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Title:

Revised Research Alignment Report

Terahertz based Ultra High Bandwidth Wireless Access Networks

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0.1	23/08/2019	Alan Davy, Saim Ghafoor	WIT	PSOC, Section 1, 2 and 3 updated
0.2	04/09/2019	Saim Ghafoor	WIT	Tables in Section 3 updated
0.3	13/09/19	Saim Ghafoor	WIT	Internal review comments addressed.
0.4	13/09/19	Saim Ghafoor	WIT	Changes addressed and final proposed

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Executive summary

The purpose of this report is to track, assess, validate and align the proposed technological developments of the project with the goals and requirements of the use cases. It closely aligns the work within the technical work packages to the scenarios previously specified. This report is in continuation of the Initial Research Alignment Report (D-2.4).

The objectives of this deliverable are to report on the activities of T2.2 which focuses on:

- aligning the research activities carried out with the project to the set of use case requirements that were initially defined
- validation and demonstration of the work through the demonstrators
- alignment with other Terahertz cluster projects and recent emerging state of the art activities in the Terahertz communication area.
- follow up the previous task activities and requirements from D-2.4 (The Initial Research Alignment Report) to track the updates.

1 Introduction

1.1 Summary

This deliverable presents the Revised Research Alignment Report for the TERAPOD project. It presents the continued alignment and validation for technological requirements and advancements carried out within TERAPOD domain particularly from Work Packages (WPs) 3 to 5 with use case scenarios specified in D-2.1. Mainly, the task activities are reviewed in detail which was previously detailed in the Initial Research Alignment Report of D-2.4 and aligned with technical requirements. These activities are also associated with the demonstrators outlined in TERAPOD proposal. Recent project activities are also aligned with other Terahertz cluster projects and recent state of the art findings in the Terahertz communication domain.

1.2 Structure of this document

This document is laid out as follows:

- Section 1 acts as an introduction to this deliverable, in summary, what it presents along with its relationship to other deliverables within the TERAPOD project and details what partners have helped contribute to this text.
- Section 2 provides an overview of how technical activities from the various WPs are mapped to requirements, in the form of the use case scenarios. It also aligns these activities to the respective demonstrators outlined in the TERAPOD proposal, where all activities are validated and demonstrated by at least one demonstrator.
- Section 3 presents how activities within TERAPOD align with other State-of-the-Art activities and technologies within the THz space across Europe and internationally. It details certain areas and publications related to the overall goals of the project.
- Section 4 provides conclusions and a summary of the next steps in relation to the project.

1.3 Relationships with other deliverables

The content presented in this document relates to the following deliverables:

- D2.1 – Initial Requirements and Scenario Specifications: this document presents an overview of the use case scenarios and detailed requirements
- D2.4 – Initial Research Alignment: this document presents an initial research alignment of task activities with technical requirements and use-case scenarios.

1.4 Contributors

The following partners have contributed to this deliverable:

- TSSG (Alan Davy)
- TSSG (Saim Ghafoor)

2 Revised Research Alignment within the Project

This section will provide the updated task activities and their mapping with use cases, technical requirements and demonstrators. It is also ensured that all activities are tied to at least one requirement and are being validated and demonstrated by at least one demonstrator. The initial research alignment was presented in report D2.4 and in this report, the updated task activities are presented.

2.1 Overview

The requirements for different use cases (mentioned below) are already discussed in detail in deliverable D2.1 and updated in D2.2.

It is important before developing any research alignment that each partner agrees on the broad definition of the requirements and use cases. A clear understanding of these requirements and demonstrator help in using the efforts towards the required deliverables. Therefore, initially, the requirements and demonstrators will be explained in this document, followed by the methodology to establish a mapping between the task activities, requirements and the demonstrators for each partner.

2.1.1 Use cases

There are four use cases which were finalized to establish the feasibility of Terahertz band communication within a Data Centre environment. These use cases are mentioned and discussed in much detail in Deliverable D-2.1 (Initial requirements and scenario specifications). We can summarise as follows;

1. TERAPOD-UC-01: Commercial Feasibility of THz DC Wireless Networks

   In this use case, the commercial feasibility of the Terahertz band is aimed to be established within a data center environment. The functional and non-functional requirements might influence the implementation of such high transmission rate bands. Therefore, different aspects for devices, antennas, transceivers, materials, and communications are considered and established to achieve the Terahertz link expected performances. The considered factors also include the geometry of data centers, topologies, achievable rates, power consumption, channel modeling, and environmental effects. All these are considered to assess the feasibility to establish a wireless Terahertz link.

2. TERAPOD-UC-02A: Static (Layer-1) THz Wireless Data Links

   This use case is focused on the integration of static Terahertz wireless link within a Datacenter environment. It also includes the performance comparison of Terahertz wireless link with wired links (optical) in terms of achievable data rate and feasibility of point to point communication. The important factors in achieving the point to point connectivity are to analyse the device and transceiver characteristics with antenna alignment to establish the distance achievable with required throughput and delay.

3. TERAPOD-UC-02B: Dynamic (Multi-Layer) THz Wireless Data Link Integration

   This use case is focused on point to multipoint communications and analysis of different network aspects including network congestion, minimising link downtime, delay and maximising throughput. It is also focused on developing efficient networking protocols to implement on-the-fly and flexible solutions.

4. TERAPOD-UC-03: Wireless Data Centre Auto-Configuration

   This use case involves the full integration of wireless Terahertz link within a data center with auto-configuration which includes automated device discovery, configuration, and synchronization with existing devices. It also involves the automated re-configuration of beam-direction, range, and other appropriate parameters.

2.1.2 Requirements

Various functional and non-functional requirements are already listed in D2.1 and D2.2 and therefore are not discussed here. A summary of the requirements for each use case is given below.

1. Use case 1: includes requirements for end-user; data transmission; scenario; interface including topologies, geometry, safety and workloads; and technology. Non-functions requirements include the testing and validation, cost and commercial factors and licensing considerations.
2. Use case 2A: includes the data transmission including data rate, bit error rate, and power consumption; detailed description of scenario; interface requirements including components and external systems with traffic load and links; technology including the communication layer parameters; device including transmitter and receiver devices such as RTDs or UTC-PDs; and non-functional requirements.
3. Use case 2B:

   Analogous to use case 2A.
4. Use case 3B:

   Mostly the same as for use case 2A and 2B, the details about the communication parameters are outlined in D2.1 and D2.2.

