Platform Driving the Ultimate Connectivity (TITAN)

Network of Networks

Work programme for TMF Extension

1 Vision

TITAN aims to **pioneer groundbreaking research** in communication network technologies with a focus on the **intersections of traditional and future communication network elements.** Our ultimate objective is to architect **a seamless, open,** and **holistically integrated** Network of Networks (NoN). This will serve as a **foundational blueprint** for the evolution of **6G networks and beyond**. To this end, the ambition is to create the ultimate **secure, self-configurable, self-optimising, self-healing, energy efficient, resilient** NoN that achieves **pervasive coverage** across the globe and can drive new applications around the emerging metaverse and diverse new autonomous systems. While bringing all the necessary network elements together, it is envisaged that TITAN will **uncover many unsolved research challenges across the interfaces** and will **solve some of these challenges.** The TITAN vision can only be realised by **co-creation** enabled by an environment that allows **active and meaningful cross-disciplinary collaboration**. Therefore, TITAN has **brought together 16 universities** that individually lead research in crucial segments of communication networks and four UK organisations/institutes that are at the forefront of translational research. TITAN will provide **strong consolidated inputs** to **global activities in telecommunications** in **partnership** with the **companion EPSRC platforms.**

2 Approach

TITAN is organised into six synergistically linked Lighthouse Projects (LPs), each led by an expert in the respective domain. These LP teams are tasked with addressing multifaceted **cross-cutting challenges** that span across various LP technology domains. Therefore, they will not only advance the state-of-the-art within their individual LPs but crucially also resolve critical issues at the intersections of these technology domains.

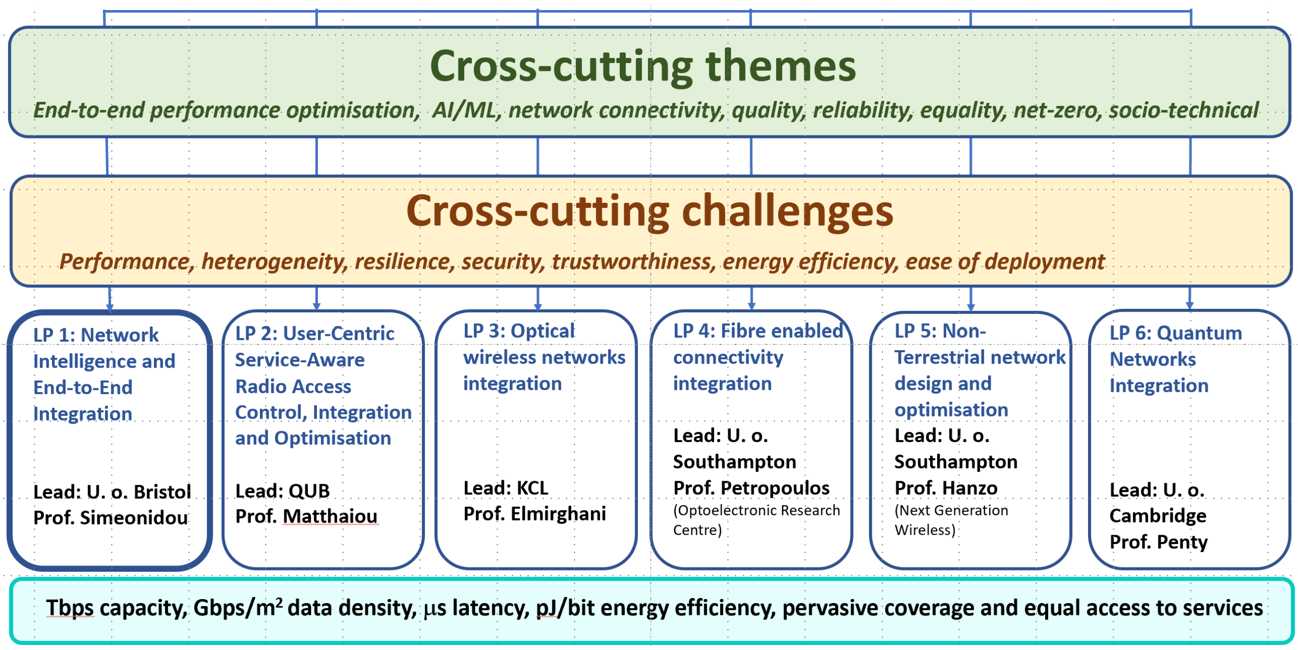

Figure 1: TITAN Lighthouse Projects (LPs) and key performance indicator targets of a future NoN.

