HORIZON 2020

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Terahertz based Ultra High Bandwidth Wireless Access Networks

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Executive summary

The Initial Requirements and Scenario Specifications form the basis for the technology development that will be carried out by the TERAPOD project. It motivates the scenarios in which the technical outputs of the project will be deployed and sets up a framework for ensuring that the technology artefacts produced by the project will meet the needs of their eventual end users. The requirements and scenarios will be iteratively revised throughout the lifetime of the project.

In this document, four use cases have been specified, each of which was derived from early engagement with potential end users of TERAPOD technologies. These four use cases are:

- TERAPOD-UC-01: Commercial Feasibility of THz DC Wireless Networks
- TERAPOD-UC-02A: Static (Layer-1) THz Wireless Data Links
- TERAPOD-UC-02B: Dynamic (Multi-Layer) THz Wireless Data Link Integration
- TERAPOD-UC-03: Wireless Data Centre Auto-Configuration

These use cases, and their detailed requirements are described in detail. These will underpin the technology development efforts for the TERAPOD project. Each use case will continue to be refined and revised throughout the lifetime of the project, in order to ensure that the project produces technology for which deployment within a data centre environment is both technically viable and commercially feasible.

1 Introduction

1.1 Summary

This deliverable presents the Initial Requirements and Scenario Specifications for the TERAPOD project. It describes the methodology used to gather requirements and select appropriate use cases, motivating these by their relevance to the requirements of the H2020 ICT-09-2017 call text. Each of the use cases is introduced and its requirements are described in detail, including both functional and non-functional requirements. Requirements related to standardisation and to test and validation activities are also described.

1.2 Structure of this document

This document is laid out as follows:

- Section 1 provides an introduction to the deliverable, including its relationship with other TERAPOD deliverables and the partners who have contributed to the text.
- Section 2 provides an overview of the TERAPOD use cases, beginning with a description of the methodology used to specify the scenarios and gather requirements and following with an introduction to each of the use cases selected by the consortium. This is followed by a description of how the use cases relate to the requirements of the H2020 ICT-09-2017 call text.
- Sections 3, 4, 0 and 6 provide the detailed requirements for each of the four selected use cases. Each of these sections follows a similar structure, starting with end-user requirements for the use case in question, followed by technology requirements, derived from the end-user requirements, and finishing with any non-functional requirements posed by the use case.
- Section 7 presents the requirements imposed on the project by relevant standards and standardisation efforts.
- Section 8 outlines the testing and validation requirements, which will underpin WP6.
- Finally, Section 9 provides conclusions and a summary of the next steps.

1.3 Relationships with other deliverables

The requirements presented in this document relate to the following deliverables:

- D7.5 – Initial Standardisation Impact Strategy: this document presents the standards which are relevant for the TERAPOD project and which serve as the basis for relevant functional and non-functional requirements.
- D2.2 and D2.3: these future deliverables will contain progressively more mature requirements and use case specifications than those presented in this initial requirements document, following the same methodology and structure outlined in the current deliverable.

1.4 Contributors

The following partners have contributed to this deliverable:

- DER (Niamh O'Mahony, Fiach O'Donnell)
- TUBS (Johannes Eckhardt, Thomas Kürner)
- NPL (Mira Naftaly)
- VLC (Marco Garcia Porcel)
- UGLA (Edward Wasige)
- UCL (Cyril Renaud)
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- VIVID (Bruce Napier)
- INESC (Luis Pessoa)

1.5 Abbreviations

For convenience, provided below is a list of some of the abbreviations used in this document.

BER	Bit Error Rate
CPW	Co-Planar Waveguide
DC	Data Centre
DCN	Data Centre Network
EIRP	Equivalent Isotropic Radiated Power
E-RTD	Electronic Resonant Tunnelling Diode
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line Of Sight
MAC	Media Access Control
OOK	On-Off Keying
QAM	Quadrature Amplitude Modulation
RTD	Resonant Tunnelling Diode
RTD-PD	Resonant Tunnelling Diode Photo-Detector
RU	Rack Unit
SBD	Schottky Barrier Diode
SDN	Software Defined Network
SNR	Signal to Noise Ratio
TOR	Top of Rack
UTC-PD	Uni-Travelling Carrier Photo-Detector

2 TERAPOD Use Case Overview

This section outlines the methodology that has been followed by the TERAPOD consortium for gathering the initial requirements, followed by an introduction to each of the four use cases which will be elaborated throughout the project and, on whose requirements, the technical work packages will depend.

2.1 Requirements Gathering and Scenario Specification Methodology

A three-step procedure was followed for defining these requirements, as follows:

1. Define use case scenarios.
2. Analyse use cases.
3. Derive technology requirements.

Each of these steps is briefly described below.

2.1.1 Definition of Use Case Scenarios

2.1.1.1 End-user interviews

In order to ensure that the TERAPOD use case scenarios were defined in alignment with the needs of the data centre, the first step for defining the use cases was to interview stakeholders from the data centre, to understand their needs. During M1 – M3 of the project, DER conducted interviews with representatives from Dell EMC's Global Solutions Labs team and from Virtustream's data centre engineering teams. These included a data centre designer as well as members of the storage, compute and networking engineering teams. TSSG also held discussions with representatives from their data centre, including the infrastructure management team.

The high level agenda followed for each of the interviews was as follows: (1) present an overview of the TERAPOD project, introducing the stakeholders to the motivation and goals outlined in the proposal; (2) ask stakeholders for insights regarding scenarios for which wireless communication would be desirable within the data centre; (3) discuss the bandwidth requirements for the various scenarios outlined, to understand whether or not THz is a requirement; (4) invite the stakeholders to join the TERAPOD mailing list and stakeholders' group, so that they can remain informed of the project's progress and can continue to contribute their ideas and insights to the use cases and technical work.

The outcomes of the end-user interviews are summarised in Appendix A. The various scenarios that were suggested by stakeholders during the end user interviews were then considered in the context of the ambitious goals (e.g. ultra-high bandwidth) of the TERAPOD wireless technologies and four use cases were outlined, each of which would meet the needs of the data centre stakeholders, as well as integrating results from the TERAPOD technical work packages. The use cases will be introduced in Section 2.2 and will each be described in more detail in Sections 3 to 6.

2.1.1.2 Core use case partners' workshop

Following the communication of the candidate use cases with all project partners, in M3, DER led a (virtual) workshop with TUBS and TSSG, with the goal of finalising the scope and definition of use case scenarios which had been outlined following the end user interviews. Several factors were considered, including meeting the business needs of the data centre stakeholders and the ability to fully exploit the characteristics of the technologies to be developed in TERAPOD (e.g. transmission distance, bandwidth, beamforming, etc.).

An iterative approach was selected, such that each use case will build upon the previous case and integrate additional functionality. This approach is expected to ensure that demonstration of the first use case(s) can begin early in the project lifetime, whilst the final use case will rely on results that will become available later. It also aims to improve the success rate of the demonstration activities, by allowing any challenges or problems to be discovered and rectified early, while the complexity of the systems and demonstrators builds gradually throughout the project.

2.1.2 Analysis of Use Cases

The goal of the use case analysis was to identify all of the requirements of each use case, in order to enable the derivation of the functional and non-functional requirements upon which the technical work packages rely. A two-phase approach was taken, first defining the top-down requirements from the end-user's point of view and, then, defining the bottom-up requirements from the point of view of what is needed to integrate the THz technologies in the data centre. A template was adopted by the consortium to facilitate the use case analysis; the content of this template is included in Appendix B and includes aspects considered under both the top-down and bottom-up approaches. The outcome of this analysis is contained in Sections 3, 4, 5 and 6 of this deliverable.

2.1.2.1 Top-down approach

The top-down requirements for each use case were derived through the following:

1. A review of the state-of-the-art for data-centre design, focusing mainly on the communications network.
2. A review of the outputs from the end-user interviews, discussed in Section 2.1.1.1.

This activity was driven by DER, as the main end-user partner in the consortium. The aspects of the use case scenarios that were considered for the top-down requirements included the storyline, goals, actors, general assumptions, pre- and post-conditions, geometrical and environmental conditions, data transmission rates, external systems/components with which the THz technologies must interface, interact or be compatible, health and safety aspects and key performance indicators (KPIs), related to business impact and end-user benefits. Diagrams illustrating the scenarios their expected operation were also derived, in order to simplify and clarify the main concepts of each use case. This step of the analysis also considered the relation of the use case to the "Beyond 5G" vision, as outlined in the H2020 ICT-09-2017 call text, in order to ensure close alignment between the project's activities and what is expected to be achieved.

2.1.2.2 Bottom-up approach

Derivation of the bottom-up requirements for integrating the TERAPOD technologies into each use case was led by the technology partners, given their familiarity and expertise with the technologies and interfaces. This step of the analysis focused on the more technical aspects, such as the detailed requirements of each network layer (physical, link, network layer), cross-layer requirements, and interactions between various TERAPOD technologies and/or components, including hardware, software and any relevant interfaces. This step also included consideration of the testing requirements, specifying the equipment, interfaces, software and other relevant elements that must be in place, in order to be able to effectively and accurately test and validate the TERAPOD technologies and quantify their performance, relative to the end-user's needs.

2.1.3 Derivation of Requirements for Technical Work Packages

The final requirements definition activity was to derive the specific requirements for each of the technical work packages (i.e. WP3, WP4, WP5 and WP6). This was carried out through a review by each WP leader and/or technology partner of the use case requirements relevant to the technologies included in their WP (including testing and validation requirements) and of the relevant standards and their implications for the TERAPOD technologies. The outcomes of this activity are described in Sections 3, 4, 5, 6, 7 and 8 of this deliverable.

2.2 Introduction to TERAPOD Use Cases

2.2.1 TERAPOD-UC-01

Use Case Overview	
Use Case ID	TERAPOD-UC-01
Short name for the use case scenario	Commercial Feasibility of THz DC Wireless Networks
Descriptive full name of the use case-scenario	A thorough commercial feasibility case study of the role of THz based wireless links within data centre systems.
Goal(s)	The output will be an advanced business model canvas that has been iteratively developed and validated in collaboration with the target end user and stakeholder group.

2.2.1.1 Storyline

In order to understand the commercial feasibility of introducing THz wireless links into Data Centre Systems, a commercial case feasibility study will need to be carried out. This study will follow the Lean Business Model Canvas methodology. The methodology consists of a structured iteration through the Business Model Canvas (see Appendix C) to determine the commercial case for a technological solution to a customer problem. Both functional and non-functional factors, which may influence the commercial feasibility of deploying THz technologies within the data centre, will be considered, including but not limited to:

- Data centre geometry.
- Network topologies.
- Achievable data rates.
- Application types or workloads in the data centre.
- Health and safety compliance.
- Interference with other electronic devices.
- Power consumption, relative to wired links.
- Impact on cooling and/or environmental control costs.

The process will involve documenting the business plan, identifying risks and systematically testing the plan and its assumptions. The concept is illustrated in Figure 1.