2.1.3 Demonstrators

The implementation, configuration and achieved goals will be validated using the following demonstrators:

1. Simulation: Simulation for proof of concept and end-to-end performance analysis.
2. Bench-top testing: Bench-top testing for implementation of point-to-point Terahertz wireless link, beam formation, spatial configuration and other designed configurations for different devices and components.
3. DC Integration: Integration and analysis of Terahertz Wireless link within a Data Centre environment

2.2 Methodology

The main objective for this methodology is to track down the progress and research outputs and their mapping with the demonstrators and requirements, essentially through the involved task activities. The research alignment should evolve with project knowledge and progress throughout the project lifeline. The following methodology (also shown in Figure 1) is used to track the project progress.

1. The requirements and goals for each use case scenario will be identified by each project partner individually.
2. Task activities should be identified clearly, as to how these requirements or goals can be achieved.
3. The proof-of-concept for each task activity should be shown using one of the identified demonstrators.
4. The identified demonstrators and task activities will be used to check the achievability of individual goals identified at the beginning of the project.

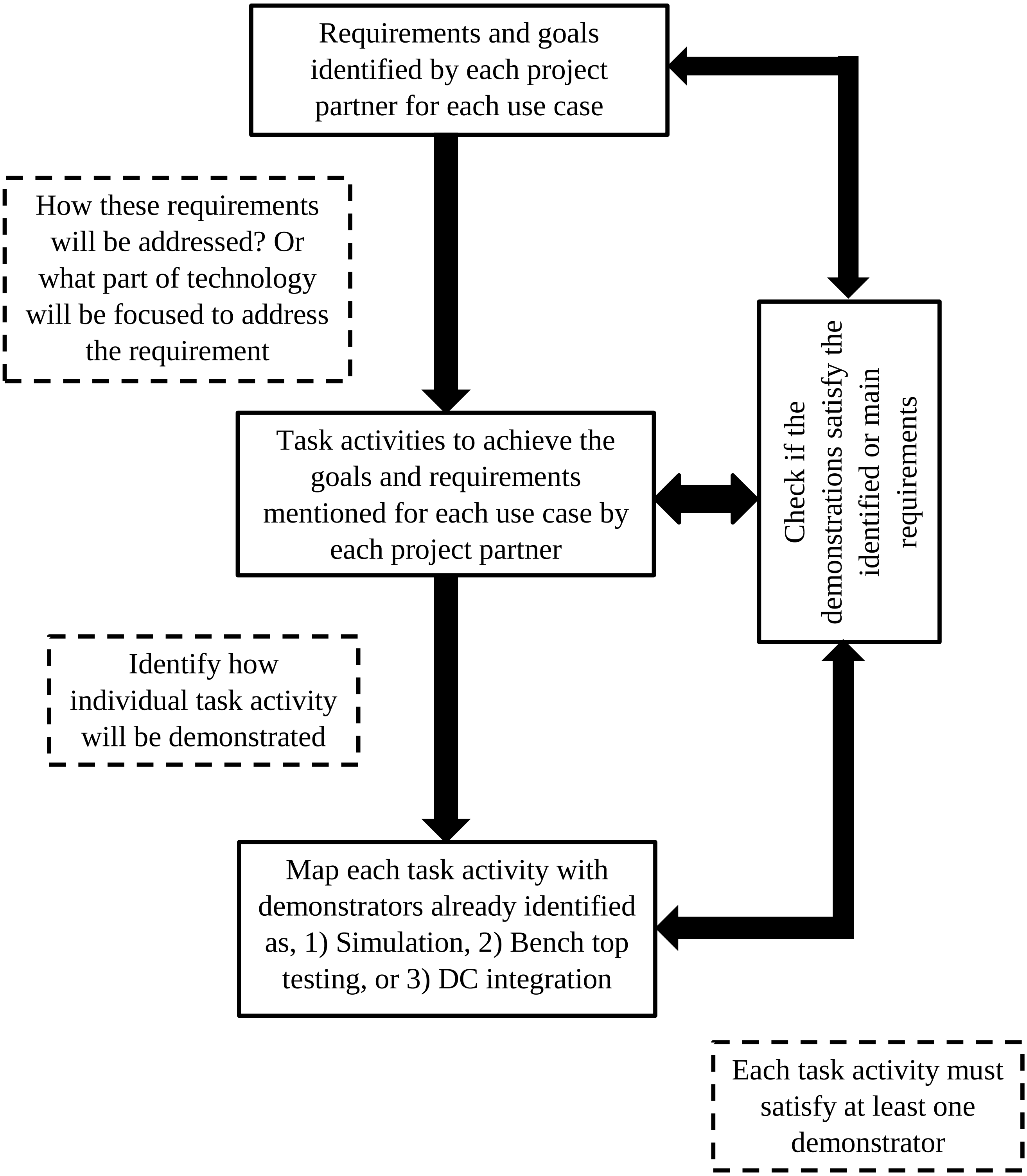

Figure 1: Research alignment methodology.

2.3 Revised Research alignment based on the use case and partner activities

The research alignment of requirements and task activities was presented in report D-2.4. In this section, the research alignment status by each partner is revised to update the completion of different task activities. Table 1 to 9 presents the updated task status by each partner.