Each LP has defined a set of objectives and high-level tasks as outlined in the original submission. This funding will allow partners to expand on these tasks and to carry out the required research to meaningfully advance the field and to contribute to the objectives of TITAN. This will be achieved through a series of strategically aligned MPs that will harness the UK's extensive and internationally recognised research capabilities in telecommunications, thereby facilitating the outcomes essential for realising the UK's ambitions in the telecommunications sector. These MPs will be highly collaborative within the TITAN consortium, and also across HASC (Hub in All-Spectrum Connectivity) and CHEDDAR (Communications Hub for Empowering Distributed clouD computing Applications and Research) and JOINER (Joint Open Infrastructure for Networks Research).

2.1 Partners

TITAN is a consortium with 16 universities and four UK institutes which will support the effective translation of research. All partners are summarised in Table 1.

1	Bangor University (BU)	11	Loughborough University (LU)
2	Queen's University Belfast (QUB)	12	University of Oxford (UOX)
3	University of Bristol (UoB)	13	Queen Mary University of London (QMUL)
4	University of Cambridge (UCam)	14	University of Southampton (UoS)
5	University of Durham (UoD)	15	University of Strathclyde (UoSt)
6	University of Edinburgh (UoE)	16	University of Warwick (UoW)
7	University of Essex (UoEs)	17	Digital Catapult (DC)
8	Heriot Watt University (HWU)	18	Compound Semiconductor Center (CSC)
9	Imperial College London (ICL)	19	Bristol Digital Futures Institute (BDFI)
10	King's College London (KCL)	20	Fraunhofer CAP UK (FCAP)

Table 1: TITAN partner universities and institutions

2.2 Strategic fit

Future Telecommunications has been identified as one of the five critical technologies by the UK government. As such the objectives of TITAN are aligned with the UK Wireless Infrastructure Strategy released by The Department for Science, Innovation & Technology (DSIT). Furthermore, the work programme interlocks with the TITAN centre-to-centre proposal with Germany which aims at jointly advancing technologies for the sixth generation (6G) networks on an international level.

2.2.1 LP1 – Network Intelligence and end-to-end integration (Lead: UoB)

The objectives of LP1 as stated in the original proposal are to develop:

O1.1) reference architectures for future E2E autonomous open networks;

O1.2) multi-access network solutions, considering future radio access network RAN and beyond (e.g. optical-wireless, fibre and satellite), including new intelligent multi-technology access control;

O1.3) frameworks for embedded, trustworthy, and verified AI for the whole system coordinating AI solutions across the different segments of the network;

O1.4) AI/ML methods for network intelligence to enable E2E autonomous and predictive service delivery;

O1.5) security by design framework for open architectures.

To address these objectives six MPs are proposed (synergies with the CHEDDAR will be exploited):

MP1: Multi-access technology real-time intelligent controller (MATRIC) (Lead: UoB)

Based on the principles of disaggregated open radio access networks, new control monitoring and orchestration functionalities will be developed for a non-real time and real-time RAN intelligent controller which seamlessly integrates multiple access technologies (wired and wireless). This work will use advanced features and metrics that are developed for new access technologies in LPs 2-6, and it will make use of existing AI/ML tools, and new ones developed in this LP. New open application specific interfaces (APIs) will be developed based on the principle of 'openness by design'. MATRIC will be implemented in Joint Open Infrastructure for Networks Research (JOINER) and will form part of a UK 6G trails programme which TITAN will spearhead. This MP will address O1.1 and O1.2.