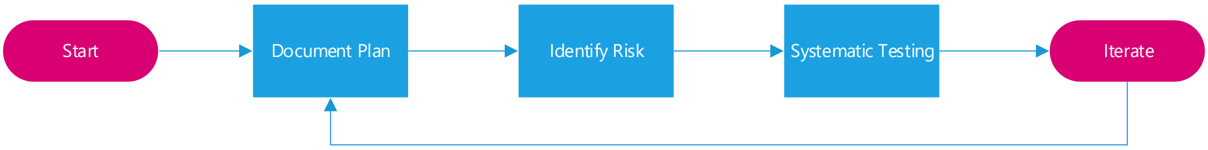

Figure 1 TERAPOD-UC-01 conceptual illustration

2.2.2 TERAPOD-UC-02A

Use Case Overview	
Use Case ID	TERAPOD-UC-02A
Short name for the use case scenario	Static (Layer-1) THz Wireless Data Links
Descriptive full name of the use case-scenario	Integration of static THz wireless data links at the physical layer of the data centre network (DCN).
Goal(s)	Seamless integration of static THz wireless links within the DCN, with data transmission performance in the THz wireless links equalling or exceeding that in the existing wired links (i.e. whether transmission occurred through a wired or wireless link should be transparent to the rest of the system).

2.2.2.1 Storyline

This use case will involve the integration of THz wireless devices at the physical layer of the DCN. This will enable the replacement of existing wired links with fixed wireless links between nodes, for example between servers within a rack (intra-rack communication) or between top-of-rack (TOR) switches (inter-rack communication). Replacing wired links with wireless links in this way will potentially mean a significant cost reduction for DCN deployment (cost of cables) and operation (cost of maintenance and cooling). Furthermore, it will improve the overall flexibility of the data centre, allowing new links to be added or modified more easily, through the addition or configuration of wireless links, rather than the addition and routing of cables. The use case also has the potential to enhance hyper-converged infrastructure offerings, by integrating wireless intra-rack and inter-rack communication links into the equipment, such that it can be pre-configured, tested and validated prior to deployment.

From the point of view of progressing towards the TERAPOD project's goals, this use case will serve as an initial proof-of-concept for the transmission of data within the data centre, which will be built upon further in the TERAPOD-UC-02B use case, to expand the integration of the technology further up the network stack. This is illustrated in Figure 2.

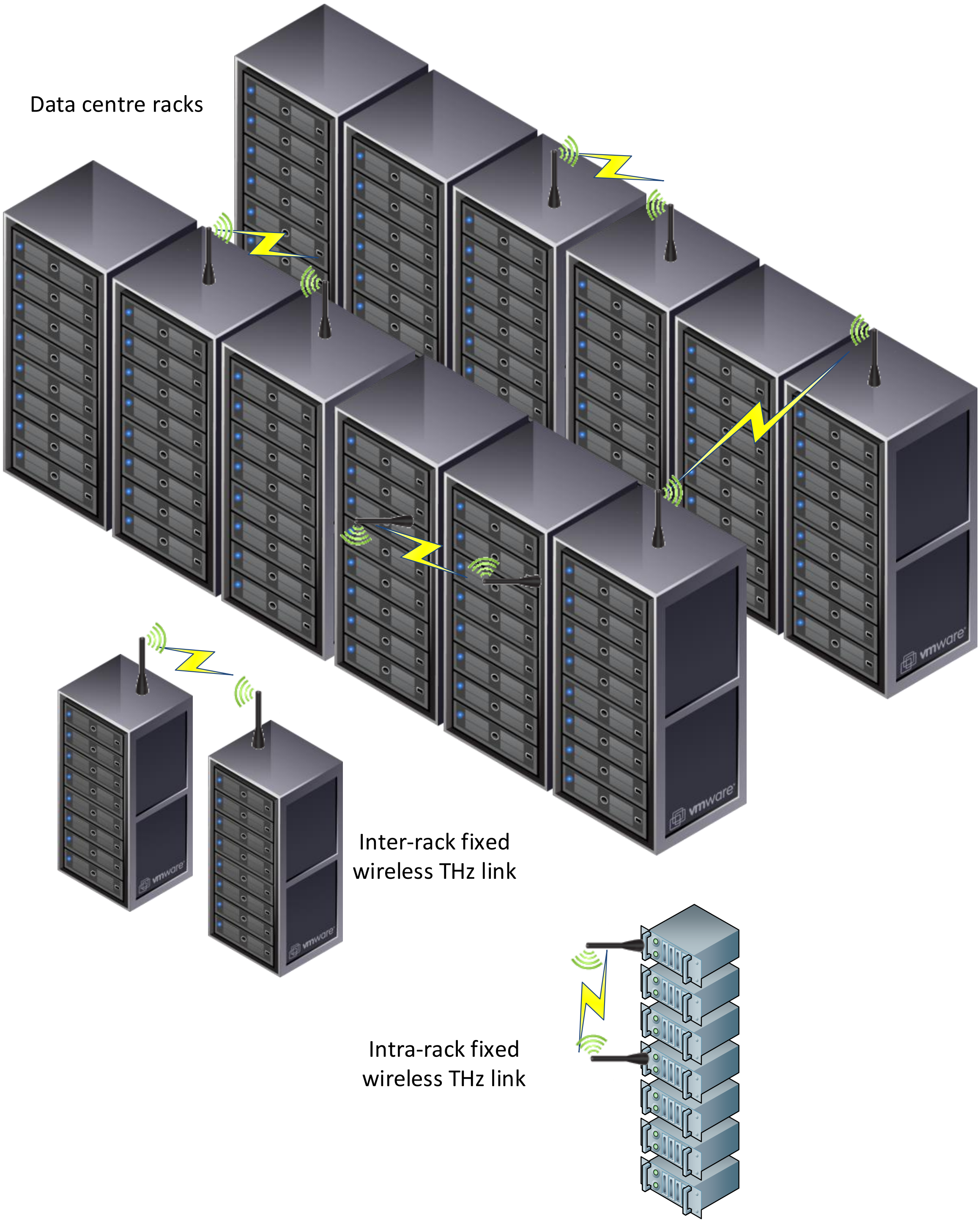

Figure 2 TERAPOD-UC-02A conceptual illustration

2.2.3 TERAPOD-UC-02B

Use Case Overview	
Use Case ID	TERAPOD-UC-02B
Short name for the use case scenario	Dynamic (Multi-Layer) THz Wireless Data Link Integration
Descriptive full name of the use case-scenario	On-the-fly replacement or augmentation of wired links with THz wireless data links, integrated across multiple layers of the DCN.
Goal(s)	Reduction in congestion and/or link down-time due to the seamless provisioning of flexible THz wireless links to replace and/or augment wired links, as automatically determined by software.

2.2.3.1 Storyline

This use case involves the same hardware as that for TERAPOD-UC-02A, with the integration, across multiple layers of the DCN, of dynamic load control and configuration of the fixed THz links which were integrated at the physical layer in TERAPOD-UC-02A. This use case will greatly enhance the benefits that can be gained from such links, by allowing the THz wireless links to act as a flexible resource, which can be configured on-the-fly to augment an existing wired (or wireless) link that is over-congested or to replace a link that has gone down.

Where congestion occurs within the DCN, for example, due to so-called “elephant flows” or large volumes of traffic between nodes, bottlenecks can occur, impeding the performance of the DCN. By monitoring the throughput of the network links, software protocols can be developed to direct traffic through wireless THz links to augment wired links which are congested or are predicted to become congested. Furthermore, if a wired link fails, a wireless THz link can be provisioned to substitute the wired link until it is repaired. Within a software defined network, the redundancy offered by the wireless THz links can be exploited to ensure that the network performance is not reduced by failed links and/or congestion. Figure 3 illustrates the concept.

It should be noted that, in this use case, the wireless THz links are configurable, with respect to dynamic provisioning, but they are not spatially adaptable; i.e. the nodes which they connect cannot be modified automatically. TERAPOD-UC-03 will address the issue of spatial adaptability.

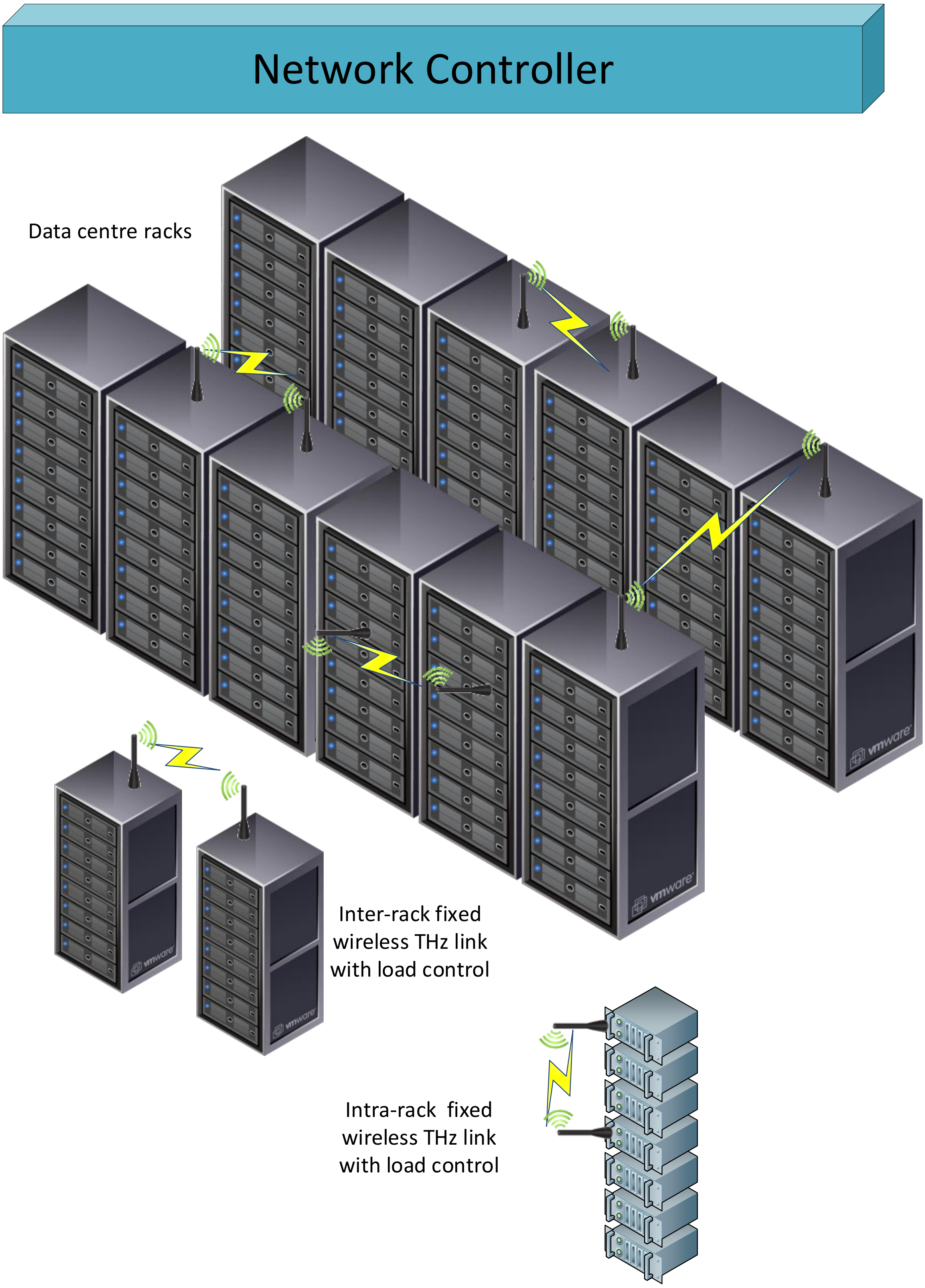

Figure 3 TERAPOD-UC-02B conceptual illustration

2.2.4 TERAPOD-UC-03

Use Case Overview	
Use Case ID	TERAPOD-UC-03
Short name for the use case scenario	Wireless Data Centre Auto-Configuration
Descriptive full name of the use case-scenario	Auto-configuration of wireless networking links within a data centre, allowing flexibility, scalability and rapid deployment of replacement or additional components.
Goal(s)	Full integration of THz wireless links within the DCN, with the following features: 1. Automatic device discovery and registration when a new device is added to the network or an existing device is replaced. 2. Automatic spatial configuration of wireless links, such that a given transmitter or receiver may communicate with more than one other transmitter/receiver, through reconfiguration of its beam direction, range and other appropriate parameters.

