TUDOR: Towards Ubiquitous 3D Open Resilient Network
Funded by the Department for Science, Innovation and Technology, under the
Future Open Networks Research Challenge

TUDOR: Towards Ubiquitous 3D Open Resilient Network

D0.7.1: Project closure report

Version: v1.0

Deliverable type	R (Document, report)
Dissemination level	PU (Public)
Due date	20/12/2024
Submission date	26/06/2025
Lead editor	Bernard Hunt
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Reviewers	
Work package, Task	WP0
Keywords	TUDOR,

Abstract

This report provides a final summary of the DSIT project TUDOR (Towards Ubiquitous 3D Open Resilient Network), run under the Future Open Networks Research Challenge, FONRC.

Document revision history

Version	Date	Description of change	List of contributor(s)
v0.1	16/06/2025	Initial integration of contributions	Chris Alais, Taisir Elgorashi, David Griffin, Bernard Hunt, Peizheng Li, Yi Ma, Jingxuan Men, Agustin Pozuelo, Riccardo Pozza, Charalampos (Haris) Rotsos, Nida Shafi, Arman Shojaeifard, Yao Sun, Ning Wang, Shixiong Wang, Lei Zhang
v0.2	18/06/2025	Introduction, TUDOR overview	Bernard Hunt
v1.0	26/06/2025	Document completed for submission	Bernard Hunt
v2.0	24/07/2025	Document revised according to DSIT feedback	Bernard Hunt

Acknowledgment

The authors would like to thank the Department for Science, Innovation and Technology for creating the Future Open Networks Research Challenge and for selecting TUDOR to be funded within the programme. We thank all the DSIT staff who worked on or with TUDOR, particularly Trevor Gill and Steve Methley (DSIT Technical Design Authorities) whose technical oversight provided valuable guidance to the project. We must also acknowledge that the text describing FONRC in section 1.1 is adapted from that provided by DSIT for our joint article in ETSI Enjoy! magazine.

The authors would like to acknowledge the work of all TUDOR partners, member organisations, subcontractors, and external advisors in contributing to the activities and results documented in this report.

Finally we would like to acknowledge the collaboration of the other FONRC projects, REASON and YO-RAN, particularly the project leads and project managers. The excellent spirit of collaboration on practical, logistical, and technical levels, and on events has undoubtedly improved the outcomes of all projects and contributed to the ongoing strengthening of the UK telecommunications ecosystem.

It has been a pleasure and a privilege to work together in this programme.

Executive Summary

This report acts both as a closure report to DSIT for the TUDOR project and as a public overview of the project and its outcomes.

TUDOR (Towards Ubiquitous 3D Open Resilient Network) was a 2 year research project funded under the UK Department for Science, Innovation and Technology programme FONRC (Future Open Networks Research Challenge). The project brought together a consortium of 25 organisations from academia and industry, led by the University of Surrey 6G Innovation Centre. The consortium included major stakeholders from both the established telecommunications ecosystem and new players.

The project looked at the application of "3D" networks, comprising terrestrial, airborne and non-terrestrial components, to future telecommunications systems such as 6G, with an emphasis on widespread ubiquitous coverage, security and openness. The specific objectives of the project were:

- Realise open networking and universal connectivity
- Maximise spectrum openness and RAN efficiency
- Increase automation and agility in open network environments
- Enable 6G-era services and deliver a step change in future network capabilities
- Validate and test against emerging use cases
- Exploit and promote 3D open networks research

The project achieved meaningful progress against all of these objectives. Whilst this progress was documented in over 100 deliverables to DSIT, more impactful dissemination has taken place through:

- Academic publications (including "multiple best paper awards", e.g. in the area of security)
- Industry events and demonstrations (e.g. commercial workshops, Mobile World Congress)
- Successful contributions to global standards bodies such as 3GPP, ETSI and IETF
- Creation of new ETSI Industry Specification Groups addressing gaps in the standardisation landscape towards 6G
- Other ecosystem building activities such as collaborations with other FONRC projects and external stakeholders
- Training – academic researchers, bespoke training courses on Standardisation and Intellectual Property delivered to the whole FONRC ecosystem, the launch of a new Centre for Doctoral Training in Future Open SecuRe NeTworks (CDT-FORT)

To quote some of the industrial feedback after the fulfilment of the project:

- *"TUDOR has been an outstanding collaboration ... and we are grateful for the opportunity to contribute to one of the UK's most forward-looking and ambitious research programmes."*
- *"TUDOR has reinforced our confidence in the strength of the UK's research ecosystem and has helped deepen our engagement with UK academic institutions. It also strengthened our strategic outlook on investing in UK-based testbeds, innovation centres, and collaborative R&D frameworks"*
- *"The TUDOR project has provided a valuable platform for exploring advanced concepts that are central to the evolution of 6G and has successfully positioned the UK to take a leading role in shaping future telecommunications systems."*

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Abbreviations

3GPP	Third Generation Partnership Project
6G IA	6G Industry Association
AI	Artificial Intelligence
AI RSG	AI RAN Scenario Generator
DC	Data Centre
DSIT	Department for Science, Innovation and Technology
DT	Digital Twin
EPSRC	Engineering & Physical Sciences Research Council
ETSI	European Telecommunications Standards Institute
EuCNC	European Conference on Networks and Communications
FONRC	Future Open Networks Research Challenge
FRMCS	Future Rail Mobile Communication Systems
GFA	Grant Funding Agreement
GTP	GPRS Tunnelling Protocol
HA	Heuristic Algorithms
HAP	High Altitude Platform
HD	High Definition
HO	HandOver
HSR	High-Speed Railway
HST	High-Speed Train
IBN	Intent-Based Networking
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ISAC	Integrated Sensing and Communication
ISASC	Integrated Sensing and Semantic Communication
ISG	Industry Specification Group
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LEO	Low Earth Orbit
MAT	Multiple Access Techniques
MIMO	Multiple Input, Multiple Output
ML	Machine Learning
MNO	Mobile Network Operator
MWC	Mobile World Congress
NF	Network Function
NTN	Non-Terrestrial Network

O-RAN	Open Radio Access Network
OSP	Open Service Platform
PPO	Proximal Policy Optimisation
QoS	Quality of Service
REASON	Realising Enabling Architectures and Solutions for Open Networks
RIC	RAN Intelligent Controller
RSRP	Reference Signal Received Power
RTT	Round Trip Time
SC	Semantic Communications
SDO	Standards Developing Organisation
SNR	Signal to Noise Ratio
SNS	Smart Networks and Services
TDL	Tapped Delay Line
TEA	Techno-Economic Analysis
TN	Terrestrial Network
TRL	Technology Readiness Level
TUDOR	Towards Ubiquitous 3D Open Resilient Network
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UKRI	UK Research and Innovation
UKTIN	UK Telecoms Innovation Network
UKTL	UK Telecommunications Laboratory
UPF	User Plane Function
WP	Work Package
YO-RAN	York Open RAN

1 Introduction

This report summarises the activities and outcomes of the TUDOR (Towards Ubiquitous 3D Open Resilient Network) project, which ran as part of the UK Future Open Networks Research Challenge (FONRC) from February 2023 to March 2025.

The project results were captured in 102 deliverables supplied to DSIT, the vast majority of which are confidential. We do not try to cover all of the topics addressed in those deliverables within this report, but rather give a flavour of the project. Many of the technical achievements of the project are, or will be, captured in academic publications, and where appropriate the project has also contributed to various industry events and workshops, as well as providing input to the ongoing standardisation activities of relevance.

1.1 UK Future Open Networks Research Challenge

In 2022, the UK Department for Science, Innovation and Technology (DSIT) announced the Future Open Networks Research Challenge (FONRC) to allow industry and academia to develop future-facing open and interoperable solutions to diversify the UK's telecom supply chain. FONRC aimed to:

- Conduct research impacting future technology roadmaps with openness and interoperability embedded by default.
- Contribute to the strengthening of UK influence in SDOs.
- Strengthen the UK telecoms R&D ecosystem and telecoms capability.
- Engage with DSIT, UK Research and Innovation (UKRI), Engineering & Physical Sciences Research Council (EPSRC), UK Telecoms Innovation Network (UKTIN), SONIC Labs, UK Telecommunications Laboratory (UKTL), and other relevant government initiatives, and actively contribute to the UK's evolving future networks and 6G vision.

FONRC enabled universities to work with large RAN vendors and other telecoms organisations to conduct R&D to drive the openness and interoperability of future network architectures. These technologies should be commercially attractive to large vendors, MNOs and investors, and promote diversification in future network architectures.

Three projects were chosen to carry out the Challenge:

- REASON (Realising Enabling Architectures and Solutions for Open Networks) led by the University of Bristol.
- TUDOR (Towards Ubiquitous 3D Open Resilient Network) led by the University of Surrey.
- YO-RAN (York Open RAN) led by the University of York.

FONRC will run until the end of 2025.

2 The TUDOR Project

2.1 TUDOR Scope

TUDOR aimed to develop solutions for an energy efficient open telecommunications system capable of providing economically viable widespread geographic coverage and contributing to the UK strategy of diversification of the telecom vendors ecosystem. TUDOR researched and developed open network components and their seamless interoperability in the wider network environment, applying them across heterogeneous networks in 5G and Beyond – including terrestrial, airborne (e.g., HAPs) and satellite networks, which we call **3D Open Network**.

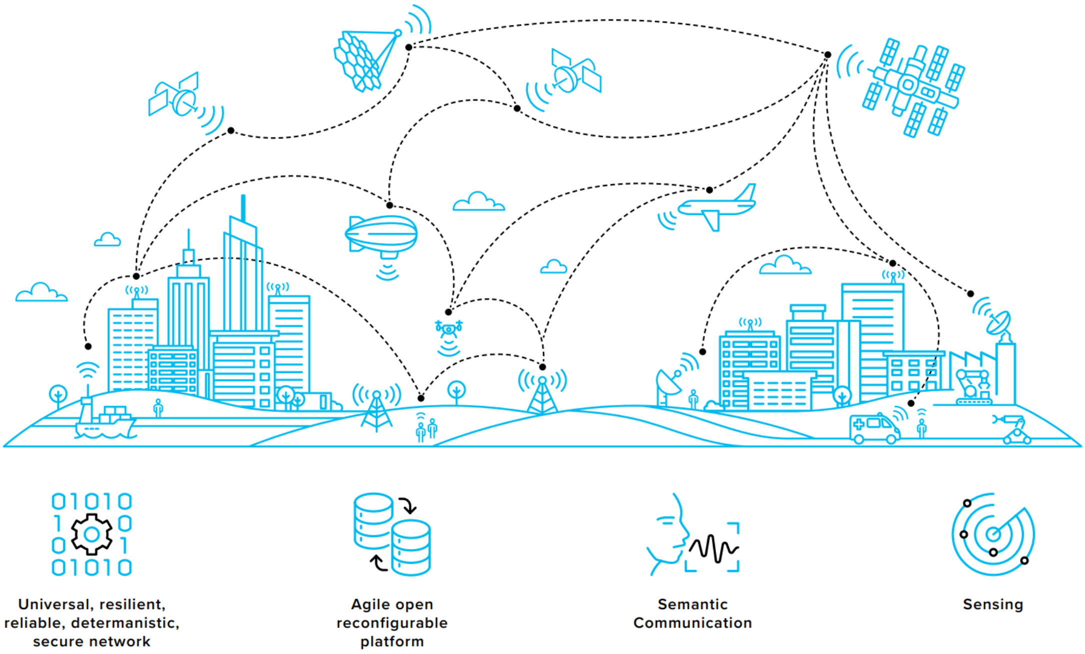

Figure 1: TUDOR 3D Open Network concept

The TUDOR project addressed the following development principles:

- Open disaggregation
- Standards-based compliance
- Demonstrated interoperability
- Implementation neutrality

The established approach to Open RAN was extended to core and transport networks including the service platform, allowing new vendors and infrastructure providers to deliver flexible, secure network services in a multi-vendor environment. Deep integration between terrestrial, airborne and satellite networks will enable reliable broadband services to be extended to all geographical regions.