Table 1: TSSG, revised research alignment summary

						Timeline to finish the task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Status**	**Demonstrator**
UC-01	To identify issues and challenges for THz MAC layer	WP-5	T-5.2	Literature review for exiting Terahertz communication protocols	D-5.3	M12	M-14	Completed	
	Initial Data Link Layer simulator	WP-5	T-5.2	Analyses and selection of existing simulators for Terahertz communications	D-5.3	M-08	M-13S	Completed	Simulation
		WP-5	T-5.2	Initial Data Link Layer Block Diagram	D-5.3	M-08	M-13	Completed	
		WP-5	T-5.2	Physical layer parameters analyses to be used in the link-layer simulator	D-5.3	M-08	M-14	Completed	Simulation
		WP-5	T-5.2	Implementation/simulation of DLL basic functionalities on MATLAB/NS3	D-5.3	M-10	M-15	In-progress	Simulation
	Traffic modeling and workload estimation of Data Centres	WP-5	T-5.2	Theoretical Frame generation and DLL buffer modeling using Markov Chain	D-5.3	M-12	M-15	In-progress	Simulation
		WP-5	T-5.2	Capturing real traces from Data Centre environment and equivalent traffic generation	D-5.3	M-10	M-24	Completed	Simulation
UC-2A	Initial Data Link Layer simulator	WP-5	T-5.2	Implementation of Point to point link for Data Centre scenario using directional antennas	D-5.3	M-15	M-18	In-progress	Simulation
		WP-5	T-5.2	Implementation of channel model and physical layer aspects	D-5.3	M-15	M-26	In-progress	Simulation
		WP-5	T-5.2	Interfacing between Physical, MAC and Network Layers	D-5.3	M-15	M-26	In-progress	Simulation
	DC Geometry	WP-5	T-5.2	Wireless topology design within a Data Centre using inter/intra rack communication	D-5.3	M-18	M-20	Completed	Simulation
	Handshaking mechanism	WP-5	T-5.2	Handshaking mechanism proposed and implemented	D-5.3	M-20	M-24	In-progress	Simulation
	Data rate and transmission distance	WP-5	T-5.2	Simulations carried out for maximum distance achievability	D-5.3	M-24	M-26	In-progress	Simulation
				Simulations performed to analyse the achievable data rate				In-progress	Simulation
				Comparison of an optical and THz link within a Data Centre environment				Not started	Simulation
UC-2B	Final Data Link layer simulator	WP-5	T-5.2	Point to multipoint scenario implemented and simulated for a Data Centre environment within a simulator using directional antennas	D-5.4	M-26	M-30	Not started	Simulation

	DC Geometry	WP-5	T-5.2	Extended simulations performed for point to multipoint scenario with directional antennas	D-5.4	M-28	M-30	Not started	Simulation
	Handshaking mechanism	WP-5	T-5.2	Advanced Handshaking mechanism proposed and implemented with directional antennas	D-5.4	M-30	M-33	Not started	Simulation
UC 03	Autonomous algorithms for discovery, synchronization, and configuration	WP-5	T-5.2	Advanced algorithms for device discovery	D-5.4	M-33	M-36	Not started	Simulation
				Advanced algorithm for handshaking				Not started	Simulation
				Advanced algorithms for synchronization, antenna alignment, and link configuration				Not started	Simulation
	Autonomous algorithms using dynamic traffic loads	WP-5	T-5.2	Simulation of different traffic loads to analyse the performance and achievable data rate with transmission distances.	D-5.4	M-35	M-36	Not started	Simulation

Table 2: DER, revised research alignment summary

						Timeline to finish the task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Current status**	**Demonstrator**
UC-01	End-user requirements Technology Requirements Non-functional Requirements	WP2	T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1	M1	M36	Completed	DC integration Benchtop End-to-end simulator
					D2.2			Completed	
					D2.3			In-progress	
UC-2A	End-user requirements Technology Requirements Non-functional Requirements	WP2	T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1	M1	M36	Completed	DC integration Benchtop End-to-end simulator
					D2.2			Completed	
					D2.3			In-progress	
	Interface requirements	WP5	T5.3	Study and develop flexible models to support multiple different network simulation scenarios within the data centre Design of Layer 3 routing algorithms/protocols and other (anycast/multicast) • Trial network simulator mapping traffic and THz communication across links within a datacentre	D5.5	M7	M36	Completed	End-to-end Simulator
					D5.6			In-progress	
	Interface requirements	WP6	T6.3	Embedding THz links into a comms network - DER data centre	D6.5	M4	M36	On-going or in-progress	DC integration
					D6.6			Not Started	
UC-2B	End-user requirements Technology Requirements Non-	WP2	T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model	D2.1	M1	M36	Completed	DC integration Benchtop End-to-end simulator
					D2.2			Completed	

	functional Requirements			Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks					
					D2.3			In-progress	
	Interface requirements	WP5	T5.3	Further design of routing protocols, simulation scenarios, etc. Partitioning of data traffic and software-defined networking (SDN) integration	D5.5	M7	M36	Completed	End-to-end Simulator
					D5.6			In-progress	
	Interface requirements	WP6	T6.3	Fully demonstrate THz links in a data centre environment through real-time device/link integration	D6.5	M4	M36	In-progress	DC integration
					D6.6			Not Started	
UC-03	End-user requirements Technology Requirements Non-functional Requirements	WP2	T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1	M1	M36	Completed	DC integration Benchtop End-to-end simulator
					D2.2			Completed	
					D2.3			In-progress	
	Interface requirements	WP5	T5.3	Further design of routing protocols, simulation scenarios, etc. Partitioning of data traffic and software-defined networking (SDN) integration	D5.5	M7	M36	Completed	End-to-end Simulator
					D5.6			In-progress	

Table 3: TUBS, revised research alignment summary

						Timeline to finish the task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliv erable**	**Starting time**	**Completion time**	**Status**	**Demonstrator**
UC-01	Sustainability Technology requirements	WP7	T7.4	Standardization activities to strengthen the Data Centre Scenario as an application for the THz technology	D7.5 D7.6 D7.7	M1	M36	In-progress	DC integration Benchtop End to end simulation
UC-2A	Data Centre geometry Network Requirements	WP4	T4.2.1	Channel measurement for Channel Characterization of Use Case Scenarios	D4.3	M1	M10	Completed	End to end Simulator
				Study of channel characteristics for different transmission scenarios (General Characterization, Top of Rack, Intra-Rack) in the data center	D4.4	M10	M20	In-progress	End to end Simulator
			T4.2.2	Build a 3D data center model for ray tracing channel simulations	D4.4	M10	M22	Completed	End to end Simulator
				Extensive ray-tracing simulations to fully characterize the channel	D4.4	M22	M28	In-progress	End to end Simulator
				Creation of a model of the THz channel which will be fed to the PHY simulator	D4.4	M26	M30	In-progress	End to end Simulator
	Data Rate of THz links Bit Error Rate	WP5	T5.1	First simple physical layer simulator implementing the current standard of THz communication which gives BER and PHY delay for the measured scenarios using a simple channel model	D5.1	M1	M15	Completed	End to end Simulator
				Implementation of the THz Channel model in the PHY simulator	D5.2	M15	M33	In-progress	End to end Simulator
				Implementation of forward error correction methods in the PHY simulator	D5.2	M15	M27	In-progress	End to end Simulator
				Analysis of Bit Errors in the PHY simulator and Development of a Statistical Error Model	D.5.2	M15	M33	Not started	Benchtop End to end Simulator
UC-2B	Interface requirements	WP5	T5.1	Definition of interfaces between simulators	D5.1	M1	M6	Completed	End to end Simulator
				Development of an Error Model Generator which enables higher-level simulations employing a realistic PHY model	D5.2	M20	M34	Not started	End to end Simulator
UC-03	Demonstration or proof-of-concept	WP6	T6.2	Development of a simulator platform/interface which serves as a demonstration platform and illustrates how all different simulators work together (DC Geometry, Raytracing, PHY Sim, MAC Sim, Network Sim, Auto Config)	D6.3 D6.4	M1	M36	In-progress	End to end Simulator