MP2: Adaptable and robust AI for networks – This MP feeds into the cross-cutting theme on "Network Artificial Intelligence" and extends to CHEDDAR and All-Spectrum hubs (Lead: ICL, named PDRA: Athanasios Gkelias)

This MP will develop new *robust and secure* AI and ML techniques for the design and control of communication networks. This is achieved by: i) mathematically formulating and creating simulated testbeds for network optimisation and control problems arising in all LPs; ii) applying adaptive, robust learning techniques (e.g., adversarial training, sensitivity analysis and robust optimisation) to tackle these problems. This MP will address O1.3 and O1.5

MP3: AI as Network Service – This MP feeds into the cross-cutting theme on "Network Artificial Intelligence" and extends to CHEDDAR and All-Spectrum hubs (Lead: ICL, named PDRA: Christian Porter)

By going beyond existing techniques (e.g., model adjustment and pruning), we aim to: i) identify critical characteristics that differentiate communication needs from AI (e.g., federated and reinforcement learning) from those in traditional communications; ii) jointly incorporate these considerations in network designs and operations to support AI/ML and re-design selected ML algorithms for given network architectures and resource constraints. This MP will address O1.4

MP4: End-to-End Integration of 5-layer non-terrestrial network (NTN) to terrestrial network (TN) (Lead: HWU, named researcher: KX Wang)

HWU maintains unique facilities for NTN to TN testbeds and has research expertise from underwater to terrestrial to drones to satellite/space communications. In this MP, HWU will, i) establish an efficient and repeatable secure connection of heterogeneous deployment platforms with specific emphasis on failure prediction, traffic prediction, delay and control predictions, planning, and recovery strategies, ii) integrate a quantum key distribution (QKD) system with partial computational and physical layer security in high-speed optical communication systems; iii) incorporate AI-based intelligence network including coding, modulation, and network routing to achieve better power gains. This MP will address O1.5 and exploits strong links with LPs 5 and 6.

MP5: Adversarial Machine Learning for Communication Network (Lead: LU)

This MP project will investigate adversarial ML-based attacks and defence against attacks based on a neural rejection technique and auto-encoder based anomaly detection technique. Particularly, we aim to i) develop gradient based attacks for a range of ML based algorithms for communication networks, ii) demonstrate susceptibility of ML-based wireless network designs for two selected problems, spectrum sensing and network anomaly detection, iii) develop defence mechanisms based on support vector machine (SVM)-based neural rejection and autoencoders. This MP will address O1.4 and O1.5.

MP6: Federated Multi-modal Learning for Sensing and Communications (Lead: QMUL)

Sensor fusion via wireless channels is important for sensing and communication systems as radio frequency (RF) sensing has relatively low range resolution. Sensor fusion needs to consider both the multi-modal and privacy-protection problems. This MP will *first* design a semi-supervised auto-encoder via variational autoencoders to avoid leaking users' privacy. *Then*, this project will integrate the proposed auto-encoder algorithm into a new federated learning structure, where communication load via wireless channels will be minimised by considering the pruning and partial model transmitting. This MP will address O1.3, O1.4 and O1.5.

2.2.2 LP2: User-Centric Service-Aware Radio Access Control, Integration and Optimisation (Lead QUB)

The objectives of LP2 as stated in the original proposal are to develop:

O2.1) orchestrate different radio access technologies for different emerging application scenarios;

O2.2) optimise radio access from a user-centric perspective considering diverse service and security requirements as well as taking into account network resilience;

O2.3) introduce new performance evaluation metrics, specifically tailored to user-centric service-aware radio access control, that can be used to assess the suitability of the proposed technologies within future 6G networks taking also into account energy efficiency and security requirements.

To address these objectives four MPs are proposed (synergies with the All-Spectrum hub will be exploited):

MP7: Cyber-Physical Systems (CPS) (Lead: HWU, named PDRA: Anis Hadamoche)

6G is expected to have human-machine communications, actuation, and control through wireless or wired trustworthy communications. Mission-critical communication links must be guaranteed, and quality of service (QoS) must be ensured even when autonomous and interactive systems operate in human-populated and cluttered environments. This MP will develop i) new ways of machine-to-machine communication, such as semantic communication (post-Shannon communications) considering constraints in resource-limited environments to constantly adapt to the changing settings for machine-to-machine contacts; ii) data-aided AI paradigms for channel prediction. Given the complexities of indoor/small-scale environments, this will bring intelligence to react to internal/external interference. Case studies will be undertaken to explore innovative approaches for integrated sensing and communication (ISAC) that are critical for integrating robotics, autonomous and interactive systems. The case studies will help understand issues around sustainability/trust/risks of CPS. This MP will address O2.3.