2.2.4.1 Storyline

The purpose of this use case is to implement automatic configuration of THz wireless links within a DCN, in terms of automatic device discovery and registration, and spatial adaptation of THz links (configurable directionality, range, etc.), as illustrated in Figure 4. This capability will improve the flexibility and scalability of a data centre, reducing the time to deploy additional or replacement components and eliminating the cost and human error associated with manual configuration. In conjunction with the other TERAPOD use cases, in particular TERAPOD-UC-02A and TERAPOD-UC-02B, this will bring the possibility of a fully wireless data centre closer to reality.

This use case will rely on advances in the TERAPOD project in beamforming for wireless THz links, using arrays of transmitters/receivers or alternative methods to achieve links whose beam profile can be altered dynamically.

Furthermore, the scope of this use case will evolve as the TERAPOD project progresses, in order to align the technical results of the project with state-of-the-art advances in DCN features and new use case scenarios that may emerge in the future.

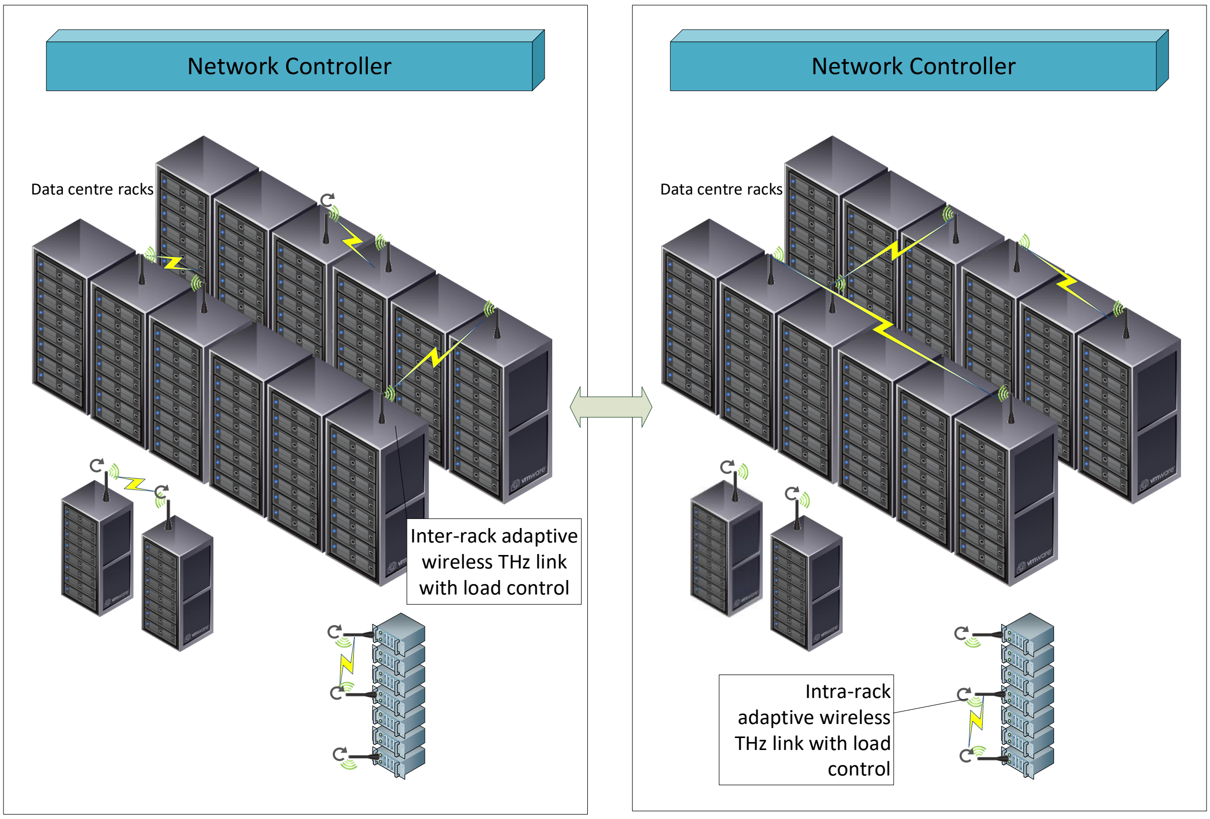

Figure 4 TERAPOD-UC-03 conceptual illustration

2.2.5 Relation to "Beyond 5G" requirements (H2020 ICT-09-2017 call text)

In the context of the "scientific and technology advances" theme identified in the H2020 ICT-09-2017 call (see B.2), the four use cases that have been selected for TERAPOD all contribute significantly towards *de-risking the technological building blocks for THz communications* in the *innovative usage scenario* of a DCN. TERAPOD-UC-01 will consider commercial aspects of the deployment of innovative THz wireless devices in a data centre, recognising that the use of such technologies is a significant change from the current state-of-the-art, which will require solid justification in commercial scenarios. By performing a thorough analysis of the feasibility of the new technology within the data centre environment, TERAPOD will be in a position to refine the technical requirements during the project, to ensure that the outcomes are commercially feasible and will provide blueprints and/or guidelines for the likely early adopters of the technology.

The iterative approach that has been selected for the technical use cases aims to de-risk the development effort, by implementing the technology in a staged fashion, such that any problems can be identified early and rectified quickly in a simplified scenario, before adding complexity to the system. By focusing on static wireless THz links within the DCN, TERAPOD-UC-02A will enable the project partners to focus on pushing the boundary for the data rates and transmission distances that can be achieved by the TERAPOD devices, with the goal of meeting or exceeding those achieved by existing wired links, whilst reducing power consumption. Building on the previous use case, TERAPOD-UC-02B will increase the level of integration of the (physically static) wireless THz links to higher networking layers, enabling dynamic use of the THz links to augment the existing wired network, as required, for example, when a wired link is damaged or overloaded. Finally, TERAPOD-UC-03 will incorporate more complex functionality, enabling spatial reconfiguration of the wireless THz links, through beam-steering and beam-shaping solutions. This functionality will unlock the potential for a significant increase in flexibility of the DCN, removing the restrictions of physical wired links between devices. It is expected that iteratively developing and implementing the TERAPOD technology in this way will reduce the risks associated with innovation and will lead to robust and viable outcomes from the project.

3 TERAPOD-UC-01 Requirements

3.1 End-user requirements

3.1.1 Assumptions

The following assumptions are made, relative to this use case:

- THz wireless technology is operational and can be deployed as a minimum viable product.
- THz wireless technology can be easily integrated into other systems through a common interface.

3.1.2 Data transmission requirements

There are no specific data transmission requirements for this commercially focused use case; such technical requirements will be considered in the technical use cases (TERAPOD-UC-02A, TERAPOD-UC-02B and TERAPOD-UC-03).

3.1.3 Detailed description of required scenario

A flow chart for TERAPOD-UC-01 is illustrated in Figure 5, with a more detailed description of the steps that should be taken described below the figure.

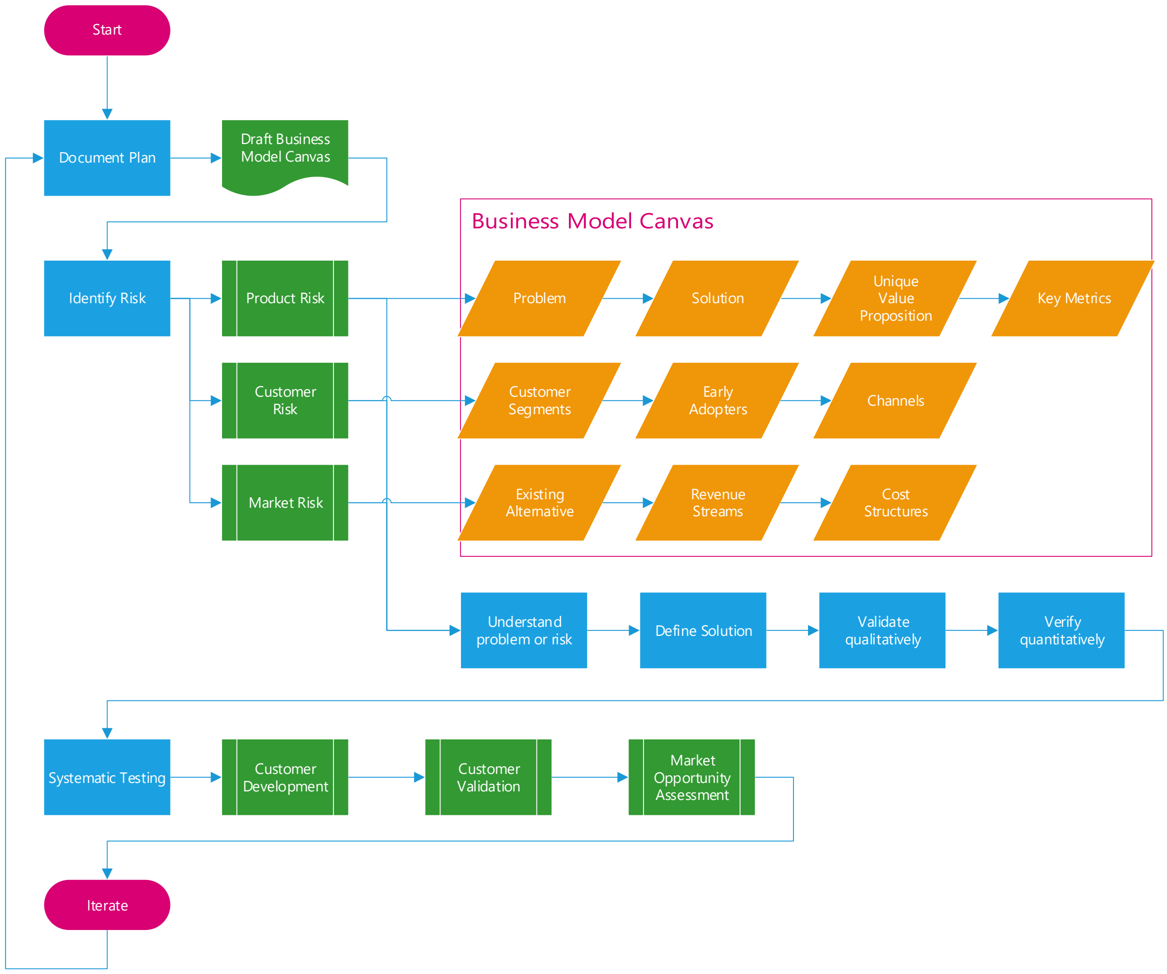

Figure 5 TERAPOD-UC-01 flow diagram

1. Initial step is to draft a business model canvas for the piece of technology in question.
2. Following this, the canvas is then used to iteratively evaluate Risk in relation to the business case. This involves resolving risk in relation to Product, Customer and Market. Each risk will leverage the canvas and improve on the canvas. To elaborate and resolve each risk, a particular pattern of iteration is used to traverse the business model canvas as follows.

a. Product Risk: 1 Problem > 2 Solution > 3 Unique Value Proposition > 4 Key Metrics
b. Customer Risk: 1 Customer Segments > 2 Early Adopters > 3 Channels
c. Market Risk: 1 Existing Alternative > 2 Revenue Streams > 3 Cost Structures.