Table 4: INESC TECH, revised research alignment summary

						Timeline to finish task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Current status**	**Demonstrator**
UC-02A, UC-02B and UC-03	Antenna solution suitable for substrate integration with UTC/RTD sources, with >11GHz bandwidth, >50% efficiency	WP 3	T 3.5	Propose and validate by simulation a substrate integrated antenna design solution compatible with existing manufacturing limitations.	D3.4	M1	M12	Completed	Bench top
				Improve initial substrate integrated antenna design solution in terms of impedance matching to the source.	D3.6	M13	M14	Completed	
				Propose and validate by simulation linear arrays of 4, 8 and 16 elements through a performance assessment (impedance matching versus scanning range and bandwidth)	D3.6	M15	M20	Completed	
	Antenna array solution suitable for substrate integration with UTC/RTD sources, with >20dBi of realised gain, >11 GHz bandwidth, >(-45º,+45º) of scanning range, <-15dB of side lobe levels	WP3	T 3.5	Propose and validate by simulation a full array of 16 x16 elements through a performance assessment (impedance matching versus scanning range and bandwidth)	D3.6	M21	M30	Completed	End to end simulator
				Improve performance of initial antenna array design from D3.6, through a parameterizable model (aiming to improve realised gain, scanning range and bandwidth)	D3.7			On going	
UC-02A	Split-block, CNC compatible horn antenna solution, with high gaussissity	WP3	T 3.5	Propose and validate by simulation a high-gaussissity horn antenna solution to be interfaced with the SBD receiver.	D3.6 /D 3.7	M13	M16	Completed	DC integration Bench top End to end simulator

Table 5: VLC, revised research alignment summary

Use case	Requirement	Work package	Task activity number	Task activities	Deliverable	Timeline to finish task: Starting time	Timeline to finish task: Completion time	Current status	Demonstrator
UC-03	Beam steering mechanism for dynamic allocation of devices and of bandwidth	WP3	Task 3.4	Design a phase distribution Photonic Integrated Circuit for dynamic reconfiguration of the emission profile. The PIC design has been fabricated.	D3.3	M1	M24	Completed	Simulations Benchtop
				Test and characterization of the Phase Distribution PIC. Test building blocks and their effect on the system. Test system and the range of tuning for each element.	D3.5	M8	M24	Completed	Benchtop

Table 6: NPL, revised research alignment summary

Use case	Requirement	Work package	Task activity number	Task activities	Deliverable	Timeline to finish task: Starting time	Timeline to finish task: Completion time	Current status	Demonstrator
UC-01									
UC-02A	Physical Layer TERAPOD components Testing and validation	WP-4	T4.1	Measure emitted power of transmitters (non-Terapod device)	D4.1	M1	M12	Completed	Bench top
				Measure power specturm of transmitters (non-Terapod device)		M1	M12	Completed	Bench top
				Measure responsivity of receivers (non-Terapod device)		M1	M12	Completed	Bench top
				Measure radiation pattern and polarisation in the far field (non-Terapod device)		M1	M12	Completed	Bench top
				Measure emitted power of transmitters (Terapod device)	D4.2	M13	M33	Not started	Bench top
				Measure power spectrum of transmitter (Terapod device)		M13	M33	Not started	Bench top
				Measure responsivity of receivers (Terapod device)		M13	M33	Completed	Bench top
				Measure radiation pattern and polarisation in the		M13	M33	Not started	Bench top

				far field (Terapod device)					
	Environmental conditions	WP-4	T4.2.1	Channel measurements in real(istic) ambient conditions using mock-up environment at NPL for systematic channel measurements and demo purposes	D4.4	M12	M24	Completed	Bench top
UC-02B									
UC-03	Physical Layer - THz transceivers which support beam-steering TERAPOD components - Beamforming sub-system Testing and validation	WP-4	T4.1	Measure emitted power of transmitters (non-Terapod device)	D4.1	M1	M12	Completed	Bench top
				Measure power spectrum of transmitters (non-Terapod device)		M1	M12	Completed	Bench top
				Measure responsivity of receivers (non-Terapod device)		M1	M12	Completed	Bench top
				Measure radiation pattern and polarisation in the far field (non-Terapod device)		M1	M12	Completed	Bench top
				Measure emitted power of transmitters (Terapod device)	D4.2	M13	M33	Not started	Bench top
				Measure power spectrum of transmitter (Terapod device)		M13	M33	Not started	Bench top
				Measure responsivity of receivers (Terapod device)		M13	M33	Completed	Bench top
				Measure radiation pattern and polarisation in the far field (Terapod device)		M13	M33	Not started	Bench top
	Environmental conditions	WP-4	T4.2.1	Channel measurements in real(istic) ambient conditions using mock-up environment at NPL for systematic channel measurements and demo purposes	D4.4	M12	M24	Completed	Bench top

Table 7: UGLA, revised research alignment summary

						Timeline to finish the task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Status**	**Demonstrator**
UC-01									
UC-2A	Terahertz Device components (RTDs and SBDs)	WP-3	T-3.2	Realisation of 150 GHz RTD in chip form with adequate output power (0.5 – 1 mW) and tunability (a few GHz) for use as local oscillators in coherent Schottky Barrier Diode (SBD) based THz receivers being developed partner ACST.	T-4.3 and T-3.5	M-1	M-15	Completed	Bench top and DC integration
				Realisation of 300 GHz RTD sources with on-chip antennas and their packaging (for use with a silicon lens, which is a classical approach that is employed for some other semiconductor sources)	T-4.3 and T-3.5	M-1	M-20	Near Completion	Benchtop and DC integration
				Realisation of 300 GHz RTD sources in substrate-in-waveguide (SIW) technology (as an alternative approach which employs proven high gain waveguide horn antennas)	T-4.3 and T-3.5	M-1	M-24	In-progress	Benchtop and DC integration
				Realisation of high power (>3 dBm) 300 GHz sources and their packaging as noted above	T-4.3 and T-3.5	M-1	M-30	In-progress	Benchtop and DC integration