At the time of project initiation, the TUDOR emphases on economically viable geographic coverage, security aspects, and NTN integration were somewhat groundbreaking, as the main focus of 6G discussions was still centred around data rates and capacity. However, it has been seen that these aspects have all taken on a significantly higher priority in the intervening time period.

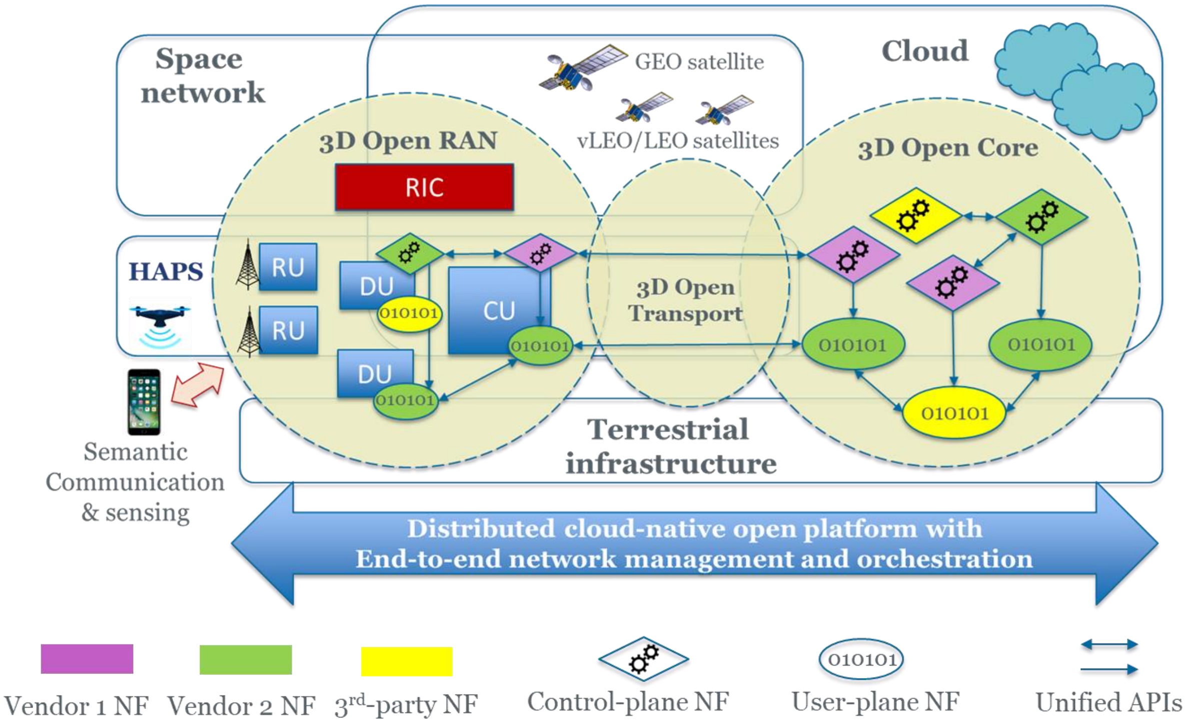

Figure 2: TUDOR Technical Goal

2.2 TUDOR Objectives

2.2.1 Objective 1: Realise open networking and universal connectivity

The aim is to design a novel 3D open network architecture to deliver seamless, reliable and secure full geographic coverage, from remote rural through to dense urban, indoor and outdoor environments.

1.1. Design a novel end-to-end 3D open network architecture supporting flexible, resilient and secured interworking across system components contributed from multiple vendors and across multiple provider networks

1.2. Apply and extend Open RAN principles throughout the 3D network to realise an open end-to-end network supporting flexible disaggregation with cloud-native support, simplifying integration and enabling seamless reconfigurations of diverse functions and resources.

1.3. Design techniques for end-to-end deterministic networking for fulfilling time-critical application requirements.

2.2.2 Objective 2: Maximise spectrum openness and RAN efficiency

Building on the 3D open network architecture, the aim is to deliver a capability which will ensure wireless network connectivity delivering the required level of service is available anywhere.

2.1. Design and develop novel solutions for user-centric, cognitive RAN intelligence in the 3D open network.

2.2. Design essential technologies for co-existence, seamless mobility between space and terrestrial networks through robust spectrum sensing and sharing.

2.3. Design an open spectrum architecture with AI-managed spectrum sharing across different 3D network elements.

2.2.3 Objective 3: Increase automation and agility in open network environments

3.1. Design automated and frictionless network control, management and orchestration solutions across network boundaries.

3.2. Develop a unique end-to-end Digital Twin platform for the 3D open network ecosystem.

3.3. Open up securely a service platform and interfaces for allowing third party clients to use the 3D open network fabric while hiding internal complexity to them.

2.2.4 Objective 4: Enable 6G-era services and deliver a step change in future network capabilities

Natively embed new functions exploiting the 3D network's potential to become the platform for radical new services and applications. Semantic communication (https://ieeexplore.ieee.org/document/9679803) is an emerging technology with the potential to deliver a step change in throughput across all network types through a radically different approach to network efficiency.

4.1. Research emerging semantic communication technologies in 3D network environments, targeting fundamental challenges on openness, energy and bandwidth efficiency and inherent security and interoperability between vendor-specific and provider-specific technology components.

4.2. Design and test new techniques for seamless integrating sensing with communication in the 3D open network environment.

2.2.5 Objective 5: Validate and test against emerging use cases

To implement and demonstrate the proposed open network solution with appropriate use cases oriented to 5G and beyond.

2.2.6 Objective 6: Exploit and promote 3D open networks research

Our aim is to ensure the UK remains in the leading position in new telecom technology development across the world toward and beyond 2030.

6.1. Generate new intellectual property from the project's innovations on beyond 5G evolution.

6.2. Actively participate in standardisation activities in key SDOs including 3GPP, ITU, O-RAN Alliance, IEEE and ETSI.

6.3. Identify future technology exploitation plans for the UK telecom industry based on TUDOR's end-to-end open networking solutions.

6.4. Build a solid UK roadmap towards future 6G and beyond network technology evolution/revolution.

6.5. Help with training of work force with new and unique skill sets with software, hardware, security, AI, network engineering, wireless and computer science. This includes training on standardisation processes and on IPR.

2.3 TUDOR Project Structure

The technical work in TUDOR was structured around 6 main Work Packages:

- Overall TUDOR Solution Architecture

  The overall solution architecture directed the work of the project towards common system requirements and design principles, bringing it together in an architecture meeting the needs of both 5G evolution and future 6G. End to end issues aspects of security, resilience, energy efficiency and techno-economic studies were also carried out here.

- Intelligent 3D RAN and Open Spectrum Architecture

  Providing both high performance and ubiquitous coverage increases the demand for efficient spectrum utilisation. The roles of spectrum sensing and AI supported spectrum co-existence, sharing and management were explored, bearing in mind the requirements of seamless integration and mobility between space and terrestrial. Deterministic networking techniques for addressing requirements beyond data rate, such as time-critical applications, were addressed.

- Distributed Cloud-Native Architecture for 3D Networks

  Key to disaggregated open networks is the development of a multi-provider, distributed, secure and resilient computational environment to house and execute network functions, applications and services. 3D networking brings increased opportunities and flexibilities in network construction, but also increased challenges in routing and service-function chaining.

- Semantic Communications and Sensing in 3D Open Networks

  The availability of data is key to enable AI techniques, and also can be used to more efficiently deliver a wide range of services to users. One unexploited source of context data is the communications system itself. Co-designing communications and sensing in an integrated fashion allowed us to tap into this potential for data and exploit it through new semantic communications techniques. Specific security issues around sensing, context and semantic communications were addressed here.

- Automated Management and Orchestration in 3D Open Networks

  Managing and orchestrating 3D networks requires an evolution of the solutions currently in use. Based on the principles of Intent-based networking developed AI-driven and close-control loop mechanisms which were tested in bespoke digital twin emulation addressing the existing RIC and TUDOR developments.

- Use Cases, System Integration and Testing

  TUDOR solutions were tested and demonstrated showcasing both technical capabilities and interoperability. End-to-end Use cases, testing scenarios and KPIs were defined not only in conjunction with project partners but also the external telecommunications industry and vertical industries. Some of these were tested and demonstrated on a large scale end-to-end prototype platform developed within the project.

These Work Packages were supported by Work Packages looking at Standardisation and IP, and Project Management.

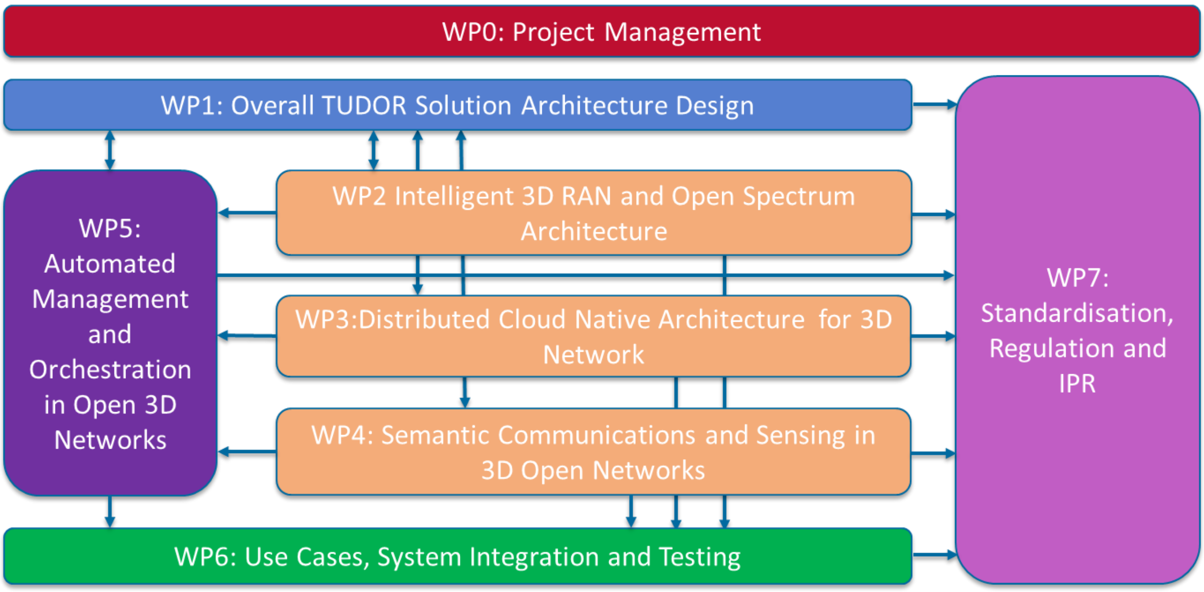

Figure 3: TUDOR Project Structure

2.4 TUDOR Consortium

The consortium, led by the University of Surrey 5G/6G Innovation Centre, brought together researchers from universities, vendors, MNOs, network/software developers and system integrators, from both space and terrestrial sectors, with strong representation of both the existing telecommunications ecosystem and new players.

University of Surrey 5G/6G Innovation Centre (TUDOR Project Lead)	
Amazon Web Services	AMD
AWTG	BAE Systems
British Telecom	Ericsson
Imperial College London	InterDigital Europe
King's College London	Lancaster University
Mavenir	National Physical Laboratory
Nokia	OneWeb
Qualcomm	Queen's University Belfast
Satellite Applications Catapult	Strathclyde University
Tactical Wireless	Toshiba
University College London	University of Glasgow
Viavi Solutions	VirginMedia O2

Table 1: The TUDOR Consortium

Figure 4: The TUDOR Consortium

3 TUDOR activities

3.1 WP1: Overall TUDOR Solution Architecture Design

WP1, titled "Overall TUDOR Solution Architecture Design" was responsible for the overall design of the TUDOR architecture framework for realising open 3D networks and it also included cross-cutting themes such as security, energy efficiency and techno-economic analysis. It aimed to tackle the overall TUDOR objective 1: "Realise open networking and universal connectivity", including its sub-objectives 1.1: "Design a novel end-to-end 3D open network architecture supporting flexible, resilient and secured interworking across system components contributed from multiple vendors and across multiple provider networks" and 1.2: "Apply and extend Open RAN principles throughout the 3D network to realise an open end-to-end network supporting flexible disaggregation with cloud-native support, simplifying integration and enabling seamless reconfigurations of diverse functions and resources."