The tasks at each phase are as follows:

i. Understand the problem / risk.
ii. Define solution
iii. Validate qualitatively.
iv. Verify quantitatively.

3. In order to develop the plan further and validate all assumptions on the canvas, the customer needs to be engaged. At this stage, a complete set of questions will be prepared for the customer to address every assumption on the canvas. This could arrive at over 100 questions. The questions will need to be divided into categories and targeted to different customer personas. Once this is complete, the interviews need to be completed. All answers will serve to progress the canvas and also may raise further questions. The aim is to focus on what information is needed from the customer to determine the validity of every aspect of the business model canvas.

3.1.3.1 Pre-conditions

THz wireless technology exists and is ready to be deployed within data centres.

Understanding about the business plan for commercialisation of the technology is lacking.

3.1.3.2 Actors and triggers

The primary actors in this use case are:

- End User – User of the technology.
- Customer – Buyer of the technology.
- Early Adopter – First Customer most likely to buy.
- Technology partners – responsible for design and implementation of THz wireless technology.
- Technology artefacts – the devices and protocols developed by the technology partners.
- The Stakeholder Group (Early Adopters, Customers and End Users)
- Project partners with relevant profiles (SMEs, Customers, End Users)

The trigger for the use case is the start of development of the business model canvas by the project partners.

3.1.3.3 Post-conditions

Understanding about the commercial opportunities and challenges for the integration of THz wireless communications in data centre environments has been developed.

3.1.4 Interface requirements

3.1.4.1 TERAPOD components

All of the technology artefacts (hardware and software) developed throughout the lifetime of the TERAPOD project will be considered in this feasibility study.

3.1.4.2 External systems

Various external systems and factors must be considered, in terms of their impact on the commercial feasibility of deploying THz wireless technology within a data centre, including, but not limited to:

- DCN topologies.
- Physical data centre layouts.
- Greenfield or brownfield status of the data centre/site.

- Characteristics of typical workloads in the data centre.

3.1.5 Other considerations

3.1.5.1 Safety

Any safety aspects that will impact on the commercial feasibility of deploying THz wireless links within a data centre must be considered in this use case, including safety standards with which the technology must comply.

3.1.5.2 Data centre geometry

Various designs and alternatives for data centre geometry, including potentially novel geometries for greenfield sites that may improve the commercial feasibility of deploying the technology, must be considered in this use case.

3.2 Technology requirements

Whilst there are no specific technology requirements for this use case, it will generate requirements for the commercial deployment of THz wireless devices within the data centre, which will be used to refine the technical requirements of the TERAPOD technologies. These requirements will be reported in the later iterations of this deliverable (i.e. in D2.2 and D2.3) and will guide the technical work carried out in WPs 3-6 of the TERAPOD project.

3.3 Non-functional requirements

3.3.1 Demonstration or proof-of-concept

The outcomes of this study will be used to generate guidelines and/or blueprints for the commercial deployment of THz wireless links within data centres.

3.3.2 Testing and validation

Engagement with stakeholder groups for the evaluation and validation of the findings of the feasibility study in this use case will be the primary method of testing and validating the proposed business model.

3.3.3 Cost and commercial factors

A varied group of stakeholders (e.g. SMEs, large industry, research organisations, etc.), incorporating both producers and consumers of data centre technology and of wireless THz devices, will be engaged to provide details of cost restrictions and other commercial factors.

3.3.4 Licensing considerations

All relevant licensing considerations, including spectrum usage licenses, software licenses and others, must be considered in this use case, in terms of their impact on commercial deployment decisions.

4 TERAPOD-UC-02A Requirements

4.1 End-user requirements

4.1.1 Assumptions

The following assumptions are made prior to the execution of this use case:

4.1.1.1 Geometry of data centre

Rack enclosures are assumed to adhere to the EIA-310-E standard for rack mounting of electronics. Further, it is assumed that rack enclosures have standard form factor, with dimensions as outlined below:

- Enclosure external width is assumed to be between 600mm and 750mm with EIA standard 19" rack rails.
- Each rack unit (RU) is assumed to have a standard height of 1.75" (44.45mm).
- Enclosure depth is assumed to be between 1000mm and 1200mm.
- Enclosure height is assumed to be one of:
    - o 24U (i.e. 24 rack units), measuring 1200mm.
    - o 42U, measuring 2000mm.
    - o 48U, measuring 2275mm.

Racks are assumed to be arranged in a standard hot-aisle/cold-aisle thermally efficient data centre topology.

- Distance between adjacent racks in the same aisle is between 600mm and 750mm.
- Distance between adjacent aisles is between 1m and 10m.

4.1.1.2 Environmental conditions

Environmental conditions within the data centre are assumed to comply with those defined by the American Society for Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) in 2011 Thermal Guidelines for Data Processing Environment – Expanded Data Center Classes and Usage Guidance[1].

For the demo environment, average supply temperature is assumed to be 22°C (range 18-27°C) and average relative humidity is assumed to be 40% RH (range 20%-80% RH).

4.1.2 Data transmission requirements

4.1.2.1 Data rate

The data rate required for use of THz wireless links in place of wired links within the DCN is dependent on the application for which data is being transmitted. Three scenarios with differing requirements for data rate have been identified through end-user surveys, as follows:

a) Host management traffic: requires links that can deliver ≥ 1 Gb/s.
b) Typical data traffic (e.g. compute and storage): requires links that can deliver ≥ 10 Gb/s.
c) Real-time analytics platform: requires links that can deliver ≥ 40 Gb/s.

These data rates may be achieved by the TERAPOD technology through single links that reach the data rate alone or, alternatively, through multiple simultaneous links that jointly meet the data rate requirements for the given scenario. In the case of multiple simultaneous links, sufficient links must be provisioned, such that the data rate and bit error rate (see below) requirements are met.

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[1] http://ecoinfo.imag.fr/wp-content/uploads/2016/08/ashrae_2011_thermal_guidelines_data_center.pdf (Accessed January 2018)

4.1.2.2 Bit error rate

In order to match the bit error rate (BER) performance of existing wired connections, this use case requires a BER of 10^{-12} for wireless THz links that will replace 10 Gb/s optical fibres in the core and access layers and a BER of 10^{-10} for wireless THz links that will replace less expensive twisted pair 1 Gb/s Ethernet links in the access layer [1]. More specific ranges for BER will be derived throughout the lifetime of TERAPOD, considering network topology and other relevant factors.

4.1.2.3 Power consumption

The primary power consumption requirement, from an end-user's point of view, is that the power consumed by the data centre does not increase with the deployment of wireless THz devices, relative to that consumed in the existing wired data centre. This means that, although wireless transmitters and receivers are less energy efficient than cabled equivalents, any increase in energy consumed by the wireless devices must be offset in terms of other energy costs, for example, cooling costs. More specific requirements for power consumption of individual links will be derived later in the lifetime of the project, when network topologies and other factors have been considered in more detail, along with models for the reduction in power consumption for cooling that can be achieved in a wireless data centre, relative to a wired one.

4.1.3 Detailed description of required scenario

Figure 6 illustrates the flow of TERAPOD-UC-02A. A more detailed description of the conditions, actors and triggers for the scenario is provided in the subsections that follow the figure.

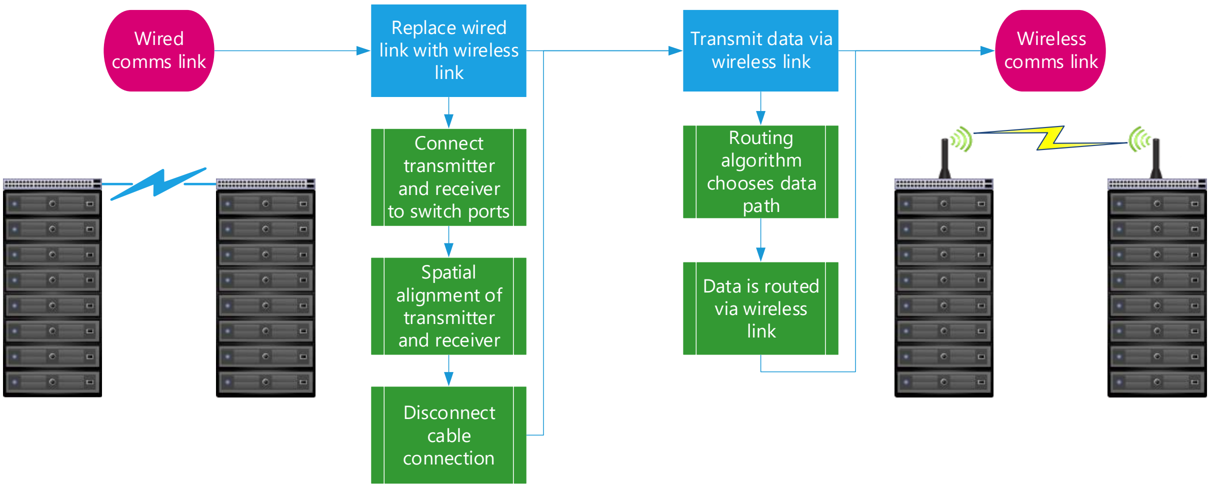

Figure 6 TERAPOD UC-02A flow diagram

4.1.3.1 Pre-conditions

A THz wireless link is put in place for use to transmit data between two racks or intra-rack within the DCN.

4.1.3.2 Actors and triggers

The initial actor is a data centre technician, engineer or similar, who triggers the use case by physically replacing a wired link within the data centre with a wireless link.

Once the wireless link has been physically configured, the primary actor in this use case is the routing algorithm, which continues the use case by implementing the transmission of a data package via the wireless THz link.

4.1.3.3 Post-conditions

The following are the expected conditions after execution of this use case, in success and failure circumstances:

- Success conditions:
    - Data successfully transmitted and received via wireless link.
- Failed end protection:
    - If BER is too high and/or the data package is not received or cannot be reconstructed, the failure must be reported to higher network layers.

4.1.4 Interface requirements

4.1.4.1 TERAPOD components

This use case requires the following components from the TERAPOD project:

- Physical layer protocols.
- TERAPOD wireless THz transmitters and receivers (UTC-PD or RTD-PD and SBD mixer).
- Electrical interface from TERAPOD wireless THz transmitters and receivers (E-RTD and SBD envelope detector).
- Substrate integrated high-gain antennas.