Table 8: ACST, revised research alignment summary

						Timeline to finish the task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Current status**	**Demonstrator**
UC-01	Requirements, challenges, and technical inputs	WP2	**T2.1**	Provide support in the definition of technical aspects and technologies compatibility. Identify technological requirements for the THz TERAPOD receiver.	D2.1	M1	M6	Completed	
UC-2A	Delivery of SBD-based THz detectors and mixers for TERAPOD receiver part	WP3	**T3.3**	Provide SBD quasi-optical detectors able to work from 0.05-2.5 THz	D3.1	M1	M3	Completed	DC integration, Benchtop
			T3.3	Development of a preliminary 300 GHz Frequency mixer based on SBD technology.	D3.2	M1	M13	Completed	DC integration, Benchtop, simulation
			T3.3	Development of an SBD-based 150 GHz doubler to provide local oscillator power for the 300 GHz mixer.	D3.6	M11	M18	Designed ready for fabrication	Benchtop
UC-2B	Delivery of SBD-based THz receiver at 300 GHz able to provide 100 Gbps	WP3	**T3.3**	Delivery of a 300 GHz receiver System for preliminary demonstration of use case in the Data Centre.	D3.3	M11	M18	Cancelled by Consortium	DC integration, Benchtop, simulation
			T3.3	Development of a 300 GHz mixer based on low barrier SBDs to reduce LO power requirements	D3.7	M17	M24	In-progress	DC integration, Benchtop, simulation
			T3.5	Development of a 150 GHz Oscillator using RTDs and/or UTCs	D3.6	M15	M20	In-progress	DC integration, Benchtop, simulation
			T3.5	Mechanical design of a 300 GHz horn antenna in collaboration with INESC	D3.6	M15	M18	Design Ready Fabrication in process	Benchtop, simulation
		WP4	**T4.1**	Characterisation of a preliminary SBD 300 GHz Mixer	D4.2	M7	M13	Completed	DC integration, Benchtop

				Characterisation of SBD 300 GHz Doubler	D4.2	M16	M18	Not started	Benchtop, simulation
				Characterisation of 150 GHz Oscillator based on RTDs and/or UTCs	D4.2	M18	M24	Not started	Benchtop
				Characterisation of the Low barrier SBD 300 GHz mixer	D4.2	M20	M24	Not started	Benchtop, simulation
			T4.2	Characterisation of the preliminary 300 GHz receiver	D4.3	M16	M18	Cancelled by Consortium	DC integration, Benchtop, simulation
				Characterisation of low barrier SBD-based 300 GHz Receiver using RTD/UTC oscillator	D4.4	M20	M24	Not started	DC integration, Benchtop, simulation

Table 9: UCL, revised research alignment summary

						Timeline to finish task			
Use case	**Requirement**	**Work package**	**Task activity number**	**Task activities**	**Deliverable**	**Starting time**	**Completion time**	**Current status**	**Demonstrator**
UC-2A	Uni Travelling Carrier Photodetector developments	WP-3	T-3.1	Development of UTCs integrated with bow-tie antenna for operation in 230 GHz - 290 GHz range	D 3.1	M-1	M-3	Completed	Bench top and DC integration
				Development of UTCs integrated with slot antenna for (a) broadband and (b) 300 GHz operation	D 3.6	M-3	M-20	Completed	Bench top and DC integration
				Development of array of UTCs	D 3.6	M-3	M-20	Completed	Bench top and DC integration
				Development of UTCs with bias tee to act as LO in THz receiver	D 3.7	M-20	M-30	In-progress	Bench top and DC integration
				Development of UTC integrated with INESC antenna	D 3.7	M-20	M-30	In-progress	Bench top and DC integration
UC-2A	Bench top demonstrator	WP-6	T-6.1	Demonstration of multi-channel transmission in the 200 GHz - 300 GHz band	D 6.1	M-1	M-16	Completed	Bench top and DC integration
				Demonstration of 40 Gbit/s at 250 GHz	D 6.1	M-1	M-16	Completed	Bench top and DC integration
				Demonstration of 100 Gbit/s transmission	D 6.2	M-16	M-33	In-progress	Bench top and DC integration

3 Research Alignment with State of the Art

This section will provide an overview of where the activities within TERAPOD sit in relation to other activities being pursued within Europe and Internationally within the THz communication space.

3.1 Alignment of TERAPOD project with other projects

The sections will be aligned with the activities of TERPAOD and will depict similar activities within these groups, to show how TERAPOD is progressing in comparison to these activities. Table 9, in this regard, shows the comparison of TERAPOD project with other European and International projects. The main difference lies in the application scenario which is a Data Centre. It mainly involves high capacity wireless link, fully integrated system and its architecture with antenna and transceiver design, whereas other projects are either focusing on a limited domain or represent a different application scenario. The indoor scenario faces different challenges than the outdoor environment including channel model and losses. The parameters focused in different projects are given in Table 10.

Table 10: Alignment of TERAPOD project with other projects.