MP8: Terahertz Integrated Sensing and Communications Theories (Lead: UoD)

Terahertz (THz) is one of the most promising frequency bands for future 6G wireless networks. Its large bandwidth and high frequency are also ideal for sensing. This MP will develop THz channel models. To this end, electromagnetic theory will be used to study THz wave propagation in both indoor and outdoor. Here the focus will be on the near-field, due to the small wavelength of THz, to recover the relationship between scattering and integrated sensing and communications. Moving on, this MP will use communications and information theories to propose new designs that optimise communications rate and/or sensing accuracy in either communications-centric, sensing-centric or Pareto settings. This MP will address O2.3.

MP9: Cell-free massive MIMO: From theory to implementation (Lead: QUB, named PDRA: Chi Yen Nguyen)

This MP will, for the first time ever, target the physical demonstration of cell-free communications showcasing uniform QoS to moving user in an indoor environment. To this end, a cell-free massive multiple-input multiple-output (MIMO) experimental system using software defined radios will be developed. This testbed is used to i) perform indoor-to-indoor and indoor-to-outdoor channel measurements and to develop new channel models; ii) compare different precoding/detection algorithms. The testbed will also be connected to JOINER to prepare for early 6G trials. This MP will address O2.2.

MP10: Friend or Foe: Securing Future Radio Access Technologies (Lead: QUB)

In future communication networks, the number of connected devices per km^2 will grow to unprecedented levels. Since the access points (APs) will be densely distributed over the area of coverage, the distances between APs and users or the potential eavesdroppers are shortened, which can increase the risk of confidential information leakage. In this MP, we are going to take large strides towards securing the future radio access technologies (RATs) with the following specific objectives: i) develop an analytical framework for modelling cyber-physical attacks in different RAT networks (e.g. cell-free massive MIMO, reconfigurable intelligent surfaces (RIS), THz networks, non-terrestrial networks, user defined networks); ii) detect and mitigate cyber-physical attacks using optimisation tools, cross-layer resource allocation, and machine learning (ML); iii) intelligently orchestrate RAT networks to enhance resilience and robustness in the network. This MP will address O2.1 and O2.2.

2.2.3 LP 3: Optical wireless networks integration (Lead: KCL)

The objectives of LP3 as stated in the original proposal are to develop:

O3.1) build resilient, net-zero optical wireless networks that achieve link data rate of hundreds of Gbps while enhancing physical layer security;

O3.2) exploit the properties of optical wireless networks to integrate sensing capabilities into networks;

O3.3) explore new architectures and transmission systems based on new device technologies.

To address these objectives eight MPs are proposed (synergies with the All-Spectrum hub will be exploited):

MP11: Low complex, resilient free-space optical backhaul (Lead: UCam)

As wireless networks expand into air, space and underwater, coupled with network densification to simultaneously optimise coverage and data throughput, there is an increasing need for innovative solutions that offer high-performance, reliable, and cost-efficient backhaul networks. Current optical free-space optical (FSO) systems typically employ expensive opto-mechanical beam acquisition and tracking (PAT) technology (e.g. gimbals). We have proposed a novel indoor optical backhaul system based on a grid-off beam (GoB) approach instead of using conventional PAT. The basis of the GoB approach is 2D transmitter arrays and 2D photodetector arrays. We now expanded this work to develop long-range FSO systems applying the GoB technique which also provides link diversity to combat turbulence effects. This MP will address O3.3.

MP12: Realisation of 100 μs latency and 1 cm positioning accuracy for industrial optical wireless communication (Lead: UCam)

Future smart factories require ultra-low latency (below 1 ms, without jitter and spikes not exceeding 10 ms) and precise positioning information to benefit from new technologies, e.g., high-precision robots. Due to the small wavelengths, the propagation of lightwaves in space can be tightly controlled. This MP will exploit this advantage to develop i) low latency optical wireless communications (OWC) communications by conceiving new digital modulation and coding techniques; i) demonstrate 100 μs latency in an optical wireless testbed in conjunction with JOINER, iii) developing sub-cm precise positioning techniques. This MP will address O3.2.