4.1.4.2 External systems

This use case requires the following external systems:

- DCN with existing wired links.
- Data flow test case with stable loads.

4.1.5 Other considerations

4.1.5.1 Safety

Transmitted power must not exceed safety limits for persons within the data centre and/or in surrounding areas.

Transmission must not interfere with other electronic equipment operating within the data centre and/or in surrounding areas.

4.1.5.2 Data centre geometry

General assumptions regarding data centre geometry, in particular, enclosure dimensions and hot-aisle/cold-aisle topology, are specified in Section 4.1.1. In addition, the following requirements should be noted:

- Top-of-rack (TOR) and intra-rack antennas will be targeted for this use case.
- Distance between TOR antennas will vary between 600mm (adjacent servers within the same aisle) and 10m (servers in adjacent aisles).
- Distance between intra-rack antennas is specified by the EIA-310-E standard for 19” racks (standard height of rack units (1U) = 44.45mm), with up to 48U per enclosure.
- Line of sight (LOS) may be obstructed by semi-transparent ‘curtains’ which separate hot and cold aisles and/or by cables for existing wired links.

4.2 Technology requirements

4.2.1 Network Requirements

Layer	Requirements
PHYSICAL	Transmit power must be high enough that transmission is possible within the range of assumed environmental conditions listed previously.

	Bandwidth must be high enough that the minimum required data rate is achieved. The modulation and coding format must guarantee that the maximum permitted BER for the targeted data, from an end-user's point of view, not be exceeded. Equivalent Isotropic Radiated Power (EIRP) must have an acceptable value so that the received power is always higher than the device sensitivity. EIRP must be chosen based on field measurements and antenna characteristics.
LINK	Media Access Control (MAC) protocol for transmission via wireless THz link should be matched to the highest data rate within data centre (up to 100 Gb/s), multiple access to a shared channel should be guaranteed. Error detection field should be inserted to data link frames. Handshaking protocol is required.
NETWORK	Packets from layer 3 must have the structure of IP format. Routing algorithm for high throughput should be implemented Packet buffer is required.
CROSS-LAYER	Interfaces between physical and data link layer must be implemented, as well as interface between data link and network layer; interfaces are responsible for message exchange to optimize resources and link parameters

4.2.2 Device Requirements

4.2.2.1 TERAPOD technologies used

The system will be based on TERAPOD wireless THz transmitters and receivers. These comprise three different base components (active and passive)[2] and passive (active phase distributions) antennas. There are two antenna types required: (1) substrate integrated antennas for the transmitter, implemented in the RTD or UTC-PD components for free space emission; (2) horn antennas for the coherent heterodyne receiver.

The first components are resonant tunnelling diodes (RTDs) which can be used as directly modulated THz transmitters. They are expected to emit up to 1 mW of THz power using on-off keying (OOK) modulation up to 10 Gb/s.

The second device is a uni-travelling photodetector (UTC-PDs). These devices can directly convert one (or several) optical channel(s) to a THz channel, while retaining the modulation format. They require a secondary laser (as in an optical digital coherent receiver), but could operate at data rates up to 100Gb/s and beyond. They offer a similar level of transmitted power as RTDs.

On the receiver side the Schottky barrier diodes (SBDs) will be used either as an envelope detector (e.g. 10Gb/s OOK from RTDs) or a coherent frequency mixer in heterodyne reception for higher data rates and complex modulation formats. A modified version of the RTD or UTC-PD components would be implemented in the receiver part as local oscillator (LO) of the SBD mixer for coherent heterodyne reception. The TERAPOD approach for the LO source would significantly reduce the cost, complexity and power consumption of the THz receivers compared to conventional approaches. Considering the current performance of the TERAPOD devices, a minimum transmission distance of 10 m for a data rate of 10 Gb/s is expected, and 1 m for a data rate of 100 Gb/s.

[2] RTDs and UTC-PDs work as active components (they must be biased to correctly oscillate), whilst the SBDs work as passive components (they do not need bias to detect signals).

4.2.2.2 Technology requirements derived from end-user requirements

TERAPOD offers a variety of technological solutions that could fit with different scenarios.

The first aspect of the current requirement is the data rate achievable for each technology.

For Host management traffic an OOK modulated RTD would offer a simple solution and sufficient throughput (demonstrations up to 10 Gb/s already exist). While for real time analytics and standard traffic a solution based on UTC-PDs seems more attractive. (Demonstrations up to 100 Gb/s already exist.)

The second aspect to consider is the distance of transmission; this would have an impact on all the different technologies developed within TERAPOD (emitters, receivers, antennas). For these requirements and in order to simplify the problem we will consider two distances relevant to the application scenarios; 1 m and 10 m. For a carrier at 300 GHz, the free space propagation losses would be 80 dB and 100 dB respectively.

- For the TERAPOD SBD receiver we should expect a detection sensitivity at 100 Gb/s (most stringent requirement) better than -45 dBm.
- Antenna design should offer a gain better than 20 dBi with a target of 40 dBi. It is unlikely to be better than 50 dBi. This is likely to be achieved by implementing a horn antenna.
- Emitters (UTC-PDs and RTDs) should offer a total emitted power (considering the worst case scenario for the antenna) of -5dBm for a 1 m transmission. To leave enough margin in the system the target should be 0 dBm.
- For a 10 m transmission a minimum gain of 30 dBi per antenna will be required while the emitter power remains constant.
- The packaged components will require a DC input for the emitters (biasing).
  - The RTDs will need a modulation input, while the UTC-PDs can take the signal directly from the optical network within the data centre and will require a laser LO to generate 300 GHz (standard fibre based components).
  - SBD for envelope detection requires a power supply for the integrated amplifiers.
  - SBD for heterodyne reception will require an LO with at least -3 dBm output power around 150 GHz, no bias for the mixer and an IF output with IF LNA amplification.
  - The RF bandwidth can be larger than 40 GHz around 300 GHz centre frequency to provide an IF bandwidth up to 15 GHz with broadband LNA able to provide up to 20 dB gain and noise figure larger than 3 dB. Shorter IF bandwidth would allow improved LNA performance with gain above 20 dB and noise figure lower than 3 dB.
  - The overall system might require mirrors or lenses to enhance the gain of the antenna.

4.2.2.3 Additional requirements for interactions between components, etc. (e.g. packaging, cabling, network cards, modulation, etc.)

For the purposes of this deliverable, no additional requirements have been identified for this use case, beyond what is described in the previous paragraphs.

4.2.2.4 Power requirements for each component to be used

Finally, one should consider the electrical power requirement of each element:

- **UTC-PD**: Typical 2V bias (about 2mW total electrical), a typical laser LO (200mW electrical) and Peltier cooling (1-2W electrical at maximum operation). Note that here the key power consumption is in cooling. That could be shared across a number of transmitter/receivers.
- **RTDs**: Typical 250mW, potentially down to 50mW. These oscillators are quite stable and do not require any temperature control.
- **SBD-based detectors**: No power consumption by SBDs. Power supply no larger than 1.8W

is required to feed the integrated amplifiers.

- **SBD-based mixer**: No power consumption by SBDs. Most power is within the LNA and the LO. Typical requirements of the LNA would be 1.5-2W electrical power. The LO would be based in RTD or UTC-PD with similar power consumption to that previously indicated.

4.3 Non-functional requirements

4.3.1 Demonstration or proof-of-concept

This use case will be demonstrated in a data centre environment during the lifetime of the TERAPOD project. Existing wired links between TOR and/or intra-rack switches in the data centre will be replaced with THz wireless links, using devices from the TERAPOD project.

4.3.2 Testing and validation

The static THz wireless links developed and implemented in this use case will be validated through a number of means:

a) bench-testing of the early device prototypes,

b) validation of transmission models through characterisation under data centre environmental conditions, and

c) integration testing within the data centre demonstration.

Testing and validation requirements are discussed in more detail in Section 8.

4.3.3 Cost and commercial factors

Cost and commercial factors will be analysed in TERAPOD-UC-01.

4.3.4 Licensing considerations

A license to access the 300GHz spectrum will have to be secured to carry out the test measurement campaign at the Data Centre at Dell EMC. WIT has secured a demo license by ComReg in Ireland to provide permission to carry out the measurement campaign at Dell EMC Data Centre Campus, Cork Ireland and at TSSG Data Centre, Waterford from 1st April 2018 to 31st March 2019 (see Appendix D). This license will be renewed in the instances where measurement campaigns will extend beyond this period.

5 TERAPOD-UC-02B Requirements

5.1 End-user requirements

5.1.1 Assumptions

This use case assumes that TERAPOD-UC-02A has been successfully executed and that all assumptions of that use case have been met.

5.1.2 Data transmission requirements

5.1.2.1 Data rate

The data rate requirements for this use case are the same as those for TERAPOD-UC-02A (see 4.1.2.1).

5.1.2.2 Bit error rate

The primary BER requirement for this use case is the same as that for TERAPOD-UC-02A (see 4.1.2.2). However, if, for a proposed network topology, determined by the software that will be integrated in this use case, the overall Uplink/Downlink Error Rate and/or Inter-Server Error Rate [1] is the same as or better than that achieved by wired links in the existing (baseline) network topology, the BER requirement for an individual wireless may be altered accordingly.

5.1.2.3 Power consumption

The power consumption requirements for this use case are the same as those for TERAPOD-UC-02A (see 4.1.2.3).

5.1.3 Detailed description of required scenario

A flow diagram for TERAPOD-UC-02B is shown in Figure 7, with more detail in the subsequent sections.

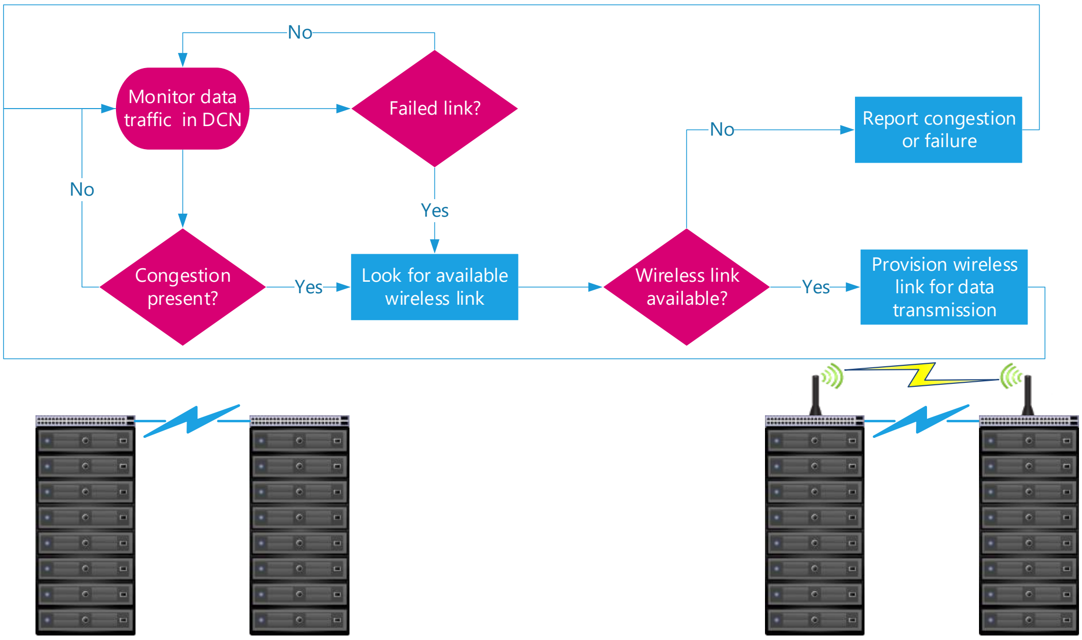

Figure 7 TERAPOD-UC-02B flow diagram

5.1.3.1 Pre-conditions

Congestion or link failure is predicted or exists and has been detected on one or more wired links in the network.