Project	Region	Focus	Alignment to TERPAOD
ULTRAWAVE	EU H2020	High capacity backhaul links to enable 5G cell densification by exploiting bands beyond 100 GHz	High capacity point to point and multipoint links within a Data Centre environment by exploiting bands beyond 300 GHz
TERRANOVA	EU H2020	System architecture for embedding broadband THz wireless links into fiber-optic links for beyond 5G networks by exploiting 270 and 330 GHz band. Mainly, focused on electro-optical baseband interfaces, Integrated THz front-ends and correction schemes for hybrid fiber optic and wireless links	Full system integration within a Datacenter environment with wireless and hybrid (optical and wireless) links by focusing on RTDs, SBDs, UTC-PDs, and communication architecture
EPIC	EU H2020	Forward error correction codes and design	FECs are also part of TERAPOD aims and objectives
DREAM	EU H2020	Exploiting radio spectrum bands like 130-174.8 GHz with beam steering functionality to reach optical systems speed	Exploiting radio spectrum beyond 300 GHz to provide higher data rates for a Data Centre environment.
WORTECS	EU H2020	Optical wireless communication and radio over 90 GHz Proof of Concept with Gbps throughput.	One of the use cases in TERAPOD is also focusing on optical wireless integration within a Data Centre
NTT & Tokyo Uni.	JAPAN	IC capable of 100Gbps at 300GHz. Target source is InP-HEMT. Single carrier.	TERAPOD is focusing on RTD and UTC-PD technologies, also at 300GHz and 100Gbps.
TERRANOVA: A testbed for Terahertz communication	US, Buffalo NSF.	Developing a fully integrated THz communication testbed targeting 1THz.	TERAPOD demonstrators are focusing on 300 GHz and will be fully integrated into a DC deployment. I.e. not a testbed.
Hybrid Graphene/Semiconductor Plasmonic Nano-Transceiver and Nano-Antenna for Terahertz-Band Communication	US, Buffalo US AFOSR	Development of a Plasmonic THz source coupled with a graphene antenna. This is a fundamentally new approach to THz generation.	TERAPOD focuses on RTD and UTC-PD with aims of advancing TRL.

Table 11: Parameters and features focused in Terahertz related projects.

Project	Scenarios	Bands	Distance/Coverage	Features / connectivity	Data rate	Latency	Mobility	Antenna	antenna gain	Channel/Propagation model	Devices	Physical layer	MAC layer	Network layer
TERRANOVA	Backhaul	270 to 320 GHz	1 Km	Optical and wireless, Small cells	100 Gbps	✓	✓	Phased array/Horn antenna	55 dBi is assumed	✓	X	✓	✓	X
IBROW	Femtocell, Wireless portable devices	60 GHz - 1 THz	10 m	Wireless transceiver design	10 Gbps	X	X	X	X	X	X	X	X	X
ULTRAWAVE	Backhaul	141-148.5 GHz (Backhaul) 275-305 GHz (Fronthaul)	Fronthaul: 600-700m Backhaul: 600 m	P2P (fronthaul), P2MP (Backhaul)	100 Gbps	✓	X	sector/terminal	20 and 39 dBi	X	X	✓	X	X
EPIC	Indoor and outdoor, short, medium and long-range chipset design	X	X	FEC Techniques	1 Tbps	X	X	X	X	X	CMOS	✓	X	X
DREAM	Backhaul/ Mesh network	D-band	300 m	P2P	100 Gbps	X	X	X	X	X	X	X	X	X
WORTECS	Virtual reality Office Stadium and Theme park	90 GHz	10 m	P2P	VR (210 Gbps) Office (25 Mbps to 1 Gbps) Stadium (20 - 50	✓	✓	X	X	X	X	X	X	X

					Mbps)									
THOR	Backhaul	252-325 GHz	1 Km	P2P, P2MP	100 Gbps	X	X	X	X	X	X	✓	X	X
NTT	Wireless downloading system	300 GHz	10 m	P2P	20 Gbps	X	X	X	X	X	X	X	X	X
TERA POD	Data centres	300 GHz	10 m	P2P, P2MP, Autonom ous connecti vity	100 Gbps	✓	X	Horn	24 dBi	✓	RTDs , SBDs , UTC PDs	✓	✓	✓

3.2 Related contributions against task activities and requirements in TERAPOD and other projects

In this section, the contributions are mentioned against the identified requirements and task activities by each partner in the previous section. The related contributions in other related projects are also mentioned for requirements given in Terapod project. In most cases the deliverables are confidential in other projects. Therefore, only those related focused areas are mentioned which they have publicly disclosed. Table 11 to 19 highlights the contributions for Terapod identified requirements and task activities and other related projects.

Table 12: Contributions and alignment by TSSG and other projects for technical requirements.

Use case	Requirement	Work package/ Task number	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-01	To identify issues and challenges for THz MAC layer	WP-5/T5.2	Literature review for exiting Terahertz communication protocols	[1] [2], D5.1	TERRANOVA discuss the challenges but for backhaul link
	Initial Data Link Layer simulator	WP-5/T5.2	Analyses and selection of existing simulators for Terahertz communications	[3], D5.1, D5.3, D5.5	TERRANOVA discusses the performance assessment under different propagation conditions. EPIC project contributes to the radio link quality using polar codes for high data rate
		WP-5/T5.2	Initial Data Link Layer Block Diagram		
		WP-5/T5.2	Physical layer parameters analysis to be used in the link-layer simulator		
		WP-5/T5.2	Implementation/simulation of DLL basic functionalities on MATLAB/NS3		
	Traffic modelling and workload estimation of Data Centres	WP-5/T5.2	Theoretical Frame generation and DLL buffer modelling using Markov Chain	[4], D5.3	
		WP-5/T5.2	Capturing real traces from Data Centre environment and equivalent traffic generation		
UC-2A	Initial Data Link Layer simulator	WP-5/T5.2	Implementation of Point to point link for Data Centre scenario using directional antennas	[3] Interfacing work is in progress	ULTRAWAVE project using high power transmitter, it is possible to reach more than 500m using THz frequencies" D2.2 Final System and Components Specifications based on the evolution of the technological processes" [5]
		WP-5/T5.2	Implementation of the channel model and physical layer aspects		
		WP-5/T5.2	Interfacing between Physical, MAC and Network Layers		
	DC Geometry	WP-5/T5.2	Wireless topology design within a Data Centre using inter/Intra rack communication		
	Handshaking mechanism	WP-5/T5.2	Handshaking mechanism proposed and implemented		
	Data rate and transmission distance	WP-5/T5.2	Simulations carried out for maximum distance achievability	D5.3	
			Simulations performed to analyse the achievable data rate		
			Comparison of an optical and THz link within a Data Centre environment		

