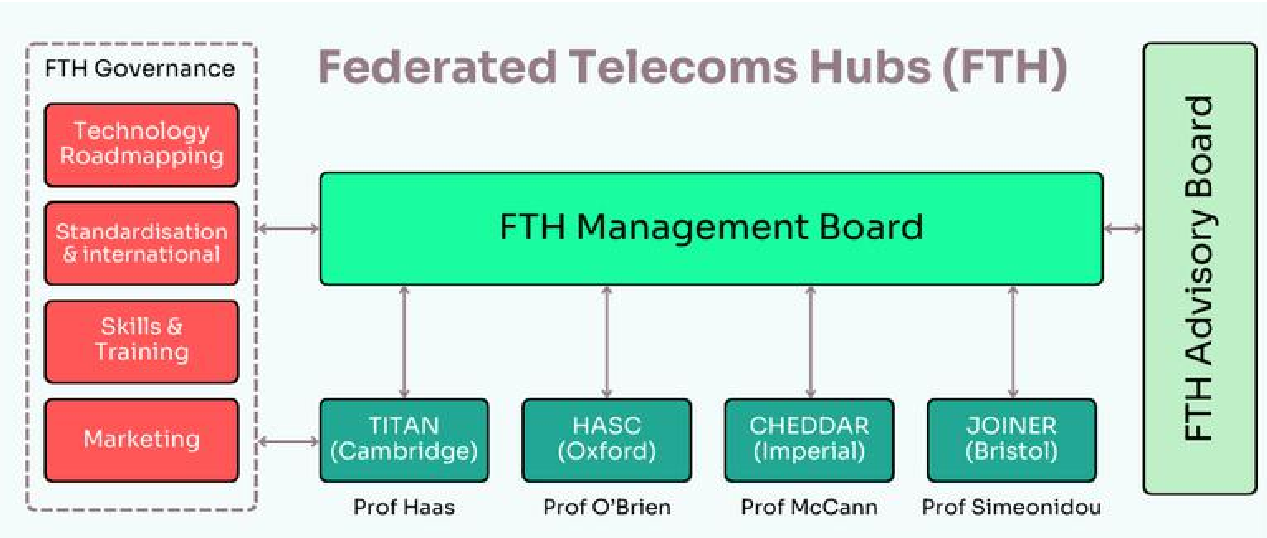
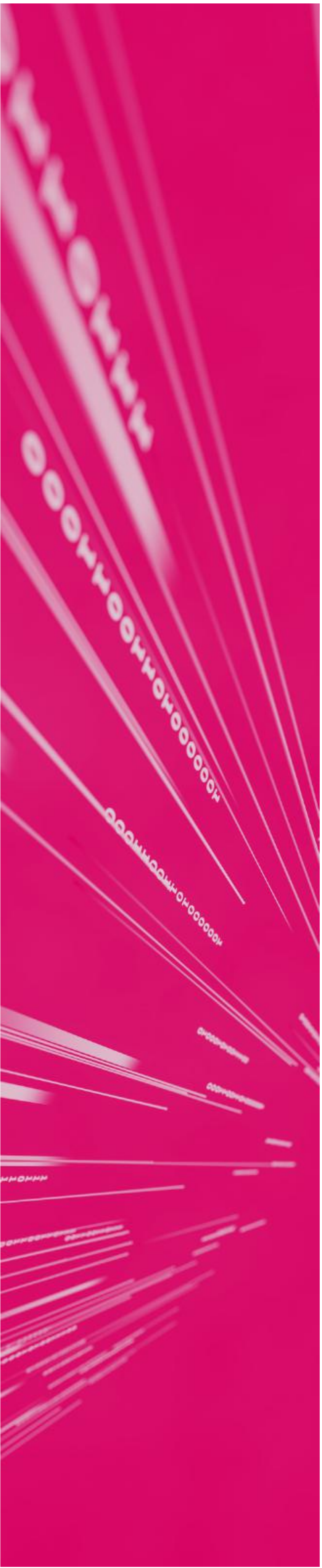


Figure 2: FTH Structure and its Boards: The four UK telecoms hubs have established a collaborative framework supported by a governance structure that includes critical functions and support. This framework aims to drive technological advancements and enhance the wider impact of research within the four hubs.