A THz wireless link is available for use to augment or replace the congested link.

5.1.3.2 Actors and triggers

The following lists the actors involved in this use case:

- Network's link throughput monitoring function detects and identifies links causing congestion/bottlenecks/failures within the network.
- Software defined network (SDN) controller determines that THz wireless links should be utilised within the network.
- Leaf-spine fabric controller determines that data should be directed through THz wireless links.

Execution of the use case begins when the link throughput monitoring function in the network detects that one (or more) of the links is over-congested and likely to lead to performance degradation. The throughput estimation of the wireless THz link promises a better performance.

5.1.3.3 Post-conditions

The following are the expected conditions after execution of this use case, in success and failure circumstances:

- Success conditions:
  - Loss of data due to network congestion is prevented or reduced by augmenting or replacing wired links with THz wireless links. The initial target for reduction of network congestion is 10-50%; this target will be refined in later iterations of the TERAPOD requirements, considering the nature of the congestion and other factors.
  - Failed end protection:
  - If the success conditions are not met, failure must be reported to higher network layers.

5.1.4 Interface requirements

5.1.4.1 TERAPOD components

This use case requires the following components from the TERAPOD project:

- Physical layer protocols from TERAPOD-UC-02A.
- Network and link layer protocols for dynamic load control.
- TERAPOD wireless THz transceivers (UTC-PD or RTD-PD and SBD mixer).
- Electrical interface from TERAPOD wireless THz transceivers (E-RTD and SBD envelope detector).
- Optical interface from TERAPOD wireless THz transceivers.
- Substrate integrated high gain antennas.

5.1.4.2 External systems

This use case requires the following external systems:

- DCN with existing wired links and fixed wireless THz links, on which traffic monitoring takes place, such that congested and/or failed links can be detected.
- Data flow test case with volatile loads.

5.1.5 Other considerations

5.1.5.1 Safety

The safety requirements for this use case are the same as those for TERAPOD-UC-02A.

5.1.5.2 *Data centre geometry*

The geometry of the data centre is assumed to be the same as that described for TERAPOD-UC-02A.

5.2 Technology requirements

5.2.1 Network Requirements

Layer	Requirements
PHYSICAL	As for TERAPOD-UC-02A.
LINK	As for TERAPOD-UC-02A. Adapted layer 2 protocols taking the volatile data flow into account.
NETWORK	Appropriate protocols which control volatile data flow.
CROSS-LAYER	As for TERAPOD-UC-02A.

5.2.2 Device Requirements

5.2.2.1 *TERAPOD technologies used*

300 GHz technology, developed by UGLA as part of the iBROW [2] project, has been identified as a suitable technology for this use case. This technology requires an on-chip antenna, which will be developed in TERAPOD. In addition, detectors being developed by ACST in the TERAPOD project have been chosen to complement the technology from UGLA.

5.2.2.2 *Technology requirements derived from end-user requirements*

As noted in the previous paragraph, an on-chip antenna for the 300 GHz sources will be required. The present technology provides up to 1mW RF power and, with external horn antennas, enables communication ranges of a few cm with modulation bandwidths of >10 Gb/s, using basic schemes such as OOK or amplitude shift keying.

5.2.2.3 *Additional requirements for interactions between components, etc. (e.g. packaging, cabling, network cards, modulation, etc.)*

A number of on-chip antenna approaches are being investigated, some proposed by INESC. These include a slot bow-tie antenna (UGLA), a broadband monopole antenna (INESC) and a circular slot antenna (adapted from Infineon). All of these emit backside (through substrate) radiation which will be directed through a silicon hemispherical lens.

Different technologies must be adapted to successfully accomplish the role of UTC-PDs and RTDs as LO of the SBD heterodyne mixer proposed for the 100 Gb/s transmission rate. The UTC-PDs and RTDs proposed for TERAPOD are currently based on coplanar waveguide (CPW) chip technology, while SBDs for the mixer are based on microstrip substrate technology. The microstrip substrate technology approach allows highly efficient microstrip to waveguide transitions and simplifies the integration of any antenna in the module. The 300 GHz mixer for TERAPOD receivers will feature an RF input and LO input waveguide ports to connect a horn antenna and the LO module respectively. A CPW to microstrip transition is required to be developed to make RTDs and UTC-PDs compatible with waveguide port modules.

5.2.2.4 *Power requirements for each component to be used*

The typical power consumption of the 300 GHz RTD source is about 250mW, but new generations are now consuming less and less, and 50mW is expected through TERAPOD.

5.3 Non-functional requirements

5.3.1 Demonstration or proof-of-concept

This use case will be demonstrated in a data centre environment during the lifetime of the TERAPOD project. Existing wired links between TOR switches in the data centre will be augmented with THz wireless links, using devices from the TERAPOD project, and the routing protocols developed in WP5 will be implemented to route traffic through the available wired and wireless links.

A proof-of-concept for the dynamic use of intra-rack THz wireless links will be carried out through simulation.

5.3.2 Testing and validation

The dynamic use of THz wireless links developed and implemented in this use case will be validated through:

a) simulation testing of layers 1-3 protocols, and
b) integration testing within the data centre demonstration.

Testing and validation requirements are discussed in more detail in Section 8.

5.3.3 Cost and commercial factors

Cost and commercial factors will be analysed in TERAPOD-UC-01.

5.3.4 Licensing considerations

Licensing requirements for this use case are expected to be the same as those for TERAPOD-UC-02A.

6 TERAPOD-UC-03 Requirements

6.1 End-user requirements

6.1.1 Assumptions

This use case assumes that TERAPOD-UC-02A and TEARPOD-UC-02B have been successfully executed and that all assumptions of those use cases have been met.

6.1.2 Data transmission requirements

6.1.2.1 Data rate

The data rate requirements for this use case are the same as those for TERAPOD-UC-02A (see 4.1.2.1).

6.1.2.2 Bit error rate

The primary BER requirement for this use case is the same as that for TERAPOD-UC-02A (see 4.1.2.2). As in the case of TERAPOD-UC-02B (see 5.1.2.2), the BER requirement for an individual wireless may be altered according to the network topology and other factors.

6.1.2.3 Power consumption

The power consumption requirements for this use case are the same as those for TERAPOD-UC-02A (see 4.1.2.3).

6.1.3 Detailed description of required scenario

Figure 8 illustrates the flow for the TERAPOD-UC-03 scenario. More detail is provided in the subsections that follow the figure.

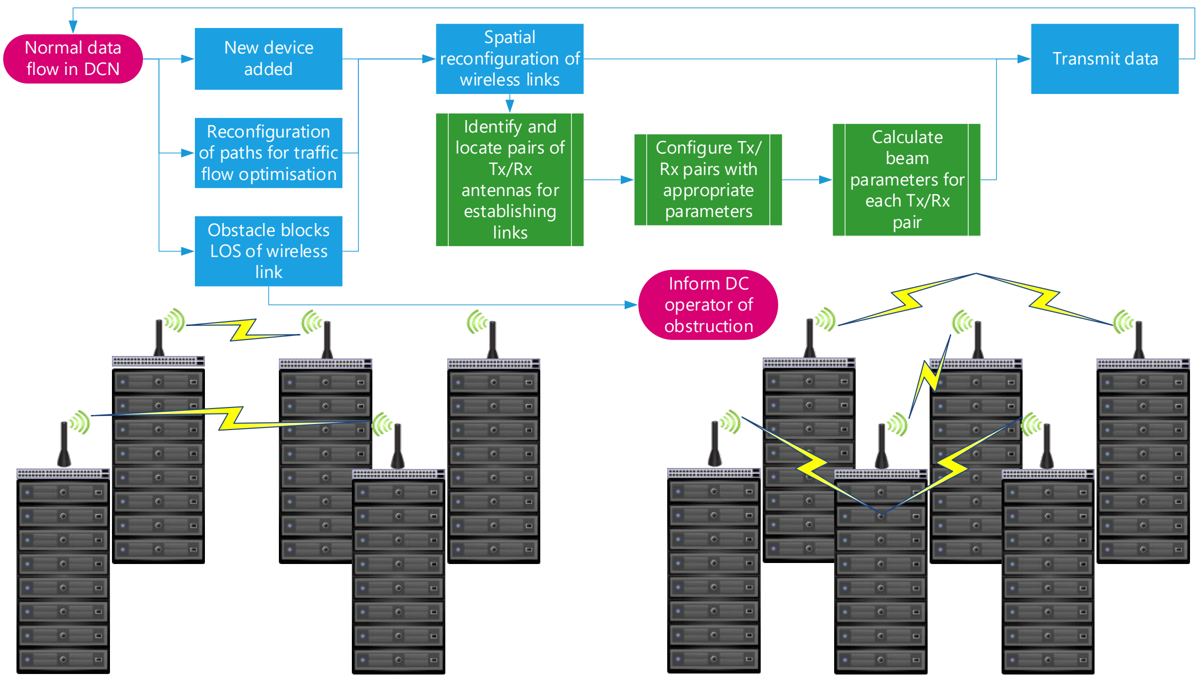

Figure 8 TERAPOD-UC-03 flow diagram

6.1.3.1 Pre-conditions

New devices to be added to the DCN have integrated wireless THz transceivers.

The network controller is capable of receiving communications from newly added and as-yet unregistered devices.

6.1.3.2 Actors and triggers

The main actors for this scenario are the following:

- THz wireless devices.
- Network controller / SDN controller / fabric controller.
- Network link throughput monitor.

Execution of the use case begins when a THz wireless link needs to be configured for communication. This may occur in one or more of the following scenarios:

- A new THz wireless device is added to the network (to expand the network or to replace an existing device).
- A wireless THz transceiver's geometrical position changes or an obstacle blocks its line of sight (LOS) to the device with which it must communicate.
- The network controller determines that a link or links within the data centre should be reconfigured.
- The network's link throughput monitoring function detects and identifies failed links or links causing congestion/bottlenecks within the network.
- The SDN controller or leaf-spine fabric controller determines that THz wireless links should be configured for use between particular nodes within the network.

6.1.3.3 Post-conditions

The following are the expected conditions after execution of this use case, in success and failure circumstances:

- Success conditions:
    - Wireless links can be spatially configured by software and transmit data, such that data is received at the required data rate and with the required signal power, without causing interference in other links within the data centre.
    - The DC operator is informed in the case of an obstacle blocking a transmitter-receiver LOS, such that the obstacle can be removed to avoid strain on the system.
- Failed end protection:
    - If the success conditions are not met, failure must be reported to higher network layers.