The design of the overall TUDOR network architecture has two purposes: the reflection of network function disaggregation in the integrated 3D network environments in the 3GPP contexts, and also the long-term impact of future network evolutions towards end-to-end openness in general. For this purpose, the project team first defined the generic network architecture with the indication of RAN-Transport-Core network function disaggregation strategies in the integrated TN/NTN network environments. Such an architecture also reflects our design strategies in natively supporting AI-based network control and also in hosting represented 6G-oriented applications such as integrated sensing and communications (ISAC) and semantic communications. The project team further tailored the TUDOR architecture based on the 3GPP terminologies which potentially facilitates the opportunities for 3GPP contributions based on specific design perspectives. Meanwhile, the project team also envisaged a variety of possible business models in the open 3D network ecosystem, in particular how MNOs can collaborate with satellite network operators to build the end-to-end network capability. The TUDOR architecture design also retains the flexibility of supporting potential business models that involve different business interaction scenarios between the key stakeholders.

As part of the TUDOR project's security efforts, we conducted an in-depth analysis of attack surfaces, attack vectors, potential impact, and likelihood of attack across various scenarios, contributing to the development of end-to-end security and system resilience across all work packages (WPs) and looking into security aspects of payload variations across the architecture. We mapped parts of security and resiliency, particularly with the service migration and containing the attack. A new authentication and key agreement protocol, built on 3GPP's hierarchical key derivation, was formally verified using TAMARIN, demonstrating that key security properties are satisfied within the TUDOR architecture. Contributions from all WPs were aligned to strengthen overall security, with further enhancements informed by recent 3GPP reports and discussions with Tactical Wireless, Toshiba, Viavi, and BAE. This included exploring best practices in zero trust architecture, AI/ML security, and integrated sensing and semantic communication (ISASC) security. Our work resulted in seven core publications with two best paper awards on digital twin-driven security and abusive adversaries for open network components.

The TUDOR energy efficiency study introduced a framework to evaluate and improve the end-to-end energy efficiency of NTNs through efficient resource allocation across the O-RAN, core network and application layers under the constrained computational capacity and energy availability of NTN platforms. The energy efficiency of the regenerative payload LEO satellite architecture considering the network function disaggregation options identified by TUDOR was analytically compared to the state of the art bent-pipe LEO satellite architecture. The analysis also considered multilayered NTNs, RAN functional split options, traffic control in dual connectivity scenarios. Comprehensive mathematical models and AI-based algorithms were developed to optimise the TUDOR architecture to minimise the operational non-renewable power consumption and ensure service continuity considering NTN constraints on energy availability and computational capacity. The models assumed adopting energy efficiency measures including consolidating demands into fewer resources, putting unused resources into sleep mode, dynamic link rate adaptation, and energy efficient power profile of transmission equipment and computational resources.

The energy efficiency models and algorithms were integrated into a simulation tool in a user–friendly interactive platform capable of simulating different scenarios. The results obtained by the simulation tool show that the optimisation of the network function disaggregation in LEO-based NTNs can improve the energy efficiency by up to 40% compared to the bent-pipe architecture at low traffic demands. The results also show that the power consumption achieved by the AI-based algorithm mostly approaches that obtained by the optimisation model.

The TUDOR techno-economic analysis (TEA) outlines a strategic vision for NTN as a critical component of future wireless infrastructure, particularly for extending connectivity to remote and underserved regions. The study introduces a comprehensive NTN analysis methodology and evaluates four key economic scenarios: a global NTN operator model, MNO leasing of satellite capacity, a terrestrial-only counterfactual, and UK-based opportunities in the NTN equipment supply chain. It assesses commercial viability, deployment costs, market potential, and regulatory barriers from the business perspective. Meanwhile, we developed a flexible system engineering tool capable of accommodating diverse system parameters and cost models for TEA-driven engineering and economic analysis. Using this tool, the study quantifies the coverage, capabilities, and costs of BlueWalker-like and Starlink-like systems, incorporating user subscription models based on global population density. The analysis also highlights that regenerative and 3D Open RAN architectures can enable lower per-user service costs compared to traditional approaches. Overall, the TEA identifies key research gaps in NTN development, spanning 3D network architecture, service availability, and deployment economics, reinforcing the strategic importance of NTN for UK innovation leadership and making a strong case for continued research and targeted DSIT investment.

3.2 WP2: Intelligent 3D RAN and Open Spectrum Architecture

WP2 investigated five technical problems from a 3D radio access network perspective: 3D channel modelling, intelligent resource management, intelligent mobility management, deterministic networking, and spectrum sensing.

3.2.1 3D Channel Modelling

Within the TUDOR project, channel modelling was central to addressing mobility and resource management challenges within the 3D Radio Access Network (RAN) ecosystem, which integrates communication services across space, air, and terrestrial domains. A key objective was to implement a comprehensive channel model that encompasses both terrestrial and non-terrestrial network scenarios, accounting for their cohabitation. This modelling effort is crucial for understanding and optimising communication links in dynamic, highly mobile environments. It requires a range of techniques to characterise and predict signal propagation across diverse landscapes and serves as a fundamental knowledge base for designing advanced mobility and resource management algorithms. The project specifically considered scenarios such as high-speed trains (HST) as a representative use case, necessitating the development of channel models tailored to these intricate demands and high mobility conditions.

The project involved a thorough review of current trends and standards on terrestrial and non-terrestrial channel models, including 3GPP standards like TR 38.901 for terrestrial and TR 38.811 and TR 38.821 for non-terrestrial networks. For mobility management, large-scale fading models were implemented, while fast-fading models, specifically Tapped Delay Line (TDL) channel models based on 3GPP, were considered for resource management to account for multipath propagation. These channel models output key parameters, such as RSRP, which are pivotal for making informed decisions regarding mobility and resource management. The project also included the design and implementation of a simulation environment for HST, incorporating both terrestrial and non-terrestrial access points, and the validation of generated channel KPIs through various simulations.

3.2.2 Intelligent Resource Management

Intelligent resource management has been a key research objective within the TUDOR project, focusing on optimising resource management in 3D radio access networks (3D RAN), particularly for high-speed railway (HSR) communication and emergency communication scenarios. The project introduced a machine learning (ML)-based resource management framework, combining proximal policy optimisation (PPO) and heuristic algorithms (HA) to allocate resources dynamically based on real-time network conditions, user requirements, and service priorities. This approach successfully addressed key challenges such as high mobility in the HSR communication scenario and connectivity maintenance in the emergency communication scenario, leading to enhanced system throughput, reduced latency, and improved service quality.

In addition to the algorithmic design, the project delivered a comprehensive simulation evaluation, demonstrating the effectiveness of the proposed schemes compared to conventional resource management methods. Although there is a lack of real-world data on resource management for HSR communication and emergency communication under 3D RAN, and unavailable to process experimental tests at its development stage, the mathematical problem formulation and 3D ORAN environment simulation provide a strong theoretical foundation for future research on adaptive resource management in heterogeneous 3D RAN. While real-world 3D RAN implementations are still evolving, the developed schemes, models, and methodologies serve as a blueprint for tackling future network resource management challenges, with potential applications in space-air-ground integrated networks, etc. Further research, collaboration, and standardisation efforts will continue to explore the long-term impact of these innovations.

3.2.3 Intelligent Mobility Management

Mobility management in an integrated 3D RAN framework is more complex than in traditional networks that operate within a single segment. This complexity stems from the integration of diverse dimensions of networks, each with its own mobility patterns, connectivity protocols, and service paradigms. One typical scenario for mobility management in the 3D RAN network is train service in terms of different speed. With different speed operation of trains, the communication link between train-to-train and train-to-ground requires frequent inter-cell handover; it isn't easy to ensure the security of the communication link. To investigate the potential solution, this report proposes the intelligent HO solution for HSR in a 3D RAN network. Specifically, we design an RL-based optimised HO trigger condition algorithm. We formulate the HO problem in such a scenario and apply average throughput as a key KPI to improve the network performance. Based on the proposed HO Schemes, we design some simulation cases to evaluate the performance in terms of the metrics, including average SNR and Data Rate at handover points, Peak Data Rate obtained from ground and satellite segments, number of HOs, and outage probability. Further, we set up three simulations to fully evaluate the performance of the metrics in terms of different ground BSs distribution and different train speeds. The simulations results show that the proposed method effectively utilises satellite connectivity to supplement ground coverage, especially in scenarios where terrestrial infrastructure is sparse. The One Satellite scheme offers a viable alternative, particularly in denser urban areas, but its performance diminishes in less densely covered regions. The A3 scheme, while the most aggressive in terms of handovers, falls short in both data rate and reliability, making it the least favourable option among the evaluated schemes.

3.2.4 Deterministic Networking

Deterministic networking was included as a challenging research objective in the TUDOR project, especially by taking into account the network and channel characteristics of NTN segments. First of all, a general design of the deterministic networking framework was proposed by the project team, mainly focusing on the systematic organisation of key components to achieve deterministic user plane performances in 3D open network environments. Secondly, with the awareness that the performance requirements for specific 6G-oriented applications are still left open, we considered three complementary case studies to illustrate potential scenarios on deterministic networking, including the specific problem formulations and algorithms to achieve the corresponding performance requirements within reasonable ranges. These included downlink data traffic scheduling from constellating LEO satellites, traffic steering based on satellite + UAV based NTN traffic delivery, as well as dual-connectivity based solutions. In summary, in absence of specific real-life 6G applications at this stage, the project team designed the novel architecture framework that can be used for tackling future possible scenarios, plus the contribution of case studies examples with mathematical problem formulations and optimisation solution algorithms in well-defined 3D network environments.

3.2.5 Spectrum Sensing

Spectrum sensing technology was identified as a key research area for the objective of maximising the availability and utilisation of spectrum in 3D networks through intelligent spectrum management. The research activities started with an analysis of spectrum requirements and spectrum access models among terrestrial and non-terrestrial components of the 3D radio access network. Based on this analysis, four key challenges were identified with regards to implementation of spectrum monitoring platform and spectrum sensing algorithm: (i) we need to sample wide bands of spectrum across multiple spectrum bands allocated to 3D networks, (ii) we need to sense signals from radio transmitters that have different transmission behaviours as a result of significant differences in their operating altitudes and hence, different sensing use cases (iii) we need a cost-effective design and implementation of continuous real-time sensing, (iv) we need to develop a spectrum sensing algorithm that can perform better in unfavourable conditions than legacy algorithms.

The project outputs addressed these research challenges through two main outputs. A spectrum monitoring platform for provision of geo-located, time-stamped spectrum usage data was implemented and which demonstrated: (i) sampling of wide spectrum bands up to 300 MHz, across eight different spectrum bands in the low band mobile and mobile satellite spectrum band, (ii) configurable sensing parameters depending on use case to avoid under- or over-sampling, (iii) implementation on the same hardware platform that is used for radios which would enable cost-effective integration of spectrum sensing in future radios. The second output was a novel blind spectrum sensing algorithm for which simulation results showed that it is more robust to channel noise uncertainty than existing spectrum sensing algorithms.

3.3 WP3: Distributed Cloud-Native Architecture for 3D Networks

TUDOR WP3 designed the cloud-native computational infrastructure and control plane architecture for 3D networks, which comprise ground-based, airborne, and satellite domains. The design addresses the integration of terrestrial and non-terrestrial components, their interplay, and their interworking.

The architecture defines how infrastructure from multiple terrestrial and non-terrestrial domains can be integrated to support interworking between network functions across computational environments. The computational infrastructure is distributed over multiple cloud elements, including edge nodes and data centres operated by the network provider as well as those operated by other network providers and cloud-computing providers. The control plane has been designed to meet the novel requirements of dynamically moving network nodes in satellite networks. It also minimises the complexity of synchronising between satellite and ground-based resources, including a new disaggregated user plane.