Table 13: Contributions and alignment by DER and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-01	End-user requirements Technology Requirements Non-functional Requirements	WP2, T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1, D2.2	N/A
UC-2A	End-user requirements Technology Requirements Non-functional Requirements	WP2, T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1, D2.2	N/A
	Interface requirements	WP5, T5.3	Study and develop flexible models to support multiple different network simulation scenarios within the data centre Design of Layer 3 routing algorithms/protocols and other (anycast/multicast) • Trial network simulator mapping traffic and THz communication across links within a datacentre	[2], D5.5	N/A
	Interface requirements	WP6, T6.2	Embedding THz links into a comms network - DER data centre	N/A	N/A
UC-2B	End-user requirements Technology Requirements Non-functional Requirements	WP2 T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1, D2.2	N/A
	Interface requirements	WP5, T5.3	Further design of routing protocols, simulation scenarios, etc. Partitioning of data traffic and software-defined networking (SDN) integration	D5.5	N/A
	Interface requirements	WP6, T6.3	Fully demonstrate THz links in a data center environment through real-time device/link integration	N/A	N/A
UC-03	End-user requirements Technology Requirements Non-functional Requirements	WP2, T2.1	Define use case scenarios Stakeholder/end-user interviews & workshops Business Model Canvas Examine commercial opportunities for THz/DC integration Identify potential safety risks and customer/market risks	D2.1, D2.2	N/A
	Interface requirements	WP5, T5.3	Further design of routing protocols, simulation scenarios, etc. Partitioning of data traffic and software-defined networking (SDN) integration	N/A	N/A

Table 14: Contributions and alignment by TUBS and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-01	Sustainability Technology requirements	WP7, T7.4	Standardisation activities to strengthen the Data Centre Scenario as an application for THz technology	D7.5, D7.6, [14,15]	
UC-2A	Data Centre geometry Network Requirements	WP4, T4.2.1, T4.2.2	Channel measurement for Channel Characterization of Use Case Scenarios	D4.3, [6,16]	
			Study of channel characteristics for different transmission scenarios (General Characterization, Top of Rack, Intra-Rack) in the data centre	D4.3	THOR and TERRANOVA also deal with channel characterisation.
			Bild a 3D data centre model for ray tracing channel simulations		
			Extensive ray-tracing simulations to fully characterise the channel		
			Creation of a model of the THz channel which will be fed to the PHY simulator		
	Data Rate of THz links Bit Error Rate	WP5, T5.1	First simple physical layer simulator implementing the current standard of THz communication which gives BER and PHY delay for the measured scenarios using a simple channel model	D5.1	Thor project contributes to the same PHY layer simulator but with focus on backhaul application
			Implementation of the THz Channel model in the PHY simulator		Thor project contributes to the same PHY layer simulator
			Implementation of forward error correction methods in the PHY simulator		
			Analysis of Bit Errors in the PHY simulator and Development of a Statistical Error Model		
UC-2B	Interface requirements	WP5, T5.1	Definition of interfaces between simulators	D5.1	
			Development of an Error Model Generator which enables higher-level simulations employing a realistic PHY model		
UC-03	Demonstration or proof-of-concept	WP6, T6.2	Development of a simulator platform/interface which serves as a demonstration platform and illustrates how all different simulators work together (DC Geometry, Raytracing, PHY Sim, MAC Sim, Network Sim, Auto Config)	D6.3	

Table 15: Contributions and alignment by INESC TEC and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-02A and UC-02B	Technology requirement: device antenna gain higher than 20 dBi for 1 m transmission (adjacent racks).	WP 3, T3.5	Propose and validate by simulation a substrate integrated antenna design solution compatible with existing manufacturing limitations.	D3.4, D3.6	Terranova is addressing phased array and beam steering, but using linear horn antenna array (Terranova D5.1, D5.2 and D5.3) Dream project proposed optimal antenna elements for array development and beam steering operating in the D-band (Dream D2.3.3 D3.1, D3.2, D3.3 and D3.4)
		WP 3, T3.5	Improve initial substrate integrated antenna design solution with antenna feed details.		
		WP 3, T3.5	Propose and validate by simulation a waveguide-based solution to interface with the substrate integrated antenna array to provide the target gain.		
	Technology requirement: device antenna gain higher than 30 dBi for 10m transmission (adjacent aisles).	WP 3, T3.5	Improve initial waveguide-based interface to substrate integrated antenna array to provide the target gain.	N/A	N/A
		WP 3, T3.5	Propose and validate by simulation a horn antenna solution to be interfaced with the SBD receiver.	[7]	Terranova proposed 300 GHz horn antenna, but without focus in High-Gaussicity (Terranova D5.1, D5.2 and D5.3).
UC-03	Technology requirement: device antenna compatible with beamforming subsystem.	WP3	Simulate antenna array radiation patterns resulting from array excitations with phase values given by the developed PIC, considering a Si lens.	D3.6	Contributions already mentioned in **Table 15.**
		WP3	Simulate antenna array radiation patterns resulting from array excitations with phase values given by the developed PIC, considering an antenna waveguide output.	D3.6	

Table 16: Contributions and alignment by VLC and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-03	Beam steering mechanism for dynamic allocation of devices and of bandwidth	WP3, T3.4	Design a phase distribution Photonic Integrated Circuit for dynamic reconfiguration of the emission profile. The PIC design has been fabricated.	**D3.3** Design report of phase distribution. · 2-stage MZI-based (tunable) power splitter · Ring resonators delaying elements. · SiN PIC tech with Aluminium metals	DREAM project has developed a Silicon BiCMOS-based transceiver with a beam steering integrated antenna array. [8] DREAM reported D2.3.3 on D-band radio front end for antenna beam steering tests and D3.4 on test system for digital control of beam steering demonstrators. Related contributions to the field (VLC not involved): 5G-PHOS has developed optical beamforming functionalities for 5G communication networks. Here, the delay is based on a set of cascaded ring resonators. The system operated in the V-band (60GHz) [9]
			Test and characterization of the Phase Distribution PIC. Test building blocks and their effect on the system. Test system and the range of tuning for each element.	**D3.5** Characterization report of phase distribution PIC · MMI imbalance below 2% · MZIs current operation for splitting tunability from 40 to 75 mA. · Maximum power rejection throughout the system of 24 dB. · Ring resonators delay at critical coupling show to be sufficient for a 0.1 THz signal to accomplish ±π/4 beam steering.	