6.1.4 Interface requirements

6.1.4.1 TERAPOD components

This use case requires the following components from the TERAPOD project:

- Physical, Link and Network Layer protocols from TERAPOD-UC-02A and TERAPOD-UC02B.
- Beamforming sub-system.
- Substrate integrated high gain antennas.
- Optical interface TERAPOD wireless THz transmitters and receivers (UTC-PD or RTD-PD and SBD mixer).
- Note: Electrical interface TERAPOD wireless THz transceivers (E-RTD and SBD envelope detector), should not be considered since the beamforming is performed in the optical domain.

6.1.4.2 External systems

This use case requires the follow external systems:

- DCN with existing wired links and fixed wireless THz links, on which traffic monitoring takes place, such that congested and/or failed links can be detected.

- Data flow test case with mixed loads.

6.1.5 Other considerations

6.1.5.1 Safety

The safety requirements for this use case are the same as those for TERAPOD-UC-02A.

6.1.5.2 Data centre geometry

The geometry of the data centre is assumed to be the same as that described for TERAPOD-UC-02A.

6.2 Technology requirements

6.2.1 Network Requirements

Layer	Requirements
PHYSICAL	THz transceivers which support beam-steering.
LINK	As TERAPOD-UC-02B. Neighbour discovery protocol to detect new nearby devices is required. Positioning protocol (for link configuration) is required. Handshaking protocol is required.
NETWORK	Protocol that controls wireless link configuration in a spatial sense (this is linked to the positioning and neighbour discovery protocols of the LINK layer).
CROSS-LAYER	Link configuration messaging and parameter selection.

6.2.2 Device Requirements

6.2.2.1 TERAPOD technologies used

In this last scenario, TERAPOD will make use of UTD-PD arrays as transducer elements. Such arrays will be driven by coherent laser light in the C-Band, in a specific configuration that generates a THz signal in the UTD-PD. Such laser light will be distributed via a photonic integrated configurable delay line, or beamforming network, towards all the array elements.

By controlling the phase of the signal at each array element, the light emitted by the array will be constructively sent towards a specific direction. This allows a very efficient use of the radiated power as well as good directionality and discovery of other available devices for connection.

6.2.2.2 Technology requirements derived from end-user requirements

Dynamic discovery and optimization of power consumption require a fast and simple hardware architecture that can send and receive THz radiation from multiple sources from multiple directions. Such systems require very long delay lines only achievable with low losses employing photonic integrated circuits, So far, the only integrated technology that can facilitate these requirements is based on photonic integration. More specifically, we will make use of silicon nitride waveguides since these show the lowest propagation loss of all.

An initial system consisting of four elements would provide a directionality gain of 3dB for non-optimal spacing between elements. In the case of optimal spacing (0.5λrad) the gain can be improved up to 8dB with a four element array. Such an array requires the use of a four channel phase distribution system for THz over laser, and would add power consumption and heat. However, the integrated nature of the phase distribution constrains this additional power consumption to a bare minimum associated mainly with the tuning capabilities of the device and the dissipation of the generated heat. The power consumption of the complete phase distribution system during dynamic scan can range from 750mW to 1100mW without temperature control.

6.2.2.3 Additional requirements for interactions between components, etc. (e.g. packaging, cabling, network cards, modulation, etc.)

Laser source:

- The coupling must be optimal for all the possible wavelengths at C-Band.
- The power delivered by the laser will be divided between different elements of the array.
- This is not a problem for the phase distribution circuit unless the laser source is pulsed. In such a case, for pulses in the sub-nanosecond range or shorter, it may lead to nonlinearities and permanent damage.
- Modulation of the signal will be done at the laser source. The photonic phase distribution circuit does not include modulation capabilities.

The design of the photonic integrated circuit must comply with the requirements for packaging.

6.2.2.4 Power requirements for each component to be used

The number of elements, also called building blocks, introduce losses in the complete circuit. For very large circuits, these elements will degrade the performance of the photonic device.

6.3 Non-functional requirements

6.3.1 Demonstration or proof-of-concept

This use case will be demonstrated in a data centre environment during the lifetime of the TERAPOD project. Spatial reconfiguration will be enabled on one or more of the wireless THz TOR links from TERAPOD-UC-02B.

A proof-of-concept for the dynamic use of intra-rack THz wireless links will be carried out through simulation.

6.3.2 Testing and validation

The dynamic reconfiguration of THz wireless links developed and implemented in this use case will be validated through:

a) bench testing for beam-forming and spatial reconfiguration,

b) simulation testing of wireless link configuration, and

c) integration testing within the data centre demonstration.

Testing and validation requirements are discussed in more detail in Section 8.

6.3.3 Cost and commercial factors

Cost and commercial factors will be analysed in TERAPOD-UC-01.

6.3.4 Licensing considerations

Licensing requirements for this use case are expected to be the same as those for TERAPOD-UC-02A.

7 TERAPOD Requirements from Standardisation

As stated in the deliverable D7.5 Initial Standardisation Impact Strategy the TERAPOD project will not only have an impact on new standards but also needs to meet several existing standards. The requirements for the Physical Layer are stated in the Std. IEEE 802.15.3d$^{\text{TM}}$-2017 which is the first standard for communication systems operating in the frequency range from 252 GHz to 325 GHz. The devices and the whole TERAPOD wireless communication system aims to comply with the IEEE 802.15.3d$^{\text{TM}}$-2017 standard regarding operation frequency, modulation bandwidth, output power, etc. Supposing that different MAC technologies will be employed in the network, a new standard IEEE P802.1ACct which will likely be published by the end of 2018, influences the MAC services. This standard can be applied to create a common bridging technology.

The frequency spectrum above 275 GHz has not yet been allocated. The Agenda Item 1.15 of the World Radio Conference (WRC-19) addresses this issue in November 2019 and will likely have a decision on the regulations. This could have an impact on the TERAPOD project at a point where fundamental changes would be extremely disruptive. TERAPOD will therefore continuously follow the developments in the preparation process of AI 1.15. As part of Task 2.2 in WP2 TERAPOD keeps up to date with any new standards that may emerge.

This process shows TERAPOD’s understanding of its relation to the standardisation bodies as shown in Figure 9. One the one hand TERAPOD meets the present standards and on the other hand TERAPOD has an impact on current standardisation with its research results.

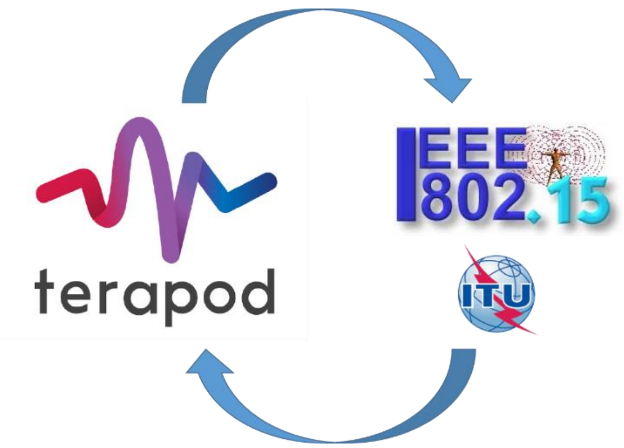

Figure 9 TERAPOD’s relation to standardisation bodies

Safety and the compliance to safety standards are a serious issue in industry as well as in research facilities. The impact of THz frequencies to the human body is still an active area of research. Nevertheless the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published reference levels for general public exposure to time-varying electric and magnetic fields which is given for frequencies from 2 GHz to 300 GHz as 10 W/m^2. It is therefore mandatory for the TERAPOD project to meet this threshold.

8 TERAPOD Test and Validation Requirements

8.1 Requirements for device testing at NPL

The types of device characterization measurements to be carried out by NPL are listed in Table 1.

Table 1 Device Characterization Measurements

Device	Measurement	Instrument availability
Emitters	Power	CA[a]
	Centre frequency and linewidth	CA
	Broadband spectral profile	LB[b]
	Noise & stability (amplitude & phase)	DT[c]
	Beam profile & divergence	DT
	Polarization	LB
Detectors	Spectral responsivity	LB
	Spectral noise equivalent power	DT
	Response time	DT
	Acceptance cone	DT
	Polarization sensitivity	LB

[a]CA: commercially available

[b]LB: laboratory-built

[c]DT: developed for TERAPOD

All device characterization measurements at NPL will be performed in free space, as depicted schematically in Figure 10 below.

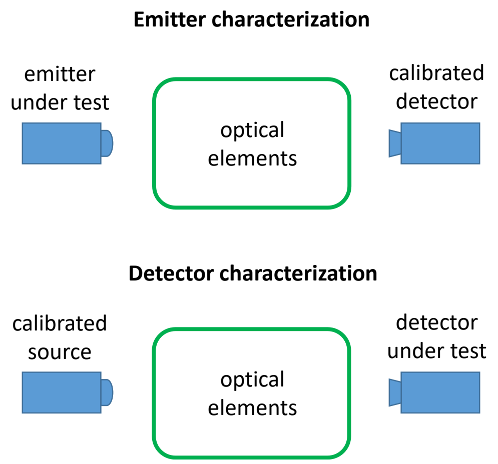

Figure 10 Schematic depiction of setup for device characterization in free space.

The test facilities comprise: optical benches; optical elements, instrumentation, and measurement setups; standard power supplies and electronic instrumentation (e.g. lock-in amplifiers, oscilloscopes).

The requirements for devices to be tested, therefore, are:

- Devices must be configured for free-space operation (e.g. with antennas or lenses).
- Devices must be packaged and portable.
- Standard connectors must be provided for power supplies, as needed.
- Standard connectors must be provided for any necessary inputs.

Additional requirement for emitters: due to the limitations of power detectors, the minimum emitted power must be at least 10 μW, and preferably 100 μW.

Additional requirement for detectors: due to the lack of high power sources, the minimum power level detectable with acceptable SNR (>10) must be no less than 10 μW, and preferably 50 μW.

8.2 Requirements for the environmental chamber

Free-space path loss for THz transmission is strongly affected by atmospheric absorption, and in particular by water vapor lines, and varies with humidity and temperature. Therefore it is necessary to test transmission links under environmentally realistic conditions. The data from such tests is also required for link modelling and network design.

To enable these tests, an environmental test chamber will be built, depicted schematically in Figure 11. The chamber will be designed to provide line-of-sight path length distances comparable to those found in the user-case scenarios. Different path lengths will be made possible by using a beam pipe comprising multiple joinable sections, as shown in Figure 11.

The chamber will have controlled humidity and temperature, and will contain an atmospheric gas mix similar to that prevalent in data centers. There will also be provision for inducing acoustic and vibrational noise and air turbulence emulating the noise environment generated by the cooling systems of a data center. In addition, the test chamber will be designed to have changeable wall linings that can be varied from wholly absorbing (anechoic) to partially reflecting/scattering (emulating indoor walls) to wholly reflecting (metallic).