Figure 5 provides a high-level abstraction of the 3D control plane as conceived in the project. At its core are the control plane functions, which are primarily responsible for orchestrating communication between User Equipment (UEs) and the 3D network infrastructure. These functions manage key tasks such as registration, authentication, session establishment, and mobility management. Additionally, they manage the 3D network itself, handling resource allocation, enforcement of quality of service (QoS) policies, session management, and interactions with other network domains.

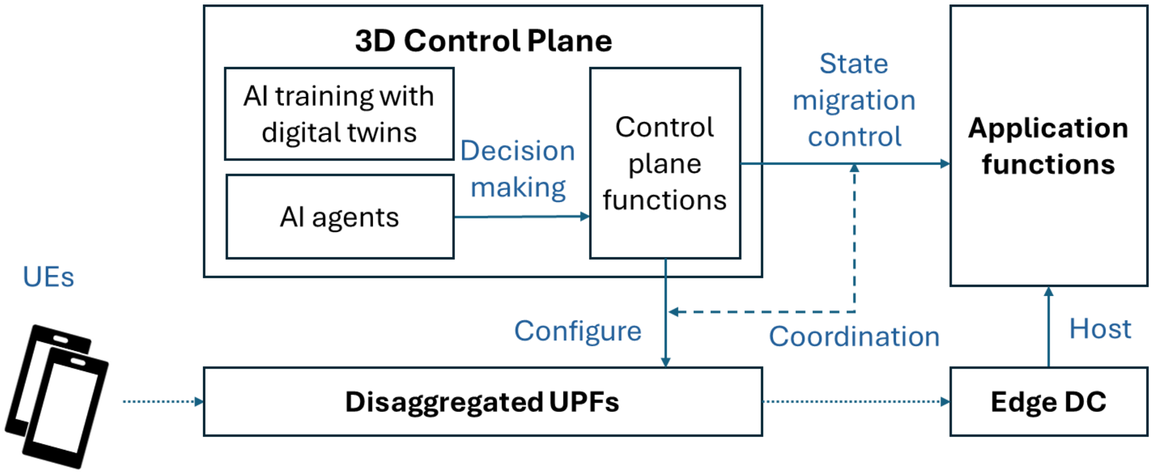

Figure 5: High level schematic of the TUDOR control plane architecture

The ultimate purpose of the control plane is to coordinate the user plane of the 3D network—the user plane being the raison d'être of the communications infrastructure. The figure represents the user plane with Disaggregated User Plane Functions (UPFs), which we have enhanced to better support non-terrestrial networks (NTNs), where not only the users but also the network infrastructure is itself mobile.

While telecommunications networks were initially designed for UE-to-UE communication, such as voice calls, modern networks predominantly enable UEs to interact with applications hosted on servers in data centres (DCs) accessible via external data networks. As shown in the figure, the user plane interconnects with edge DCs, which host the applications accessed by UEs. While accessing ground-based edge DCs is well-studied within the scope of Multi-access Edge Computing (MEC), we also support applications hosted on-board NTN nodes. This introduces new challenges in coordinating the user plane with application servers—both of which may be in motion—and in enabling lightweight migration of application states to facilitate latency-sensitive, long-lived sessions with minimal overhead.

The figure also highlights the integration of Artificial Intelligence (AI) as a fundamental component of the control plane. Our architecture incorporates AI for both inference and training, leveraging a digital twin of the 3D network during the training cycle.

The main functions of the TUDOR cloud-native environment are: firstly, to integrate multiple cloud sites from one or more cloud providers, creating a common multi-domain computational and communications substrate; and, secondly, to manage the lifecycle of virtualised network functions that are deployed and are executed upon that multi-domain substrate. The substrate needs to support virtualised RAN and Core network functions, virtualised application elements, TUDOR functional enhancements such as sensing and semantics communications, as well as management and orchestration functions responsible for the deployment, optimisation, and ongoing management of the entire network.

We consider two main usage scenarios integrating NTNs with TNs in 3D networks: (i) UEs accessing the NTN with sessions that terminate at UPFs on the ground, for access to terrestrial data networks such as the Internet; (ii) UEs accessing application servers hosted on the satellite constellation itself. In both cases, NTNs need to host network functions of the 3D network provider, and our computational architecture defines how this will be achieved.

Enhancements to the control plane were proposed to enable seamless interworking between terrestrial and NTN domains. A novel Service-Based Radio Access Network ensures stable connectivity and session continuity in dynamic environments where satellites or high-altitude platforms are mobile. New mobility management functions and an early breakout user plane were introduced to enhance handover efficiency, reduce signalling overhead, and maintain robust NTN operations.

The design incorporated a disaggregated user plane to streamline interactions between satellite and ground-based network functions. By employing programmable switches, it simplifies GTP tunnel processing and minimises the need for re-tunnelling, reducing processing demands on UPFs on-board satellite payloads. Additionally, by coordinating the configuration across disaggregated UPFs with a centralised controller we alleviate the signalling burden between satellite nodes and ground-based control functions, further enhancing network performance. Our prototypes achieved comparable forwarding performance to the state-of-the-art switches whilst decreasing handover latency by three times compared to current 3GPP UPF reselection mechanisms.

As previously mentioned, the 3D network infrastructure is physically distributed across terrestrial, airborne, and space-based components. Of particular interest is the collection of servers resident on satellites, and the applications that run on them. We proposed solutions to support stateful applications running in such an environment. As satellites hosting applications move, the application server that the user is connected to also moves. This requires that the application state is relocated closer to the user to keep latency within acceptable bounds and to prevent multi-hop inter-satellite link communications from becoming unmanageable. We developed control-plane coordination and state management strategies for this challenging environment. Our findings demonstrate that whilst low RTT can be achieved, which is critical for certain classes of application, it comes with increased overhead for state migration. The optimal balance between RTT constraints and state migration frequency depends on application requirements, satellite positions, and migration overhead costs.

We envision AI as an integral part of the future control plane of 3D networks, where any algorithm running in any network function could deploy an AI model that was either trained beforehand or is continuously trained throughout the network's lifetime. We designed a network digital twin to facilitate AI training and testing in a sandboxed environment, enabling experimentation with diverse configurations and scenarios without impacting live production networks. The TUDOR approach to AI-based control planes revealed that whilst significant resources are required for complex AI training workflows under realistic conditions, these requirements remain manageable. Digital twins provide superior realism compared to traditional simulators, though this comes with higher resource costs. Further research could explore hybrid approaches combining abstracted simulations with digital twin training.

The final aspect of the TUDOR computational and control-plane architecture is the Open Service Platform (OSP), which enables seamless orchestration of services across multiple providers and domains. This innovation enables 3D network providers to evolve beyond traditional service offerings to deliver "Network of Networks as a Service," unlocking new possibilities for customers in complex, interconnected environments. The OSP's east-west interworking enables direct resource consumption between operators without exposing subscribers to third-party platforms, whilst maintaining minimal additional latency for cross-domain requests. This architecture establishes a foundation for 6G and NTN technologies, promoting enhanced interoperability and resource efficiency.

3.4 WP4: Semantic Communications and Sensing in 3D Open Networks

3.4.1 Overview

Work Package 4 (WP4) of the TUDOR project worked on Semantic Communications and Sensing in 3D Open Networks, to be specific, the systems design, algorithmic developments, and experimental verifications of Semantic Communications (SC) and Integrated Sensing and Communications (ISAC). Involved partners include Imperial College London, University of Surrey, Ericsson, Nokia, Toshiba, Viavi Solutions, InterDigital Europe, Satellite Applications Catapult (SAC), and National Physical Laboratory (NPL).

The work of WP4 established a foundation and provided validation results for SC and ISAC, enabling enhanced efficiency and radio function reuse across integrated terrestrial (TN) and non-terrestrial (NTN) networks. From a system design perspective, WP4 explored architectural changes spanning multiple network layers, from physical layer mechanisms such as power allocation and beamforming to higher-layer protocols including user scheduling and network management. A key aspect of WP4 was the integration of SC and ISAC functionalities into Open RAN frameworks, leading to a semantic-aware and ISAC-enabled Open RAN architecture. This includes defining functional blocks, interfaces, APIs, and data flows to support these technologies within Open RAN environments. Additionally, WP4 investigated and validated novel RAN use cases for SC and ISAC, demonstrating their potential benefits within real-world network scenarios. The findings contribute to the advancement of Open RAN architectures and next-generation network designs, addressing the evolving requirements of future communication systems.

3.4.2 Technical Details

WP4 has committed 11 working milestones and 17 deliverables; all of them have been successfully approved by DSIT. To be specific, WP4 made the following technical contributions:

Specification of system requirements for supporting SC and ISAC in open networks. This includes designing systems architectures and function blocks, specifying interfaces and signalling strategies, and performance evaluation metrics and target values. For details on this aspect, see Deliverables D4.1.1, D4.1.2, D4.2.1, and D4.2.2.

Identification of real-world use cases. This includes Holographic Teleportation, Sensing Assisted Autonomous Vehicle Networks, Robot Swarms, Restricted Area Warning Systems, etc. For details on this aspect, see Deliverables D4.1.1, D4.1.2, D4.2.1, and D4.2.2.

Development of SC and ISAC techniques. This includes semantic coding and decoding, ISAC channel modelling, beamforming and waveform design, semantic-aware resource allocation, security issues for SC and ISAC, etc. For details on this aspect, see Deliverables D4.3, D4.4, D4.6, D4.8, and D4.9.

Design of testing scenarios, testbeds, and testing plans. For SC, holographic teleportation was worked on, while for ISAC, a MIMO downlink scenario was studied. The above two tests are based on physical testbeds in NPL. Experiments have shown significant data compression rate for SC and validated the feasibility of ISAC on a shared hardware. For details on this aspect, see Deliverables D4.5.1, D4.5.2, D4.7.1, and D4.7.2. In addition, the resource allocation and security solutions for SC and ISAC have been tested based on simulated and physical testbeds. Experiments demonstrated the power of the proposed solutions in enhancing connectivity, efficiency, security, and user experience in modern communication systems. For details on this aspect, see Deliverables D4.10.1, D4.10.2, D4.11.1, and D4.11.2.

Grounded in the above contributions, WP4 has generated 29 research papers that have been published on, or submitted to, reputed IEEE conferences, transactions, magazines, and letters. In addition, WP4 has filed 12 UK or US patents. Moreover, WP4 has contributed 15 items to international standardisation bodies such as 3GPP and ETSI.

3.4.3 Future Considerations

For future research based on this project's results, it is suggested considering some larger-scale and more-realistic scenarios for SC and ISAC testing, which would enable and facilitate the commercial developments of SC and ISAC concepts and techniques. In addition, in consideration of the flexibility and operationality for testing of semantic-aware and sensing-oriented (SASO) resource allocation and security solutions, simulated platforms are designed instead of the physical testbeds. This is because to test a specific resource allocation or security solution tailored to a complex use-case, the system architecture varies from one to another. Therefore, it is difficult to develop a unified testing platform that can support all user cases of interest. Therefore, the future industrial research in this direction may consider real-world platforms to validate the efficacy of the proposed frameworks and solutions.

The real-world demonstration of Semantic Communications for Immersive Media Delivery at Mobile World Congress (MWC) received highly positive feedback, paving the way for the practical adoption of semantic communication technologies. Attendees showed great interest in how AI impacts communications, including questions about the concept of semantics, AI's role in enhancing communication, cost implications, and the performance improvements compared to traditional methods—highlighting the potential commercial value of this field.

Additionally, attendees had the opportunity to experience firsthand the rapid and high-quality semantic transmission of live HD 3D video, gaining a deeper understanding of how semantic communication enhances the immersive media experience for users. These valuable insights from industry professionals provide meaningful references for the future development of semantic communication in immersive media applications.

3.5 WP5: Automated Management and Orchestration in 3D Open Networks

WP5 focused on developing a framework for service orchestration and management in a 3D Open Network infrastructure. The work package produced two components for the TUDOR architecture. Firstly, we created an autonomous management plane that facilitates end-to-end network service delivery by configuring individual technology domains within 3D open networks. The platform supports Intent-Based Networking (IBN), an emerging network management paradigm that offers built-in support for AI/ML models and provides programmable full-service life-cycle management (i.e., supporting both service provision and adaptation during network changes). Secondly, we developed an AI-driven Digital Twin (DT) platform to enable close-to-real-life emulation of end-to-end 3D open network behaviours.