MP13: Integration of high-speed micro-LED transmitters with reconfigurable intelligent surfaces (micro-LED RIS) (Lead: UoSt)

Light-emitting diodes (LEDs) have opened up the possibility of alleviating bandwidth congestion in wireless networks through modulation of the light intensity. Micro-LEDs have particularly high bandwidth, enabling multi-Gb/s data rates in line-of-sight links. To make these data rates available in typical 6G application scenarios, beam-forming and beam-steering capability will be required, which is not intrinsically offered by micro-LEDs. In this project, RIS will be used to enable the required functionality. In this MP, micro-LEDs will be integrated with RIS, e.g., micro-electromechanical Systems (MEMS) mirror arrays, meta-surfaces, deformable membrane mirrors, etc., through assembly or through heterogeneous integration methods available at UoSt. This MP will address O3.3.

MP14: Integrated Sensing and Communications for Efficient Optical Wireless Networking (Lead: UoE)

It is envisaged that integrated sensing and communication (ISAC) will be a key 6G technology to optimise the utilisation of resources such as spectrum, energy, and hardware. The literature is scarce in the design of ISAC systems for OWC networks, even though they can offer much higher sensing resolution. In addition, important 6G applications with high-quality sensing requirements such as autonomous vehicles and extended reality typically use optical sensing components such as cameras and LIDAR. This project will define the key use cases of ISAC in OWC networks and develop a proof-of-concept demonstration of the technology. This MP will address O3.2.

MP15: Waveform Design for Resilient Underwater Optical Wireless Communications (Lead: UoE)

Future networks will expand into space and underwater. Therefore, it is important to develop underwater wireless communication technologies. The poor propagation of radio signals and slow speed of acoustic waves in underwater provide the motivations for the growing interests in underwater optical wireless communication (UOWC). However, the underwater optical channel refracts, diffracts, absorbs and scatters photons travelling through it, leading to reliability challenges. This MP will design a signalling/waveform that is best suited to the UOWC with the aim of achieving reliable underwater wireless connectivity at 10s of Gbps data rate. This MP will address O3.1.

MP16: End to end network slicing across multiple environments (Lead: KCL)

Network slicing enables the coexistence of multiple virtual logical networks in a shared physical network. To create a network slice, dedicated physical resources will be allocated across the different network segments; RAN, transport and core networks, in addition to cloud and edge computing resources. Furthermore, a network slice might span terrestrial and non-terrestrial platforms in a 3D networks. This mini project aims to study the integration of optical wireless communication networks with other networks to provide fronthauling, midhauling and backhauling in network slices of diverse QoS. This MP will address O3.1 and will strongly interlink with LPs 1 and 5.

MP17: Modelling tool for optical wireless networks integration (Lead: KCL)

This mini project will design and build a platform that integrate the optimisation models and algorithms of optical wireless networks developed in LP3 to serve as a modelling tool with a user-friendly interface. The modelling tool can be used by researchers to plan testbeds and gain further understanding of their environments and scenarios before building the testbeds. Insights from the modelling tool will feed into the refinement of the optimisation models and algorithms in LP3, and will provide crucial data for the JOINER testbed expansion. This MP will address O3.1.

MP18: Photonic Lanterns for Turbulence Mitigation in FSOC (Lead: UoS)

Turbulence, and the resulting scintillation it causes in a signal, is an inevitability for terrestrial free-space optical communications (FSOC), resulting in reduced reach, datarate and loss-of-service. Whilst turbulence can be mitigated using spatial light modulators (SLMs), the approach is prone to increased cost, weight and attenuation. Recently, photonic lanterns (fibre-based mode-demultiplexers) have been considered as a cheaper, lighter, and lower loss alternative. We propose to construct a fully fibre-based solution to turbulence mitigation, using optical (and importantly, not digital) recombination, with phase tracking performed using fibre stretchers and phase dithering (reducing photodiode count). This MP will address O3.3 and will leverage links to LPs 4 and 5.