Table 17: Contributions and alignment by UGLA and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-2A	Terahertz Device components (RTDs and SBDs)	WP-3, T3.2	Realisation of 150 GHz RTD in chip form with adequate output power (0.5 – 1 mW) and tunability (a few GHz) for use as local oscillators in coherent Schottky Barrier Diode (SBD) based THz receivers being developed partner ACST.	Not yet	The 150 GHz RTD devices could find use in the ULTRAWAVE cluster project (discussions with coordinator underway)
			Realisation of 300 GHz RTD sources with on-chip antennas and their packaging (for use with a silicon lens, which is a classical approach that is employed for some other semiconductor sources)	D3.6, Paper submitted to IEEE Trans. THz Science and Technology	Sources will be availed to some cluster partners for evaluation
			Realization of 300 GHz RTD sources in substrate-in-waveguide (SIW) technology (as an alternative approach which employs proven high gain waveguide horn antennas)	Not yet	Sources will be availed to some cluster partners for evaluation
			Realisation of high power (>3 dBm) 300 GHz sources and their packaging as noted above	Not yet	TBC

Table 18: Contributions and alignment by NPL and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-02A	Physical Layer TERAPOD components Testing and validation	WP-4, T4.1	Measure emitted power of transmitters	D-4.1, [10,11,12]	
			Measure the power spectrum of the transmitter		
			Measure responsivity of receivers		
			Measure radiation pattern and polarisation in the far-field		
			Measure emitted power of transmitters		
			Measure the power spectrum of the transmitter		
			Measure responsivity of receivers		
			Measure radiation pattern and polarisation in the far-field		
	Environmental conditions	WP-4, T4.2.1	Channel measurements in real(istic) ambient conditions using mock-up environment at NPL for systematic channel measurements and demo purposes		
UC-03	Physical Layer - THz transceivers which support beam-steering TERAPOD components - Beamforming sub-system Testing and validation	WP-4, T4.1	Measure emitted power of transmitters	D-4.1, [10,11,12]	
			Measure power spectrum of the transmitter		
			Measure responsivity of receivers		
			Measure radiation pattern and polarisation in the far-field		
			Measure emitted power of transmitters		
			The measure power spectrum of the transmitter		
			Measure responsivity of receivers		
			Measure radiation pattern and polarisation in the far field		
	Environmental conditions	WP-4, T4.2.1	Channel measurements in real(istic) ambient conditions using mock-up environment at NPL for systematic channel measurements and demo purposes		

Table 19: Contributions and alignment by ACST and other projects for technical requirements.

Use case	Requirement	Work package	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-01	Requirements, challenges, and technical inputs	WP2, T2.1	Provide support in the definition of technical aspects and technologies compatibility. Identify technological requirements for the THz TERAPOD receiver.	Contributions in D2.1 and D2.2 Design report of phase distribution. · 2-stage MZI-based (tunable) power splitter · Ring resonators delaying elements. · SiN PIC tech with Aluminium metals	
UC-2A	Delivery of SBD-based THz detectors and mixers for TERAPOD receiver part	WP3, T3.3	Provide SBD quasi-optical detectors able to work from 0.05-2.5 THz	Described in D3.1. Used by NPL for measurements	
			Development of a preliminary 300 GHz Frequency mixer based on SBD technology.	Presented in D3.6 · Noise figure lower than 6 dB · ~ 2-3 mW LO power required · 270-320 GHz bandwidth	This is a commercial product at ACST
			Development of an SBD-based 150 GHz doubler to provide local oscillator power for the 300 GHz mixer.	This proposal from ACST as a back-up solution for TERAPOD wasn't accepted by the project managers as ACST output in the project.	The doubler was done, and it is a commercial product at ACST
UC-2B	Delivery of SBD-based THz receiver at 300 GHz able to provide 100 Gbps	WP3, T3.3	Delivery of a 300 GHz receiver System for preliminary demonstration of use case in Data Centre.	This proposal from ACST as a back-up solution for TERAPOD wasn't accepted by the project managers. This is not an ACST output in the project.	This receiver was presented in [13]
			Development of a 300 GHz mixer based on low barrier SBDs to reduce LO power requirements	This is on-going. The fabrication of diodes is required	
			Development of a 150 GHz Oscillator using RTDs and/or UTCs	This is on-going. Only chips from UGLA are available. There are no chips from UCL	
			Mechanical design of a 300 GHz horn antenna in collaboration with INESC	This is an on-going project. We are still in negotiation with the manufacturer due to problems in the implementation of the design	
		WP4, T4.1, T4.2	Characterisation of a preliminary SBD 300 GHz Mixer	Presented in D3.6 · Noise figure lower than 6 dB · ~ 2-3 mW LO power required · 270-320 GHz bandwidth	This receiver was presented in ISSTT2018 entitled "High Power Discrete Schottky Diodes Based 275-305 GHz Transceiver for FMCW-Radar"

Table 19: Contributions and alignment by UCL and other projects for technical requirements.

Use case	Requirement	Work package	Task activity number	Task activities	Published contribution in paper or deliverable report	Related contribution in cluster projects
UC-2A	Uni Travelling Carrier Photodetector developments	WP-3	T-3.1	Development of UTCs integrated with bow-tie antenna for operation in 230 GHz - 290 GHz range	D 3.1	
				Development of UTCs integrated with slot antenna for (a) broadband and (b) 300 GHz operation	D 3.6	
				Development of array of UTCs		
				Development of UTCs with bias tee to act as LO in THz receiver		
				Development of UTC integrated with INESC antenna		
UC-2A	Bench top demonstrator	WP-6	T-6.1	Demonstration of wireless bridge with multi-channel transmission in the 200 GHz - 300 GHz band	D 6.1 & [17]	Terranova is also demonstrating high data rate THz links with PIN-PD. In their case no second portion of optical fibre is included
				Demonstration of 40 Gbit/s wireless bridge at 250 GHz	D 6.1 & [17]	
				Demonstration of 100 Gbit/s wireless bridge		

4 Conclusion/Further work

This report presents the progress update on the requirement and task activities which are highlighted for different use cases by each project partner. The objective here is to align the research for each use case according to work package progress in terms of the requirements, task activities and deliverables. The goal is then to track down the progress, match the deliverable and demonstrator with the identified requirements of each use case, and if required then to rectify them ahead of time. Initially, the progress update is presented on previously mentioned task activities (D2.4) within TERAPOD project. Requirements and features of different Terahertz related projects are highlighted. Finally, the contributions against each requirement are mentioned with focused contributions in other Terahertz related projects.

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