- Titan Cambridge
- All Spectrum Hub
- CHEDDAR Hub
- JOINER

All FTH governance activities coordinate with corresponding activities in other UK funded interventions such as UKTIN, UKTL and Digital Catapult. The overall aim is not simply to generate research but to create actual prototypes and test new ideas in the field. The FTHs want to innovate within particular verticals, showcasing how different technologies can have a positive impact on society, as well as be a commercial success. Assistance and guidance is provided to universities in the filing of patents that could have great value in the networks in the future. In so doing this will help to create a shop window for IPR, illustrating value for the benefit of the investor community. The ultimate result is viable products and new spinouts on the UK telecoms market. The hubs are a seeding ground for the unicorns of the future. Telecoms relies on a well-functioning supply chain, but with increasing global isolationism, there is a risk of supply chain gaps. The governance within the FTH could be expanded into large-scale programmes to minimise the risk of critical communications infrastructure failures, which could impact many industries. Additionally, there is potential to develop dual-use technologies to support the UK intelligence and defence sectors.



Summary and Recommendations

6.1/ Summary

This white paper, developed by the UKTIN Future Networks Academic Strategy Group, serves as a strategic guide to strengthening the UK's leadership in next-generation telecommunications research and innovation. It builds upon the findings of the group's first white paper, which provided an initial assessment of the UK's academic-led research, innovation, and development (R&I&D) landscape in future networks. This second white paper focused on:

1. Identifying Specific Research Strengths: The report highlights areas where the UK has strong capabilities, both in government-funded research and organically growing sectors. Key technological domains include optical wireless communications, spectrum technologies, non-terrestrial networks (NTN), native AI, and optical fibre systems. The UK also excels in software platforms for the telecom sector, leveraging the confluence of its strong engineering innovation and ecosystem in software and telecom sector. The paper provides a structured assessment of UK research contributions, showcasing strengths in each of these fields.
2. Strengthening Cross-Disciplinary Collaboration: Recognising that future networks will increasingly integrate adjacent fields, the document explores the role of artificial intelligence, quantum technologies, semiconductor advancements, and new computing paradigms. These areas are vital for ensuring the UK's global competitiveness in telecommunications.
3. Fostering Business and Entrepreneurial Skills: The paper assesses how research communities are integrating commercial acumen into their work. It highlights successful initiatives where academic research has translated into spinouts, patents, and industry collaborations, ensuring that the UK's technological advancements also lead to economic impact.
4. Driving Economic Success: The UK has one of the strongest research outputs in telecoms. The FTH has launched effective programmes to translate this strength into commercial success, safeguarding critical infrastructure and industries while driving economic growth and boosting productivity across multiple sectors.

The white paper underscores the UK's position as a global leader in telecommunications research, supported by world-class universities, collaborative research hubs, and government-backed initiatives. However, maintaining this leadership requires sustained investment, stronger industry-academia partnerships, and a stronger focus on standardisation commercialisation pathways.

6.2/ Recommendations

The UK has world-class research institutions leading advancements in telecommunications, with significant expertise in optical wireless communication, spectrum technologies, wireless networks (including NTN), and several adjacent fields, most notably software and cloud platforms, artificial intelligence and quantum. The transition to Open RAN and automated network management presents a strategic opportunity for the UK to lead in software- and AI-driven telecom solutions. Additionally, the UK is well-positioned to pioneer quantum-secure communications and integrated quantum networking, reinforcing its role in shaping the future of secure and resilient telecommunications infrastructure.

UK academics, researchers, and companies are already playing a vital role in shaping international standards, particularly in areas such as Optical Wireless Technologies, Open RAN, optical communications, and AI-powered networks, ISAC and Multi-Access technologies. However, while the UK demonstrates strong research and development capabilities, it faces critical challenges. The US, EU, and China are making substantial investments in 6G, quantum networking, and AI-driven telecoms, intensifying global competition. Moreover, the UK lacks large-scale national telecom equipment and device vendors, which typically play a pivotal role in setting mobile communication standards. This creates a pressing need for the UK to sustain its leadership in future network technologies through strategic interventions. Furthermore, the UK's telecom sector thrives on top talent, but challenges like funding gaps for early-career researchers and barriers for international experts could impact long-term innovation. A national talent retention strategy, with better funding and targeted incentives, would help strengthen the pipeline and support continued progress.

To sustain the current momentum and bridge existing gaps, this white paper highlights the key strengths, gaps, opportunities, and challenges within the UK's telecommunications research and innovation ecosystem. The following recommendations are designed to strengthen the UK's position as a global leader in telecom innovation.

Recommendations

- Increase funding for targeted research in high-impact areas such as AI-native networks, quantum-secure communication, and next-generation wireless technologies. This will enable the UK to remain competitive in emerging fields where it has existing expertise.

- Expand support for testbeds and infrastructure projects (e.g., expansion and enrichment of JOINER and SONIC), ensuring UK research is translated into deployable solutions. Strengthening these initiatives will help bridge the gap between research and commercial implementation.