2.2.4 LP4: Fibre enabled connectivity integration (Lead: UoS)

The objectives of LP4 as stated in the original proposal are to develop:

O4.1) Develop flexible fibre network architectures that exploit the physical characteristics of the fibre channel across different parts of the spectrum to support heterogeneous traffic and to explore sensing capabilities;

O4.2) Develop models based on ML to inform and optimise dynamic spectrum allocation and switching;

O4.3) Exploit the potential of new fibre, transmission and amplifier technologies for the implementation of low-latency, high-capacity access networks.

To address these objectives four MPs are proposed (synergies with the All-Spectrum hub will be exploited)

MP19: Technologies for all-optical access systems (Lead: UoS)

Future access networks will necessarily incorporate a variety of technologies, including RF, OWC and fibre solutions. Many of these access technologies are powered by a direct connection to the regular power grid. There are instances (e.g. health and security) where this exclusive dependence on the power grid is undesirable, since it compromises network resilience. Power-over-Ethernet (where power and data are delivered over copper network cabling) has been proposed to help address this vulnerability, however, data rates fall short of fibre-optic solutions and its range is limited to 100 m. Here we will explore all-optical solutions for extending this range or data rate, using power-efficient receiver electronics and the transmission of power over optical fibre. The project will look to identify the key technologies to enable such systems, as well as the application scenarios (i.e. range, in both distance and power) over which such solutions are viable. This MP will address O4.1.

MP20: High-capacity transceivers for next generation optical access networks (Lead: UCam)

The combination of transmission impairments and loss in the optical distribution network (ODN), requires new approaches for optical access networks in order to increase data rates for the next generation. In 2021 the ITU standardised a direct detection based 50 Gbit/s downstream with 25 Gbit/s upstream with up to 32 dB ODN loss. This mini project would use a low complexity, low-cost coherent receiver in the optical network unit (ONU) for the next generation optical access networks targeting 200 Gbit/s and higher. This MP will address O4.3.

MP21: Chaotic digital filtering for realising ultimate "Security by Design" networks (Lead: BU, named PDRA: Roger Giddings)

"Security by Design" is one of the most important features required by future data networks of various types. However, no physical-layer, low-cost solutions have been reported to offer sufficient compatibility with existing networks and excellent transparency to future technologies of various layers. BU has proposed a ground-breaking chaotic digital filtering technique, in which privately generated noise-like security keys are introduced into the network-embedded digital filter construction processes to make these filters chaotic. This MP will identify optimum filter design parameters for different application scenarios. In addition, it will experimentally validate the proposed technique in various point-to-point (PtP) and point-to-multipoint (PtMP) network architectures based on fibres, optical wireless and converged fixed and mobile. This MP will address O4.1.

MP22: Data-carrying optical signal-based sensing in legacy fibre networks (Lead: BU, named researcher: Wei Jin)

Commercially available optical sensing uses dedicated high-power optical pulse trains as sensing signals, thus requires physically large and power-hungry lasers. They are expensive, have a large form-factor and high energy consumption. On the other hand, no data-carrying optical signal-based sensing has been reported for cost-sensitive fibre networks based on intensity modulation and direct detection. This MP will develop, demonstrate and optimise fibre sensing techniques using ML tools to further improve the sensing performance for a specific application scenario, reduce its DSP complexity, and further enrich its overall functionalities. This MP will address O4.2.

2.2.5 LP 5: Non-Terrestrial network design and optimisation (Lead: UoS)

The objectives of LP5 as stated in the original proposal are to develop:

O5.1) develop techniques that will allow maintaining a uniform quality of service in a network with increasing non-terrestrial network elements, and thus effectively mitigating the digital divide;

O5.2) develop techniques for prompt, low-delay on-line optimisation allowing each network element to make its decisions independently - ideally based on local constraints and on limited cooperation strictly with immediate neighbours only, while approaching the Pareto-front of centrally controlled solutions;

O5.3) conceive Pareto-optimal RA solutions without relying on high-overhead central control.