Our network management framework was developed through four main tasks. Task 5.1 focused on creating a semantic intent-based networking and management architecture for 3D Open Networks. This task delivered the intent handler architecture and identified the key interfaces and technologies we could support in our prototype. Task 5.2 produced an implementation for automated end-to-end slicing and SLA assurances. The *OZ prototype intent handler* offered an extensible intent handler platform that allowed operators to integrate multiple network management domains with the platform and implement custom intent scenarios. We developed a custom *semantic web knowledge base* to store intent, management, and monitoring information. We also developed the first ontology that models the radio, transport, core, and cloud domains, as well as the TMForum Intent Common Model. Furthermore, a rule-based inference engine was designed for intent translation and verification. To test the generality of the platform, we created an automated slice delivery and adaptation scenario for 3D Open Networks. The slice intent allows a network tenant to dynamically deploy a new slice in a 3D Open Network in under two minutes and control the bandwidth and slice priority across the radio, transport, core, and cloud domains.

Task 5.3 explored the integration of the intent handler with the *Data and Information Fabric*, developed in collaboration with WP3, to support end-to-end and unified monitoring of network and service performance. As part of this activity, we created *an adaptive and flexible monitoring service* called Uniprobe. Uniprobe leverages the lightweight nature of the unikernel runtime, a cloud-native operating system (OS), and provides a cloud monitoring service comprising common network testing tools, such as ping and traceroute, with minimal memory and CPU requirements. Finally, Task 5.5 explored the integration of the intent architecture with the Open Service Platform, developed in WP3, to enable trustworthy multi-provider/tenant coexistence and end-to-end evaluation.

As part of the development activity, we open-sourced two prototype systems. OZ is the first extensible intent handler that provides native support for the TMForum Intent Common model[1]. Our ongoing efforts to implement the intent handler architecture were presented twice at IEEE NOMS [Alcock24] [Alcock25][2][3], an influential academic venue for network management topics. Furthermore, we have presented our work on the Oz platform twice in the TMForum Autonomous Network group [ANTMF][4], the leading standardisation group for the TMForum Intent Common Model. In parallel, we open-sourced

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[1] OZ intent handler code repository, https://github.com/lancs-net/oz

[2] P. Alcock, C. Rotsos and N. Race, "Oz: Towards an Extensible Intent Handler Architecture with Semantic Reasoning," NOMS 2024-2024 IEEE Network Operations and Management Symposium, Seoul, Korea, Republic of, 2024, pp. 1-5, doi: 10.1109/NOMS59830.2024.10575364.

[3] P. Alcock, R. Anand, C. Rotsos and N. Race, " SWIFT: Semantic Web Intent Framework for intent Translation," NOMS 2025-2025 IEEE Network Operations and Management Symposium, Honolulu, US, 2025, to appear.

[4] TMForum, Autonomous Networks Group, https://www.tmforum.org/topics/autonomous-networks/#networks

our network monitoring platform [Uniprobe][5], and we are currently exploring the adoption of our code by the Unikraft code distribution repository [Unikraft][6], the first production-ready Unikernel runtime.

The development of the DT platform was organised as a single task (T5.4). In the early stages of the work, we identified that a single Digital Twin model encompassing all physical, transport, and application layer characteristics would be highly computationally expensive, and a more scalable solution needed to be adopted. Consequently, we developed an architecture that utilised a pipeline model to coordinate the execution of multiple domain-specific DT platforms and to propagate estimated properties across layers. Our final deliverables consisted of two DT models: an Open RAN DT and a 3D Open Core DT. The Open RAN DT is constructed using a neural network model and provides accurate RAN power consumption and performance predictions when given a radio topology and a user equipment (UE) load and mobility scenario. Furthermore, the 3D Open RAN enables the integration of ORAN RIC controllers via the O1 interface and facilitates dynamic adjustments to the RAN configuration. The 3D Open Core DT employs modern emulation technologies to accurately model the functionality of a 5G core network and predict the performance of an end-to-end service under a specific network configuration scenario. To support 3D Open Network technologies, we developed an enhanced emulation link for NTN links using open-source measurement data from a satellite network provider. In parallel, a DT management framework and northbound interface were designed, allowing the execution of a custom 3D Open Network scenario. The service design aimed to support continuous integration (CI) scenarios, and a management architecture was outlined to facilitate what-if scenario testing by management services like the intent handler.

Both DT models are currently released and have achieved TRL 7 and TRL 4 technology readiness levels, respectively. The Open RAN DT model is now part of the Viavi AI RSG solution as a component of the Application Validation Engine[7]. The company showcased the DT model at the recent Mobile World Conference in Barcelona [VIAVI25][8]. This activity exceeded the original benefit BR 2.1a of the project, which aimed to improve the technology readiness level to level 4. Similarly, our 3D Open Core DT model has been open-sourced [Auto-6G][9] on the GitHub platform. To demonstrate the model's applicability, we prepared a video demonstration of its integration with the GitHub Actions CI pipeline as part of the D5.10 project deliverable, which enables a management process to assess the impact of cloud allocation policies on end-to-end performance. The model has been presented in various outreach activities, including the 2nd Summer School on 5G Connected Automated Mobility across Europe (Poster) [Anand24][10], and the NMRG – Network Digital Twin (NDT) side meeting during IETF 121 [King24][11]. Finally, a paper has been submitted to the IFIP Networking 2025 conference [Anand25][12].

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[5] Uniprobe monitoring service code repository, https://github.com/uniprobe/

[6] Unikraft Unikernel code repository, https://github.com/orgs/unikraft

[7] Viavi, TeraVM AI RSG, https://www.viavisolutions.com/en-uk/products/teravm-ai-rsg [online]

[8] Viavi, MWC Barcelona 2025: VIAVI Collaborations Showcase Importance of Ecosystem in Advancement of AI-RAN, 6G, NTN and Open Networks, https://www.viavisolutions.com/en-uk/news-releases/mwc-barcelona-2025-viavi-collaborations-showcase-importance-ecosystem-advancement-ai-ran-6g-ntn-and

[9] Lancaster Network GitHub organisation, https://github.com/lancs-net

[10] Revika Anand, Charalampos Rotsos, Nicholas Race, "ACTION-5G: Towards a 5G TN/NTN Digital Twin", 2nd Summer School on 5G Connected Automated Mobility across Europe, Paris France, July 2024.

[11] Daniel King, Revika Anand, Charalampos Rotsos, Nicholas Race, "Assured automation with Emulation-based Digital Twins", NMRG and ETSI ZSM joint workshop, IETF 121, Dublin, Ireland, Novemer 2024, https://datatracker.ietf.org/meeting/interim-2024-nmrg-04/materials/agenda-interim-2024-nmrg-04-nmrg-01-01.md.

[12] Revika Anand, Edward Austin, Charalampos Rotsos, Nicholas Race, "AUTO-6G: An emulation-based testing framework for TN/NTN integration", IFIP Networking 2025, Limassol Cyprus, under review.

3.6 WP6: Use Cases, System Integration and Testing

The Work Package 6 (WP6) work carried out the overall system environment development and integration activities to implement a realistic end-to-end prototyping platform for the 3D open network architecture, unifying space, cloud and terrestrial networks, where to test beyond 5G/6G oriented disaggregated, integrated and open network architectures.

Scope of this work package in the project, was to define use cases, testing scenarios as well as key performance indicators (KPIs) and metrics for the design and validation of an end-to-end TUDOR integrated testing platform for experimentation, which allows for systematically and comprehensively testing the operation and performance of TUDOR solutions.

The TUDOR integrated testing platform has been used to evaluate four use cases, which have been defined during the initial months of the project:

1. Safe and Secure Railways.
2. Emergency Services supported by the 3D open network.
3. Cloud Native Personalised Media Delivery.
4. Flexible Coverage Extension with interconnected Terrestrial/UAV platform.

Eight output deliverables have been provided, with details about the use cases, testing components, integrated platform, local components testing and end-to-end testing to evaluate target KPIs on the defined testing scenarios for each use case.

The realisation of an integrated testing platform has allowed to test scenario representative of the use cases defined, and thus to evaluate necessary capabilities of 3D open and integrated TN/NTN networks, which were defined early, matching the requirements and objectives of the whole project.

One of initial requirements of “High-speed Vehicle-on-the-move” emulation and traffic steering over integrated TN and NTN networks, has been validated and tested for the rail use case, whose objective was to evaluate scenarios of Future Rail Mobile Communication Systems (FRMCS), where resiliency and mission critical rail functions operation are deemed key elements.

“Handovers between TN and NTN networks” was another requirement evaluated in the project for the Emergency Services use case, where mission critical push to talk services where evaluated, with scenarios covering “Disaggregated Network Functions over the 3D networks”, critical for the implementation of resilient solutions, required during emergencies.

“Cloud Native and Virtualised Network Functions” based platforms have also been investigated through the Personalised Video Delivery use case, which allows deployment of dedicated network slices over the edge to cloud continuum, in scenarios of 3D open and integrated TN and NTN networks to deliver live and personalised media experiences.

Finally, through the flexible coverage extension use case, with interconnected terrestrial/UAV platform, it was possible to evaluate scenarios of “Disaggregated Network Functions in-space”, critical for 3D open networks on-the-spot deployment to increase coverage capacity, either in emergency situations or temporary events.

Concerning activities/engagement, part of the work was presented at the Mobile World Congress (MWC) 2025 in Barcelona, Spain, as part of the TUDOR stand, showcasing the University of Surrey Network Operations Centre, a management and orchestration solution capable of onboard and commission network slices and deploying disaggregated network functions over 3D integrated TN/NTN networks.

Overall, the implementation of all these use cases allowed the design of an experimental platform that will be extended in the near future to conduct research and development to drive the openness and interoperability of future network architectures.

The unique mix of low TRL open-source software with high TRL industry standard solutions shows that diversification in future network architectures is possible, thus allowing equipment interoperability and boosting resilience. Working with low TRL solutions however required some initial work to improve such solutions, which project partners will continue in the future, thus moving towards fully commercially viable solutions.

3.7 WP7: Standardisation, Regulation and IPR

Supported by the UK Government's Department for Science, Innovation and Technology (DSIT), the TUDOR project has delivered strong results in both dissemination and standardisation, reflecting its central role in advancing 6G research and development.

The project team made 55 substantial contributions to major standardisation bodies—36 to 3GPP, 13 to ETSI, and 6 to IETF. This significantly exceeds the original target of 20 and highlights the consortium's active engagement in shaping future standards. These inputs have addressed key technology areas, including AI, Non-Terrestrial Networks (NTN), and Integrated Sensing and Communication (ISAC)—all critical for the evolution of 6G.

In parallel, dissemination to the wider research community has been a key priority. The project resulted in 56 research papers across reputable conferences and journals, helping to ensure that TUDOR's technical work is visible, accessible, and influential beyond the project consortium.

Innovation was also a strong focus. The filing of 13 patents demonstrates the consortium's ability to generate tangible intellectual property from its research activities. These filings reflect a clear commitment to translating advanced technical work into real-world impact—something that aligns well with DSIT's broader objectives around UK innovation leadership.

The consortium has well exceeded its targets for standards contributions and paper publications. The number of patents created in turn is lower than the set target, attributed to the efforts towards other means of dissemination.

The project partners, in particular industries, will actively engage into 6G standardisation process post-completion of the project towards disseminating the results of the project, in particular targeting standards-essential and non-essential (implementation) mappings.

4 High Level Summary of Project Costs

The TUDOR consortium consisted of 22 project partners (2 as subcontractors) and 3 unfunded project members across academia, industry and research institutes.

The project was funded by the completion of milestones across 8 claim periods, with funding allocated by financial years. Claims could only be made against milestones completed within the respective period. Given the project plan for TUDOR was split into 42 tasks across 8 work packages, the consortium completed 93 milestones across the duration of the project, which in turn produced 102 deliverables.