- Provide long-term baseline support for the hubs alongside the development of supplementary funding programs from industry and other sources. Sustainable funding will enhance the stability and effectiveness of research initiatives.

- Strengthen the governance of the FTH and develop it into large-scale governance programs that maximise investment in telecoms research in the UK and help secure critical supply chains. This will enhance the UK's ability to maintain a resilient and autonomous telecom sector.

- Strengthen participation in global standardisation bodies to ensure UK-developed technologies influence international telecom regulations. Active engagement in standardisation efforts will ensure that UK innovations are adopted on a global scale.

- Create accelerated commercialisation pathways, including targeted investment funds, venture capital incentives, and regulatory fast-tracking for telecom start-ups. Facilitating the transition from research to market will enhance the UK's economic competitiveness in telecoms.

- Launch a national talent retention strategy, including better funding for early-career researchers and incentives for international experts to work in UK-based research institutions. A robust talent pipeline is critical to sustaining long-term innovation.

- Ensure sustained government funding and policy stability in telecom research, creating long-term certainty for academic and industry stakeholders. Policy consistency will foster a stable environment conducive to long-term investments and breakthroughs.

- Strengthen international research collaborations, ensuring UK institutions remain engaged with and are able to influence key industry players in global telecom innovation and standardisation in 6G and beyond. International partnerships will help the UK remain a significant player in future telecom developments.

By implementing these recommendations, the UK can reinforce its position as a leader in telecom research and innovation, ensuring that its expertise in AI, quantum, and next-generation networks translates into global influence and economic growth.

Appendix A

List of Contributors

Members of the Working Group who have contributed to this paper are listed below. 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 B

Version Control

Revision	Description	Author(s)	Reviewed by	Date
1.0	First draft	Maziar Nekovee & contributors in table	WG, UKTIN	04/02/2025
2.0	Second draft	Maziar Nekovee & contributors in table	WG, UKTIN	
3.0	Third draft	Maziar Nekovee & contributors in table	Maziar Nekovee & WG and DSIT	21/02/2025
4.0	Final report	Maziar Nekovee & contributors in table	Maziar Nekovee	07/03/2025

Appendix C

List of Acronyms

Acronym	Description
AI	Artificial intelligence
AoAs	Array of Arrays
APs	access points
ARC-OTA	Arieal RAN CoLab Over-The-Air
CMOS	Complementary Metal-Oxide-Semiconductor
CHAPA	Centre for High Altitude Platform Applications
DL	Deep Learning
DPD	Digital Predistortion
EPSRC	Engineering and Physical Sciences Research Council
FOS	Free Space Optical
FTH	Federated Telecoms Hubs
HAPs	High-Altitude Platforms
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
ISTN	Integrated Satellite Terrestrial networks
JSAC	Joint Sensing and Communication
LED	Light Emitting Diode
LEO	Low Earth Orbit
LiFi	Light Fidelity
LoS	Line of Sight
MAT	Multiple Access Technologies
MIMO	Multiple Input, Multiple Output
ML	Machine Learning
NFV	Network Function Virtualization
NOMA	Non-Orthogonal Multiple Access
NPL	National Physics Laboratory
NTN	Non-terrestrial Network
OAM	Orbital Angular Momentum
OCC	Optical Camera Communications
OFDM	Orthogonal frequency-division multiplexing
OLED	Organic Light Emitting Diode
OMA	Orthogonal Multiple Access
ORAN	Open RAN

Appendix B

OTFS	Orthogonal Time Frequency Space
OWC	Optical Wireless Communication
PAT	Pointing, Acquisition, Tracking
PoC	Proof-of-concept
QC	Quantum Computing
QKD	Quantum Key Distribution
QML	Quantum Machine Learning
R&I&D	Research, Innovation, and Development
RAN	Radio Access Network
RF	Radio Frequency
RIC	RAN Intelligent Controller
RIE	Reconfigurable Intelligence Edges
RIS	Reconfigurable Intelligent Surfaces
RITICS	Research Institute in Trustworthy Industrial Control Systems
RSMA	Rate-Splitting Multiple Access
SDMA	Spatial Division Multiple Access
SDN	Software defined Networking
SLAs	Service Level Agreements
SON	Self-Organising Networks
SWaP	Size, weight and power
TOWS	Terabit Optical Wireless System
TRL	Technology Readiness Levels
UKTIN	UK Telecoms Innovation Network
UV	Ultraviolet
UVC	Ultraviolet C
VLC	Visible Light Communication
WPT	Wireless Power Transfer