To address these objectives seven MPs are proposed:

MP23: Network-slicing aided multi-component optimisation of NTNs/ space-air-ground integrated networks (SAGINs) (Lead: UoS, named PDRA: Kangda Zhi)

As an attractive enabling technology for next-generation wireless communications, network slicing supports diverse customised services in the global SAGIN with diverse resource constraints. This is particularly critical in the face of the extremely heterogeneous characteristics of the terrestrial, aerial and satellite layers, where the propagation conditions, including the bandwidth, carrier frequency, distances, line-of-sight (LOS) vs. non-line of sight (NLOS) conditions are substantially different. The throughput, the delay and the coverage area of these three classes of RAN slices will be jointly optimised by carefully considering the distinct channel features and service advantages of the terrestrial, aerial and satellite components of SAGINs. Given the potentially excessive complexity of solving the above problems to find the Pareto optimal solutions in high-Doppler scenarios, sophisticated AI techniques will be conceived for solving the associated problem. This MP will address O5.2 and O5.3.

MP24: Adaptive physical layer design for NTN/SAGIN systems (Lead: UoS, named PDRA: Wanli Li)

In the 2G, 3G and 4G terrestrial systems different Gaussian minimum shift keying (GMSK)/ time division multiple access (TDMA), code division multiple access (CDMA) and orthogonal frequency division multiple access (OFDMA) solutions have been used, but the 5G systems opted for a similar OFDM-based physical layer (PHY) to that of the 4G systems. However, current PHY layer technologies fall short of accommodating the demands of high-mobility scenarios envisioned for 6G networks. One significant limitation is their inability to effectively handle the elevated Doppler spread commonly encountered in SAGINs. This MP will develop new PHY layer techniques for NTN/SAGIN networks and will address O5.1.

MP25: Task Specific Security Solutions for Space-Air-Ground Networks (Lead: UoEs, named PDRA: Nihan Ari)

Ensuring security, reliability, and resilience in NTN/SAGIN networks is an open challenge. In this mini project, we will develop an innovative task-specific security protocol leveraging physical layer security (PLS) techniques that aims to provide security measures for the semantics of the data rather than the data itself and adjust to requirements of the different parts of SAGIN. This MP will address O5.2.

MP26: Semantic Aware Modulation Schemes for Space-Air-Ground Networks (Lead: UoEs)

NTN/SAGIN networks suffer from long delays and cannot guarantee sufficient bandwidth resources to facilitate emerging applications based on extended reality, among other applications. These applications typically require transmission capabilities in the region of 10s -100s of Mbps at less than 10 ms delay. Semantic communication has been proposed as an efficient way to improve the effectiveness of communication by considering the semantics of the data rather than trying to reconstruct the data faithfully. In this MP, we aim to revolutionise the design of modulation schemes for SAGIN networks by considering the content/context (semantics) of the data to deal with excess delay and inefficient use of network resources. This MP addresses O5.1

MP27: Quantum Signal Processing and Optimisation Algorithms for Non-Terrestrial Communications (Lead: UoW)

The computational capability outpaced by demand has become the bottleneck in the development of future non-terrestrial communications that cannot be dealt with by today's supercomputers. Quantum computing has emerged as a new tool, but its current applications in communications are still very limited, and are yet to show tangible advantages over classical methods. This MP will address the computational bottleneck by exploiting quantum computing techniques through effective modelling and algorithm design for channel estimation and prediction, channel decoding and quantum optimization algorithms. This MP will address O5.1 and will leverage synergies with LP6.

MP28: NTN design and optimisation (Lead: QMUL)

Unmanned aerial vehicles (UAV) play a critical role in future NTNs. However, the flight trajectory must be optimised to maximise coverage. In this context, multi-objective (MO) optimisation plays a pivotal role in the realm of airport flight planning, and its relevance extends to the domain of UAV swarm trajectory planning in NTNs. In addition to conventional objectives, e.g., communication quality, energy consumption, and collision avoidance, UAV swarm introduces a new optimisation domain, i.e., swarm structures. This MP will develop MO soft actor and critic (SAC) algorithms to find the full potential of a sensing and communication system under bandwidth constraints. This MP will address O5.2.