Project costs were split as follows:

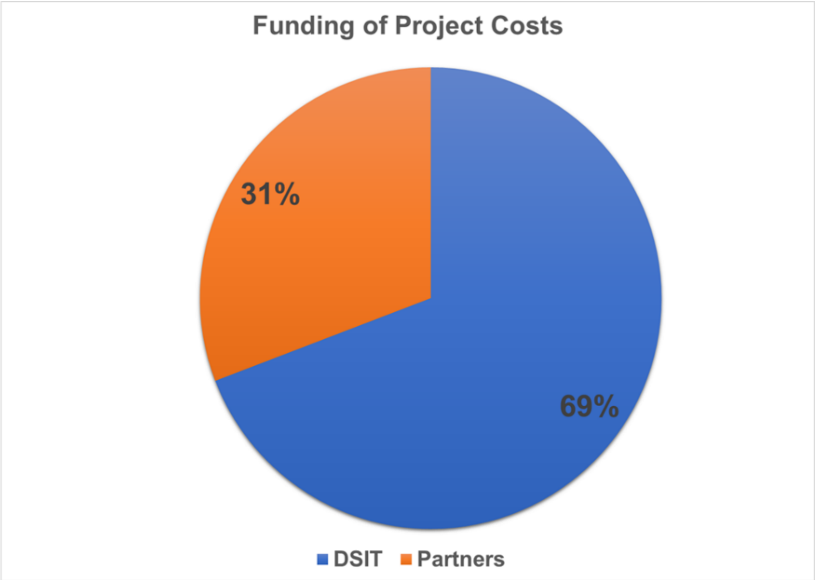


Figure 6: Funding of Project Costs

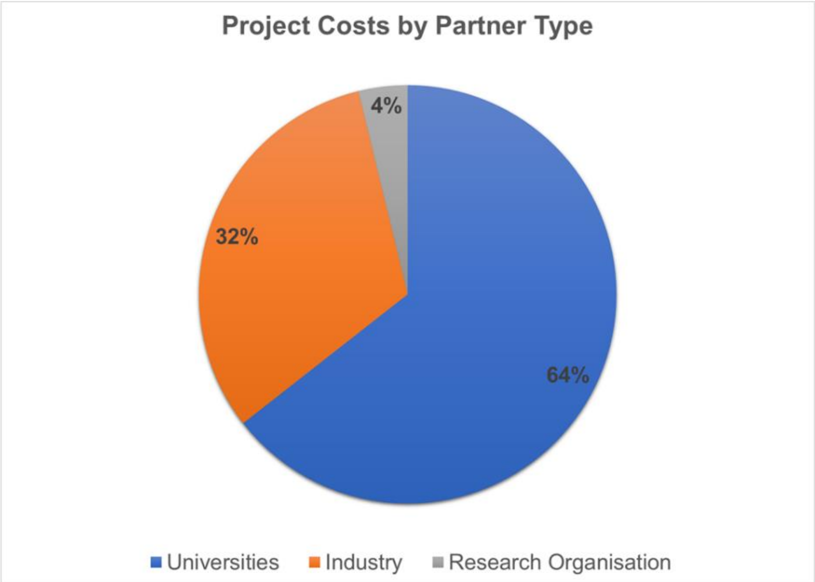


Figure 7: Project Costs by Partner Type

Over a 2 year research project involving so many partners, it was inevitable there would be changes in workload and spending within the consortium. Coupled with the ringfencing of funding by financial year, the project underspent it's grant funding by 10%. The following graphs show the spending profile of grant funding and distribution of costs by category:

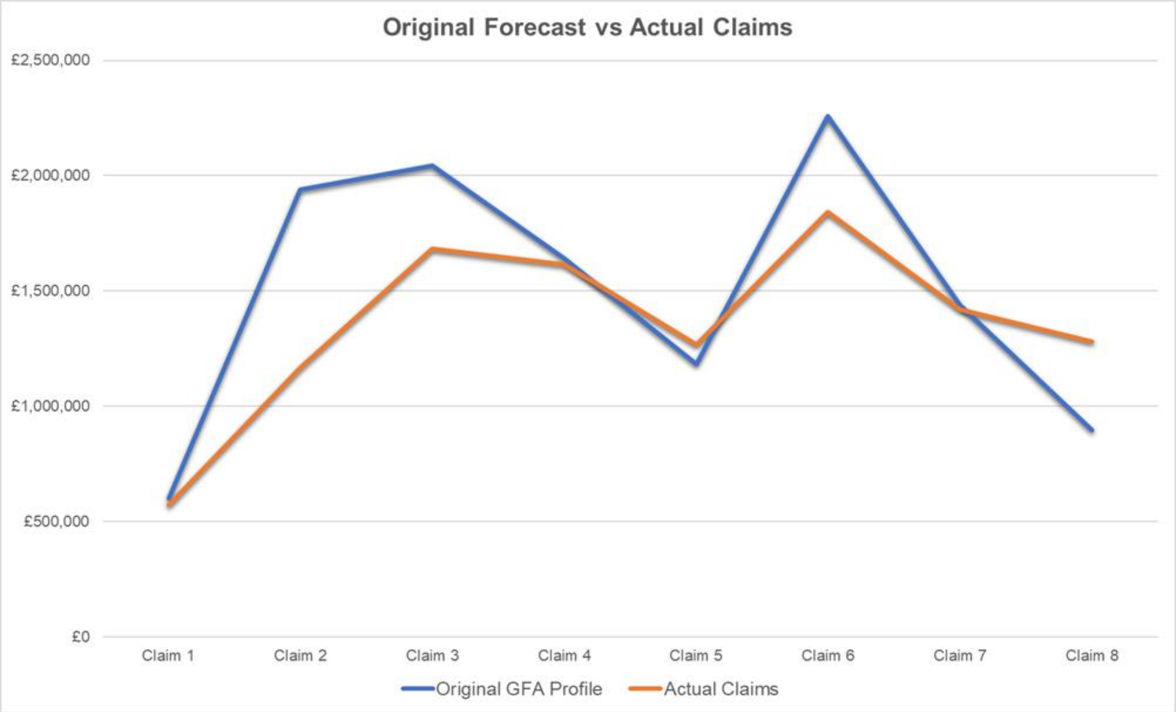


Figure 8: Spending Profile

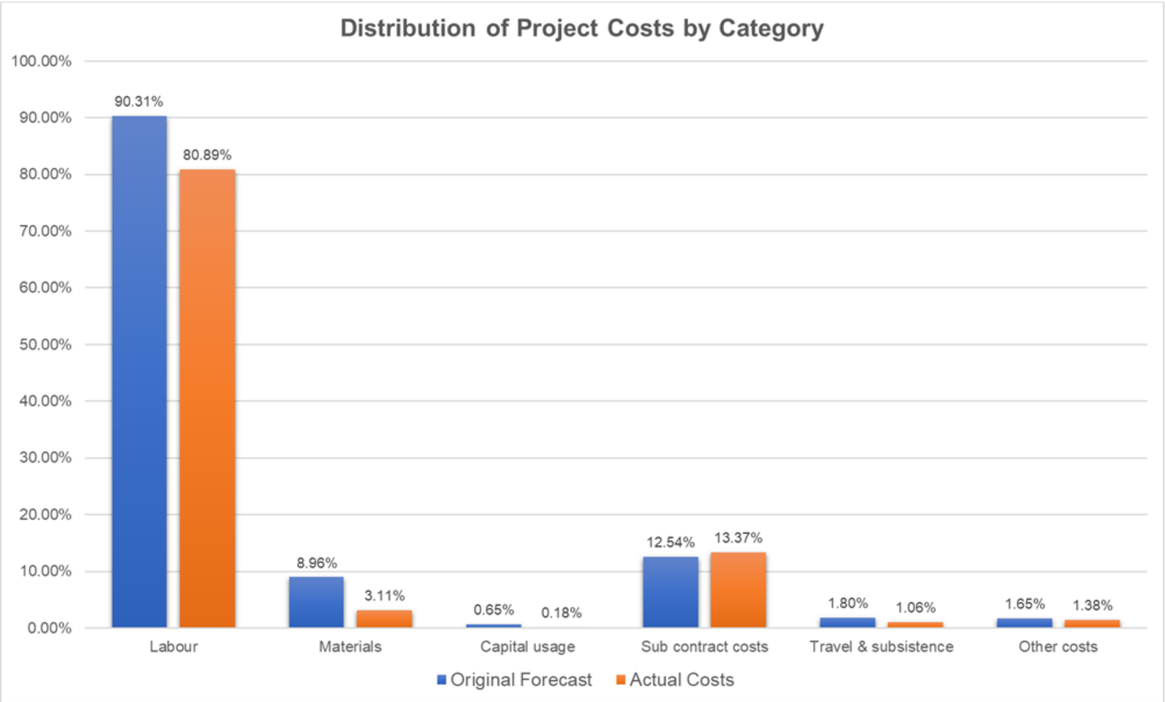


Figure 9: Distribution of Costs by Category

Whilst the project underspent, it did not have a negative impact on technical delivery or reduce project scope and objectives. As mentioned above, the consortium completed all planned milestones and deliverables.

Whilst overall project costs were reduced, there were significant in-kind contributions from partners (namely use of existing testbeds, hardware and software) and resources committed to the project from the non-funded project members.

5 TUDOR Outcomes

5.1 Benefits

DSIT and TUDOR agreed 16 "Benefit" metrics to be addressed by the project. These were mostly technical, but also addressed other topics such as system capabilities, deployment costs and sustainability goals. The benefits were grouped into a framework of three classes as shown in the diagram below:

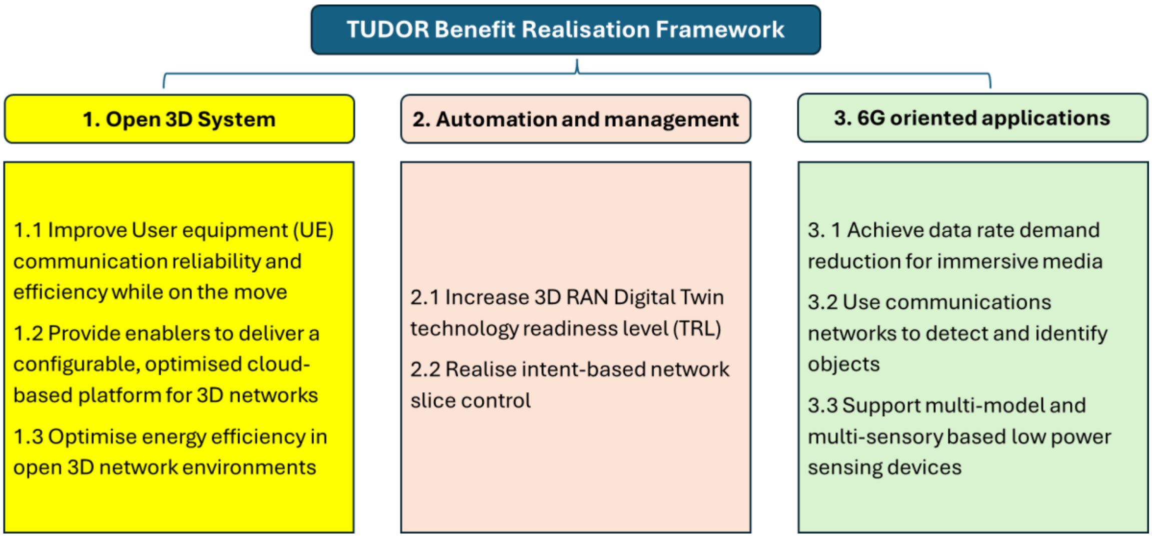


Figure 10: TUDOR Benefits Framework

5.1.1 Open 3D system

TUDOR technology aimed to deliver a network architecture which integrates terrestrial, airborne and space platforms. This grouping of benefits reports on key research areas aimed at enabling the infrastructure to deliver 'universal' and 'meaningful' wireless connectivity, taking into account constraints such as financial cost and energy use.

5.1.2 Automation & management

The 3D open network integrates a different network to provide a seamless wireless infrastructure. TUDOR undertook research to make the management of network practical and give the ability to exploit the network to provide advanced services. This grouping of benefits reports on research focused on the creation of enabling technologies to efficiently deliver wireless connectivity in a fully automated fashion, typically through AI-powered solutions.

5.1.3 6G-orientated applications

This benefit grouping reports on the research into new and novel services enabled by future wireless capabilities, namely semantic communications and integrated sensing and communication (ISAC).

It can be seen that these classes of Benefits represent a refinement of the originally proposed TUDOR technical objectives given in 2.2. Objectives 1 (Realise open networking and universal connectivity) and 2 (Maximise spectrum openness and RAN efficiency) map to Open 3D System, Objective 3 (Increase automation and agility in open network environments) maps to Automation & management, and Objective 4 (Enable 6G-era services and deliver a step change in future network capabilities) maps to 6G-orientated applications.

Objective 5 (Validate and test against emerging use cases) is the methodology by which we assessed the project performance against these Benefits classes, and Objective 6 (Exploit and promote 3D open networks research) is covered in the following sections.

5.1.4 Benefits Outcomes

TUDOR was able to make progress against all 16 Benefits targetted. This was documented to DSIT within their formal Benefits Realisation process, but additionally with a supplementary 26 page detailed explainer. Whilst the official Benefits Realisation documentation is not in the public domain, all of the activities within TUDOR have been carried out with the goal of achieving real world impact and influence. In some cases, typically relating to the 6G Oriented Applications class of Benefits, the progress was a progression in the state of the art on research topics, documented through academic publication, which still remain at a relatively low TRL. In contrast some of the results of the Automation and Management class of Benefits are being implemented as components of commercial offerings from TUDOR organisations, and some of the concepts and architectural components relating to Open 3D Systems have been taken into standardisation activities to lay the foundation for future 6G systems which align with the TUDOR aims of ubiquitous quality coverage and openness.

5.2 Dissemination

Beyond the measured "Benefits", one of the most important activities of TUDOR was dissemination of various forms. As a lower TRL research project, TUDOR was not so focussed on producing commercial products going directly to market, although in a few cases TUDOR results are able to be included directly in commercial products. However, by introducing TUDOR techniques and results into the global thinking on 6G and 6G technologies they can become embedded into the standards and commercial implementations of the future, where the UK should be well placed to exploit our role in their foundational development.

5.2.1 Academic dissemination

As listed in 3.7, TUDOR recorded 56 academic contributions to leading conferences and journals during the project run-time. Many more papers and PhD theses have been written after the conclusion of the project, although are no longer being tracked centrally, and the academic research activities from TUDOR will continue to generate further papers and theses going forward.

TUDOR delegates were able to present papers and results at multiple international academic conferences. In a heavily globalised market such as telecommunications, it is vital to take our results internationally and influence the global directions of research in order to secure impact from UK developed technologies.

5.2.2 Standardisation

Active participation in standardisation activities is one of the best ways to create meaningful global impact from research activities. Many of the TUDOR organisations (both industrial and academic) already have a presence in the most relevant SDOs such as 3GPP, ETSI, O-RAN Alliance, ITU, IEEE and IETF. In the first instance this provided a route for TUDOR concepts and results to be brought into SDOs' thinking, but this was bolstered by additional activities supported directly by TUDOR.

As outlined in 3.7, this led to 55 contributions to 3GPP, ETSI and IETF. Several of these were adopted into standards/specifications/reports, some of which were related to TUDOR developed IPR. Whilst there were no direct contributions of TUDOR results, some of the TUDOR thinking was contributed to discussions within the O-RAN Alliance.

TUDOR representatives also participated in the 3GPP Stage-1 Workshop on IMT2030 Use Cases, setting the direction for 3GPP standardisation on 6G which will allow for the introduction of TUDOR developed technologies when the more detailed Stage-3 activities commence in the future.

Within the IETF, TUDOR organised a TUDOR/IETF/ETSI workshop on Network Digital Twins at IETF meeting 121, in addition to contributing on this and various other topics, raising the profile of TUDOR and FONRC/DSIT.

Whilst the 3GPP 6G activities are only just commencing, ETSI has been an excellent forum for socialising TUDOR interests and driving activities in their Industry Specification Groups (ISGs), whose output specifications will be one of the major sources of input into the 3GPP activities at the appropriate time.

- In particular, TUDOR partners were the drivers behind the proposal and formation of a new ISG on the topic of Integrated Sensing and Communication[13]. This group is now running under the chair of InterDigital, who led the standardisation work package within TUDOR, and the University of Surrey has hosted plenary meetings of the group.
- TUDOR partners were also co-founders of the new ETSI ISG on Multiple Access Techniques (ISG MAT). Whilst MAT was not specifically a topic of study for TUDOR, the key focus for the group is large area coverage and broadcast/multi-cast, so there will be opportunities to introduce use cases and requirements related to TN/NTN integration which have been developed within TUDOR.
- In addition to the training detailed in 5.3.1, TUDOR made use of good relations with ETSI to agree the promotion of the FONRC Programme and its projects in the ETSI Enjoy! Magazine. TUDOR was featured in the October 2023 edition[14].

5.2.3 Key Events

In addition to attendance at academic conferences, TUDOR has been actively participating in various events both in the UK and abroad. In some cases, TUDOR or TUDOR partners have been involved in organising or hosting such events. For some events TUDOR invited other FONRC projects and/or DSIT to be involved, and for some events we were invited by other FONRC projects and/or DSIT.

Examples of some events are listed below, and we go into more detail on two of the most important events in which we participated, EuCNC and MWC.

- Open Network Ecosystem Projects and Open Networks Programme Collaboration Event
- Connected Futures Festival
- ETSI Conference on Non-Terrestrial Networking
- 6G World 6G Symposium
- Cambridge Wireless event: Open RAN and Small Cells – The Analogue Radio Reality Check
- Keysight workshop on Non-Terrestrial Networking
- 6G CLICK Workshops on ISAC and NTN

5.2.3.1 EuCNC 2024

EuCNC[15] (European Conference on Networks and Communications) is one of the largest conferences on telecommunications in Europe, sponsored by the European Commission. It comprises both technical and industrial conference sessions (academic papers, seminars, workshops, tutorials etc.) and a large exhibition space. One of the primary attractions of EuCNC is that it attracts both academic and industrial research, and particularly it is the de facto gathering for representatives of the SNS European sponsored research projects and the 6G Industry Association.

The three FONRC research projects, REASON, TUDOR and YO-RAN, collaborated to attend EuCNC 2024 together to promote the UK telecommunications research ecosystem, and our interest in collaboration, to the rest of Europe, as well as some of our project specific results. Our participation took the form of two different activities:

1. The projects proposed and hosted a workshop session on the topic of "From Open RAN to Open Networks for 5G and 6G Applications". In addition to an overview of FONRC and the three

[13] https://www.etsi.org/committee/2295-isac

[14] https://www.etsi.org/e-brochure/Magazine/October-2023/mobile/index.html#p=18

[15] https://www.eucnc.eu/

projects, and some of our technical presentations, the session also included presentations from the 6G IA "Open Smart Networks and Services" Working Group, and two of the EU projects. This session was well attended and sparked some interesting discussions both during the session and afterwards.

Figure 11: Vaia Kalokidou (Satellite Applications Catapult) presenting TUDOR results at EuCNC 2024

2. The projects arranged a joint booth in the exhibition space to promote our activities. From the TUDOR point of view there were some good discussions with visitors: Semantic Communications was a new and interesting topic for many; it was good to show Integrated Sensing and Communications where the sensing component was not related to location/positioning; and discussions on energy efficiency contributed to at least one new academic collaboration between a UK and mainland European university.

   As a side benefit of the joint stand, this proved an excellent opportunity for researchers from each of the three FONRC projects to spend time together and get to know each other and share ideas and experiences.

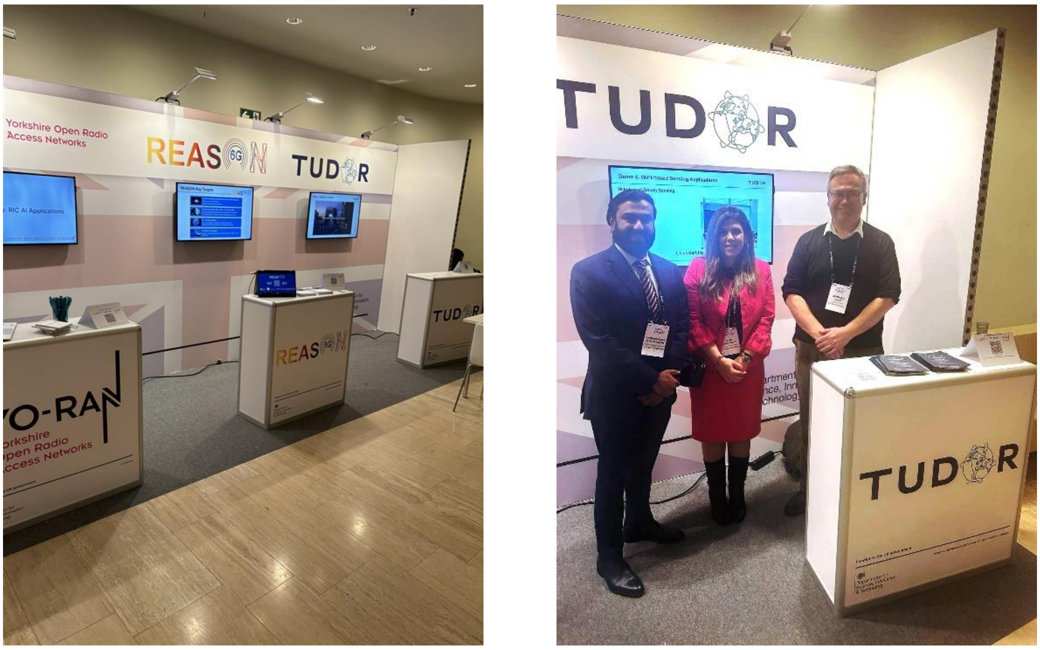


Figure 12: FONRC/TUDOR exhibition stand at EuCNC 2024 with TUDOR representatives Arun Jayaprakash, Vaia Kalokidou, Bernard Hunt

5.2.3.2 Mobile World Congress 2025

The annual MWC Barcelona[16] is considered the world's largest mobile industry and technology event, attracting well over industry 100,000 visitors over 4 days every year. TUDOR attended MWC with a stand as part of the UK Pavilion, along with other FONRC projects, EPSRC Hubs, UK Space Agency, UK Telecoms Innovation Network, InnovateUK and the Department for Business and Trade.

On our stand we showcased a number of technologies including: Integrated Terrestrial and Non-Terrestrial network management, Holoportation and Semantic Communications, Advanced signal processing for massive MIMO, and Reconfigurable Intelligent Surfaces.