MP29: Low-complexity Channel Estimation and Data Detection in High Doppler Non-Terrestrial Networks (Lead: LU)

The currently used orthogonal frequency-division multiplexing (OFDM) modulation technique is primarily designed for time-invariant frequency-selective scenarios. However, in the high-mobility NTNs, mainly doubly selective fading is encountered and the substantially increased Doppler frequency leads to intercarrier interference (ICI) that damages the OFDM's subcarrier orthogonality. Orthogonal time-frequency space (OTFS) has been proposed as a promising candidate for high-mobility communications. However, OTFS modulation will dramatically increase the system complexity, especially at the receiver side. Thus, designing low complexity OTFS receiver with high reliability is essential for OTFS modulation to be adopted by new-generation wireless communication systems. To address these challenges, this MP contributes to development of signal processing and ML solutions for channel estimation and signal detection for OTFS-based NTNs. This MP address O5.3

2.2.6 LP 6: Quantum Networks Integration

The objectives of LP6 as stated in the original proposal are to develop:

O6.1) create an effective research forum comprising research groups with activities in application of quantum networking in future telecom networks;

O6.2) create a collaborative research program to address application and challenges of Quantum Networking in future telecom networks with focus on security, distributed computing and sensing;

O6.3) create a collaborative research program to address technological and architectural challenges for co-existence of quantum and classical information channels in terrestrial and satellite telecom networks.

To address these objectives four MPs are proposed:

MP30: Co-existent Entanglement based QKD with Classical data on metropolitan networks (Lead: UCam)

This mini project will build upon the photon entanglement based quantum cryptography system currently being built in Cambridge. It will initially provide the real-time software to optimise the rate of secure key generation and enable these keys to interface with our 100Gb/s classical data transmission systems. The project will then focus on optimising the operational parameters of both the quantum and the classical systems to provide the greatest achievable key rates while facilitating multiple 100Gb/s data channels to co-exist on the same fibre. This will be demonstrated over field trials on metropolitan scale deployed fibres within the Cambridge dark fibre networks and JOINER. This MP will address O6.2

MP31: Solar-blind Ultraviolet Micro-LEDs for Optical Communications and Quantum Key Distribution (SUMO-QKD) (Lead UoSt in collaboration with UOX)
Light-emitting diodes in the solar-blind region of the ultraviolet spectrum (UV-C, <280 nm) can provide an optical channel in a noise-free region of the spectrum, with state-of-the art communications demonstrations up to 10 Gb/s and over distances >100 m. Micro-LEDs emitting in the UV-C will provide very high modulation bandwidths and commensurately short optical pulses suitable for both classical optical communications and QKD. These properties will be exploited to build new Quantum Key Distribution (QKD) using UV-C LEDs which will be fabricated at UoSt. This MP will address O6.1.
MP32: Quantum Networks and Cryptography (Lead: ICL)
To realise quantum networks (QN), we aim to develop efficient entanglement routing and coupling of distributed nodes to perform given computation and communications. For security, post-quantum cryptography (PQC) is quantum-safe classical cryptography based on computational assumptions that features large-scale, inexpensive software/hardware implementation. Security of quantum communication (QC) does not rely on computational assumptions, but it requires dedicated hardware. Our goal is to break the boundary between PQC and QC. This MP addresses O6.2 and O6.3.
MP33: Distributed computing over quantum multiple access networks (Lead: KCL)
This MP investigates the application of quantum protocols and the stabiliser coding formalism to the problem of communication cost reduction, efficiency improvement, possibly with privacy and security constraints, in multiple access networks, wherein, several transmitters/nodes/sensors are communicating with a central unit to accomplish a distributed computation task. The potential improvements are expected to come from superdense coding gain, which is the unique opportunity created by quantum entanglement amongst the transmitters, together with classical techniques. This MP will address O6.2 and O6.3.

JOINER plays a crucial role in harmonising and validating the outcomes of MPs by enabling seamless end-to-end experimentation towards the ultimate network of networks. This federated infrastructure is particularly vital as it allows us to thoroughly assess the effectiveness of technology-specific innovations originating from LPs by means of MPs that target very specific problems. This unique symbiosis not only paves the way for early 6G trials but also empowers the UK Telecoms ecosystem to present well-founded, practically proven ideas to Standard Development Organizations (SDOs).