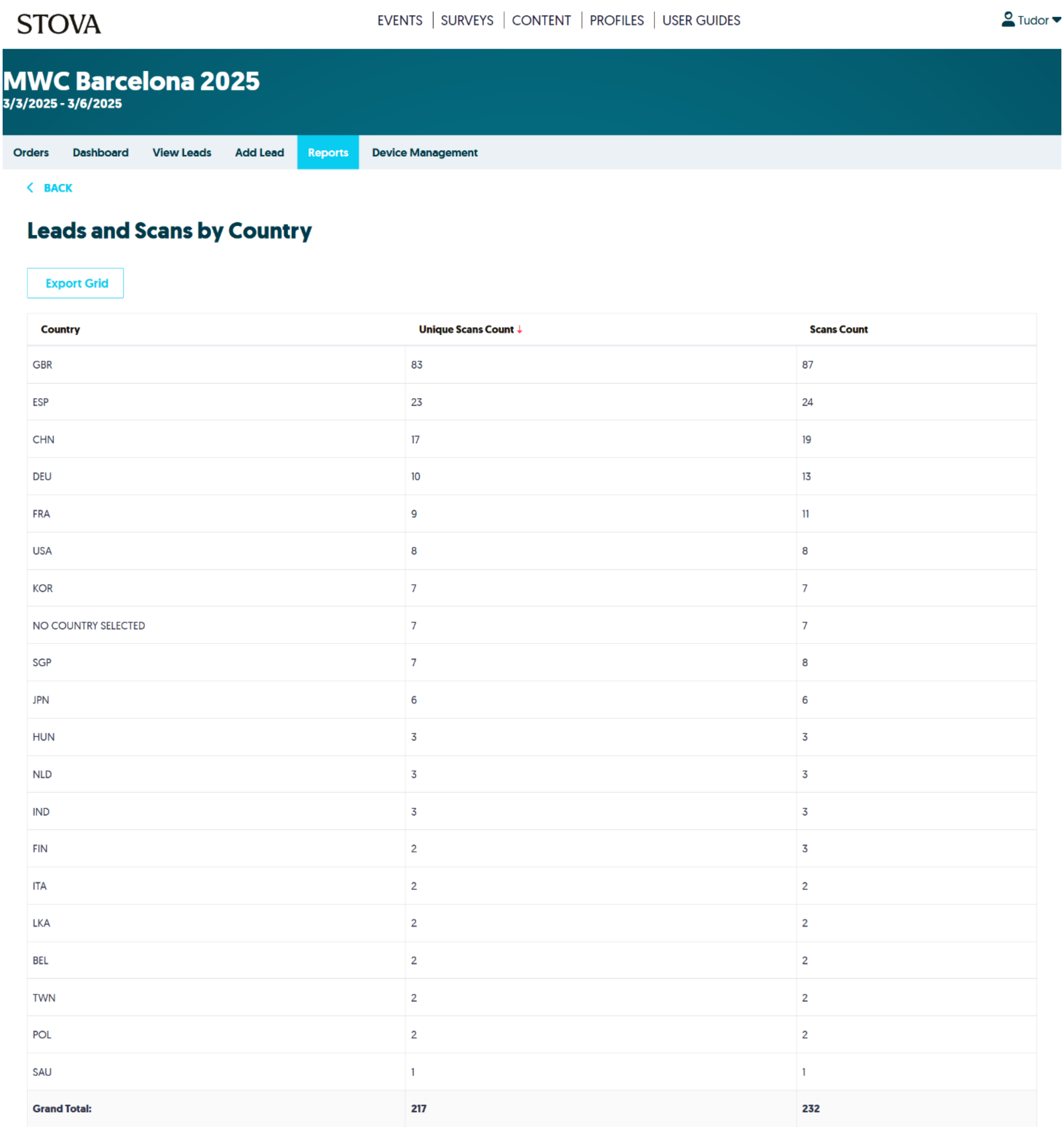
Figure 13: TUDOR stand at Mobile World Congress 2025

All of the stands in the UK Pavilion took part in pavilion tours, promoting the UK ecosystem and capabilities to attract investment and partnerships from the rest of the world.

Visitors to the TUDOR stand had the opportunity to share their contact details for potential information sharing or discussions/follow-up after the show. Not all visitors chose to do this, but during the 4 day event we were able to record over 200 visitors from 175+ companies in 35+ countries. Some particularly notable visitors include: Baroness Gustafsson, the UK Minister for Investment; the UK Ambassador to Spain; the CEO of British Telecom; as well as media and market analysis companies such as Bloomberg.

Figure 14: Baroness Gustafsson, UK Minister for Investment, visiting TUDOR at MWC 2025

[16] https://www.mwcbarcelona.com/



STOVA

EVENTS | SURVEYS | CONTENT | PROFILES | USER GUIDES

Tudor

MWC Barcelona 2025

3/3/2025 - 3/6/2025

Orders Dashboard View Leads Add Lead Reports Device Management

BACK

Leads and Scans by Country

Export Grid

Country	Unique Scans Count ↓	Scans Count
GBR	83	87
ESP	23	24
CHN	17	19
DEU	10	13
FRA	9	11
USA	8	8
KOR	7	7
NO COUNTRY SELECTED	7	7
SGP	7	8
JPN	6	6
HUN	3	3
NLD	3	3
IND	3	3
FIN	2	3
ITA	2	2
LKA	2	2
BEL	2	2
TWN	2	2
POL	2	2
SAU	1	1
Grand Total:	**217**	**232**

Figure 15: Recorded visitors to TUDOR MWC stand by County

STOVA

EVENTS | SURVEYS | CONTENT | PROFILES | USER GUIDES

Tudor

MWC Barcelona 2025

3/3/2025 - 3/6/2025

Orders | Dashboard | View Leads | Add Lead | Reports | Device Management

BACK

Leads and Scans by Job Title

Export Grid

Job Title	Unique Scans Count ↓	Scans Count
CEO	14	14
NO JOB TITLE SELECTED	7	7
Sales Manager	6	6
Business Development Manager	4	5
CTO	4	4
Manager	4	4
Managing Director	4	4
Director	3	3
Marketing Director	3	3
Student	3	3
Associate Professor	2	2
Consultant	2	2
Embedded Systems Engineer	2	2
General Manager	2	2
PARTNER	2	2
Professor of Wireless Communications	2	2
Research Associate	2	5
Research Engineer	2	2
Research Fellow	2	2
Sales Account Manager	2	2
Grand Total:	**217**	**232**

Figure 16: Recorded visitors to TUDOR MWC stand by Job Title

5.3 Training

In addition to generating scientific and technical results and impacts, one of the goals of TUDOR was to build the UK skill base in the field of telecommunications.

With 8 well regarded universities in the TUDOR consortium there is an obvious element of training within their academic departments. Whilst it is not possible to fully attribute any 3(+) year PhD to a 2 year project, many PhD candidates were involved in TUDOR research and presented and discussed their research with other PhD candidates within the relevant departments. At the same time, academics were involved in, and had oversight of, world leading research in some of the key developing research areas for 6G and are able to take that through into their teaching, supervision, and future research proposals.

In addition to the general technical skills, collaboration skills and networking developed by all researchers participating in TUDOR, specific training was conducted within the project, addressing key areas of knowledge which have often been underserved in the training of early career researchers, both in academia and industry.

5.3.1 Standardisation training

Experienced standards delegates from TUDOR organisations worked closely with ETSI to create a dedicated training on basics of standardisation. This included not only the official procedures on how things are supposed to work, but also some tips based on real world experience on who to more effectively be involved in standardisation. This training was delivered by ETSI representatives in an online platform to any interested members of all TUDOR organisations, not only those researchers working in TUDOR. The full recording of the training, including interactive Q&A sessions was made available to all TUDOR organisations for future use. An edited version of the training, without TUDOR internal specific discussions, was made available to the other FONRC projects, and now also forms part of the public ETSI “Education about Standardization” portal[17]

Following this introduction to standardisation training, further training related to the working methods and activities of specific and relevant SDOs was delivered within TUDOR by active standards delegates from within the TUDOR organisations.

5.3.2 Intellectual Property training

In a similar manner to the TUDOR standardisation training, experienced members of the TUDOR consortium worked with Venner Shipley LLP[18] Intellectual Property firm to develop a bespoke training course on Intellectual Property. As with the standardisation training, this did not only cover the formal processes, but included hints and tips based on the experiences of TUDOR representatives. The training was delivered online by one of the Venner Shipley attorneys, with interactive Q&A. The recording of the training session is available to all TUDOR organisations, and is still in use in some of these beyond the life of the project. The edited version of the training, without TUDOR specific Q&A, was also shared with the other FONRC projects.

5.3.3 CDT FORT

During the TUDOR project UNIS (overall TUDOR lead) and Queens University Belfast (TUDOR security lead) made a successful proposal to launch The Centre for Doctoral Training in Future Open SecuRe NeTworks (CDT-FORT)[19]. This is the only EPSRC centre for doctoral training with a telecoms focus. The CDT aims to:

- Produce industry-conscious thinkers and leaders with expertise in wireless communications, cybersecurity, networking, and AI
- Address industry-relevant challenges in future open, secure, and resilient communication systems
- Conduct responsible research and effective innovation in emerging technologies
- Create a pipeline of skilled professionals from school pupils to alumni

The CDT is targetted at UK home national students, and the programme is drawing on many UK based institutions, including other TUDOR partners, for guidance to ensure that the syllabus directly addresses the needs of the UK ecosystem.

The programme will run for the next 8 years and expects to graduate at least 50 students.

5.4 FONRC and UK Ecosystem

As mentioned at various points in this report, there has been an excellent approach to collaboration between the FONRC projects, beyond that achieved in many national and international programmes. In

[17] https://www.etsi.org/education/related-events

[18] https://www.vennershipley.com/

[19] https://www.fort-cdt.ac.uk/

addition to good intent and approaches, the complementary skills of the project managers across events organisation, project management, government relations, technical/scientific knowledge, and industry ecosystem/standardisation/IPR enabled them to work well together.

This has resulted in joint activities related to e.g. events, training, and technical information sharing and coordination. Beyond the life of the TUDOR project, agreement has been reached to share some project internal work as well as published results with other FONRC projects which have not completed yet where it is complementary to their activities and enhances the overall outcomes of FONRC.

The FONRC activities have created new networking and collaboration opportunities both within individual projects and across the organisations involved in the different projects. Unsurprisingly for a smaller ecosystem such as the UK there has already been some personnel exchange between organisations and projects, and multiple new collaborations have started or are being proposed between different combinations of FONRC participants. In the longer term it is likely that the new and improved bonds created by the programme will prove every bit as valuable as the shorter term technical outcomes, to the benefit of the whole UK ecosystem and economy.

6 Conclusions

The TUDOR project set out with 6 ambitious objectives:

- Realise open networking and universal connectivity
- Maximise spectrum openness and RAN efficiency
- Increase automation and agility in open network environments
- Enable 6G-era services and deliver a step change in future network capabilities
- Validate and test against emerging use cases
- Exploit and promote 3D open networks research

It is hoped that this document alone has given enough of an overview of the TUDOR activities to show that excellent progress has been made against all of these objectives, even if full details and justification lie within the 100+ confidential deliverables produced for DSIT. This progress is also represented in a body of academic publication, participation in industry events, IPR, contributions to standards and commercial exploitation – all of which will lead to greater impact and help shape the future development of 6G systems.

This has been backed up by an array of ecosystem developing activities such as education, training, collaboration within the UK and internationally, and driving new standardisation activities where gaps were seen in the existing processes. These activities will have wider and longer-term implications and benefits for the UK beyond the scope of 6G and FONRC.

As part of the reporting to DSIT, individual partners were invited to express their views on the TUDOR project and FONRC programme, and their relevance to ongoing business. We conclude this report with selected anonymised quotes from this feedback:

- *"TUDOR has been an outstanding collaboration ... and we are grateful for the opportunity to contribute to one of the UK's most forward-looking and ambitious research programmes."*
- *"TUDOR has reinforced our confidence in the strength of the UK's research ecosystem and has helped deepen our engagement with UK academic institutions. It also strengthened our strategic outlook on investing in UK-based testbeds, innovation centres, and collaborative R&D frameworks."*
- *"Working in TUDOR under DCMS/DSIT FONRC was a hugely positive experience, and our ongoing innovation and research will benefit from the collaborations, partners and contacts made through the process."*
- *"As a leader in the Open RAN ecosystem, we are pleased to see the principles of Open RAN being applied to TUDOR developed architectures. It underscores that Open RAN is a key enabler for innovation and a platform to support NTN to TN integration in a flexible manner."*
- *"The insights and results from TUDOR will drive our continued exploration of how machine learning can enhance wireless network management and optimise the benefits of 3D networks. Further research aligned with TUDOR's objectives will continue, and we will present key findings at upcoming international conferences ... to extend the project's impact."*
- *"We are coming out of TUDOR with two new commercial features."*
- *"We are pleased to see TUDOR's role in supporting the launch of the ETSI ISG ISAC group. The use cases outlined in their first deliverable align well with several of our ongoing research priorities ... We anticipate contributing to future ISAC activities and believe this work complements gaps not currently addressed by 3GPP"*
- *"The TUDOR project has provided a valuable platform for exploring advanced concepts that are central to the evolution of 6G and has successfully positioned the UK to take a leading role in shaping future telecommunications systems."*

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