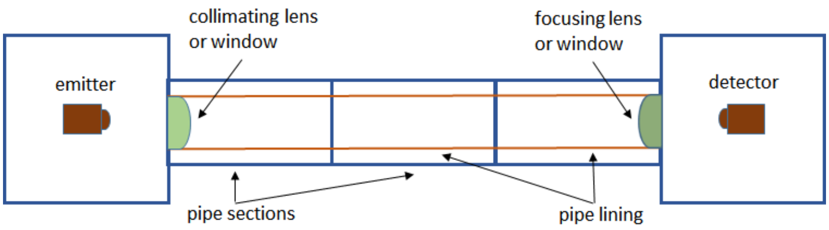

Figure 11 Schematic depiction of the environmental test chamber

Design requirements for the environmental test chamber:

- Length:
  - Minimum: 1 m
  - Maximum: 10 m
- Humidity range: 20% - 80% RH.
- Temperature range: 18 – 27 ° C.
- Air turbulence/ noise:
  - Initial testing in the environmental chamber will use a variable speed fan to create a range of turbulence conditions.
  - Characterisation of air turbulence within the data centre must be investigated further.
- Wall reflectivity:
  - 1 (metallic);
  - <0.05 (anechoic);
  - typical walls – variable; Semi-reflective wall panels will be made from materials similar to actual wall coatings in a DC, in order to replicate both reflections and scattering of the THz beams.

8.3 Requirements for bench testing

Within the project we will demonstrate some of the functionality of the TERAPOD system within a laboratory controlled environment. The bench testing should incorporate the following:

- A background optical network to simulate the optical network of a data centre

- Modulation possibilities for up to 100 Gb/s (from 1 Gb/s OOK to 16 (or higher) QAM up to 25 GHz bandwidth)
- Antenna system for minimum gain of 30 dBi
- Distance of wireless transmission up to 10 m
- Possibility of multicarrier propagation and wavelength switching
- Envelope detection and coherent detection
- BER and real time oscilloscopes for off-line demodulation.

For information an example lab demonstration system is shown in Figure 12 (already implemented).

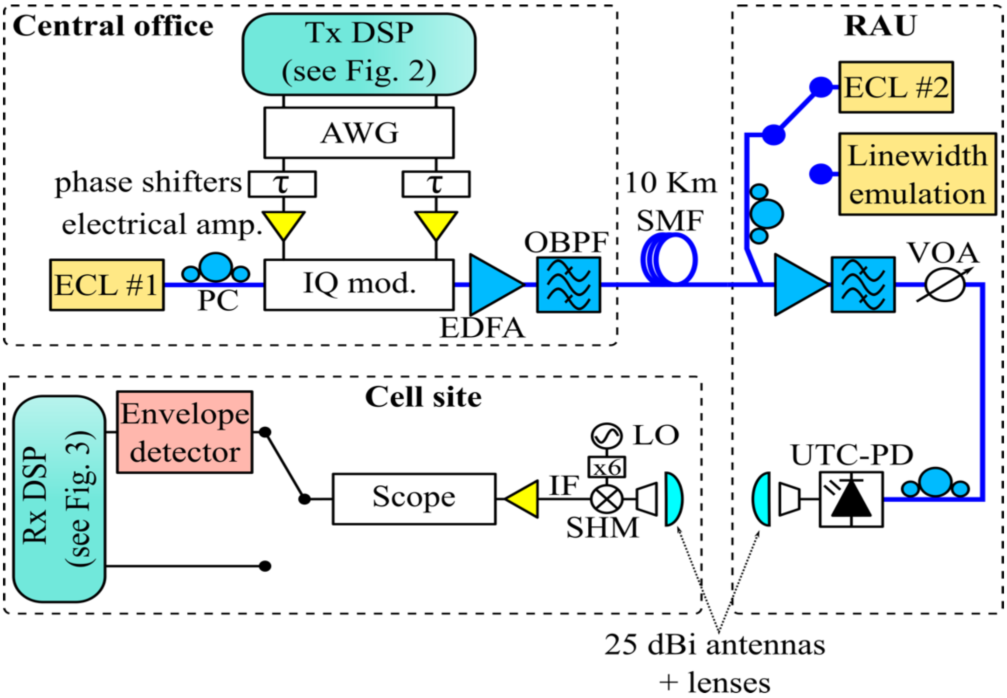

Figure 12 Example of a lab system for demonstration of link capacity

8.4 Requirements for simulation testing

Simulations are mainly effected in WP5. During the development and programming stage testing and verification methods need to be designed in parallel. The results from T5.1 will be verified with appropriate test cases which will be compared to literature references. Hence, a comparability of existing standard values and the interface values of the Physical Layer Simulator must be guaranteed.

The channel model from T4.2.2 will be validated via channel measurements effected in T4.2.1. Therefore a comparable reference is required which will be determined during the channel measurements.

The Data Link Layer simulation tool in T5.2 is required to model and simulate the Data Link Layer which implements the MAC and the Logical Link Control. The developed algorithms will be verified in a logical way and converted to a hardware language to be tested in real time. Timing and synchronization are generally the main issues in algorithm testing. Therefore, the related hardware and measurement equipment must be available. Furthermore, the algorithms will be tested virtually on simple transmission cases and their behaviour will be compared with the prediction. As a reference, already validated models are needed for the comparison.

For testing the layer 3 routing protocols that will be developed in T5.3, the following requirements exist:

- The layer 3 protocols must be provided with (dynamic) parameters (from Layer 1 and Layer 2 protocols) describing the link characteristics, e.g. media type, bandwidth, expected data rates and BERs, expected variability in data rates.

- The layer 3 protocols must be provided with information regarding application type (e.g. to physically separate control and data plane traffic).
- A network emulator, such as mininet (http://mininet.org/overview/) or Core (https://www.nrl.navy.mil/itd/ncs/products/core), will be required to generate network traffic for simulation purposes.

9 Conclusion/Further work

In this document, four use cases have been specified, each of which was derived from early engagement with potential end users of TERAPOD technologies. These use cases, and their detailed requirements, will underpin the technology development efforts for the TERAPOD project. Each use case will continue to be refined and revised throughout the lifetime of the project, in order to ensure that the project produces technology for which deployment within a data centre environment is both technically viable and commercially feasible.

References

[1] C. e. a. Fiandrino, “Performance Metrics for Data Center Communication Systems,” in *IEEE 8th International Conference on Cloud Computing*, 2015.

[2] iBROW project, “iBROW, Innovative ultra-broadband ubiquitous wireless communications through terahertz transceivers (accessed February 2018).,” 2018. [Online]. Available: http://ibrow-project.eu/.

Appendix A Output from End-User Interviews

The following provides a brief summary of the primary insights given and scenarios suggested by interviewed end-users:

- Wireless technology to separate host management traffic from data traffic within the DC would be very desirable. This scenario would not be likely to require the ultra-high bandwidth that can be achieved by THz wireless links (estimated approximately 1 Gb/s required). However, separating this traffic from the data network could alleviate challenges, such as, for example, network reconfiguration commands being obstructed or delayed by the very network congestion that they intend to resolve.
- A separate network to push out patches, updates, and similar to equipment in the data centre was suggested as a potentially useful use of wireless technologies. As in the afore-mentioned case of host management, this would not require the ultra-high bandwidth of THz links; requirements are estimated to be in the region of 5-10 Gb/s with intermittent communication.
- Using the wireless THz links as a backup path for increased resilience within the data centre was suggested as a potentially useful use case. This scenario would require sufficient bandwidth to match the existing wired links.
- Data rates that would need to be achievable in order to consider wireless links within the data centre were estimated as follows:
    - Host management traffic: 1 Gb/s.
    - To match current wired network links: 10 Gb/s.
    - To facilitate very high powered environments: 40 Gb/s.
- The ability to automate the configuration of new devices added to the data centre in addition to, or in replacement of, existing equipment would be a very attractive use case. This could save on human resource costs and help to eliminate human error, as well as improving the scalability of the DC. Auto-provisioning of a minimum configuration would be a useful feature in DC infrastructure.
- Some of the biggest challenges of current cabled DCNs include the volume of cables, the cost (which can be up to 10-20% of equipment costs) and the power draw, in particular, for long-haul links. The opportunity to save on some of these costs with short multi-hop wireless links would be attractive.

Appendix B Use Case Description Template

This appendix contains the text of the use case description template which was the basis of the top-down requirements gathering for the TERAPOD use cases.

TERAPOD <Scenario> Use Case Description

B.1 Use Case Definition

This use case template has been adapted by the TERAPOD consortium to meet the specific needs of the TERAPOD project, working from a template used in the EU 5G-PPP SliceNet[3] and SELFNET[4] projects. The approach is similar to that of the IEC 62556-2:2015 standard use case methodology. The purpose of this template is to define sufficient details of each project use case, in order that technical requirements for the design, implementation and validation of the TERAPOD artefacts can be derived and that the use cases can be executed to demonstrate the advances and capabilities achieved by the TERAPOD project.

There are three sections in the use case template:

1. An overview of the use case and description of the elements required to understand its key aspects.
2. Further details about the use case; these details describe the expected system behaviour and technical requirements to implement the use case.
3. Information on prototyping, validation/evaluation of the use case and expected impact.

i) Use Case Overview

Use Case Overview	
Short name for the use case scenario	
Descriptive full name of the use case-scenario	
Storyline	*<describe the storyline of the use case essentials to give* • *An overview of the use case purpose,* • *Problem statement and motivation,* • *Expected solutions.* *This should not be very technical; It should be understandable to people outside of the project. About 500 words.>*
Relation to “Beyond 5G” requirements/visions (see Appendix)	*<a more technical argument of the use case in the context of specific “beyond 5G” requirements or visions>*
Goal (s)	*<the functionality or behaviour that is expected to be provided by the system once the use case is executed >*
Figure to visualize the use case	*<use MS Visio or other tools to illustrate the big picture/concept>*

[3] https://slicenet.eu/

[4] https://selfnet-5g.eu/

Actors	*<the individuals and their means that trigger system scenario>*
General assumptions	*<list technical and non-technical assumptions including inter-dependence with other TERAPOD elements/modules>*
Other TERAPOD system components	*<the macro system entities expected to be involved in the execution of the use case and which role(s)/function(s) they may need to fulfil, e.g. based on the description of the action (DoA)>*
External Systems	*<systems external to TERAPOD that will interact with or be involved in the execution of the use case>*

ii) Detailed Steps and Technical Requirements

Detailed Steps & Technical Requirements	
Preconditions	*<describe those conditions/actions that must occur before the execution of the use case in order to obtain the described behaviour>*
Pre-condition Metrics	*<propose the main metric(s) used to measure the preconditions, including:* • *High-level metric(s), e.g., service/application-level metric(s);* • *Low-level metric(s), e.g., network/link-layer Quality of Service (QoS) metric(s) that may be useful for identifying bandwidth and similar requirements.>*
Trigger	*<describe the main action that starts the use case execution>*
Post conditions	*<describe those conditions that could occur once the use case has been executed and the system continues its operations, explaining when the execution of a use case scenario can be considered as a success or failure. The section should be short and not extremely technical.>* Success conditions: *<which conditions demonstrate the correct and successful completion of all the steps in use case>* Failed End protection: *<which conditions/actions should occur to keep everything consistent in the case of a failure>*
State/flow chart and/or activity/sequence/workflow diagram and/or pseudo code	*<explain the steps or sequence of interaction in the scenario>*

Detailed description of steps	*<explain the "states" and "transitions" in the state chart or "activities" and "flows" in the activity diagram>*
PHY layer requirements	…
LINK layer requirements	
Cross layer protocol requirements	*<a way of capturing dependencies across layers of the protocol stack; i.e. device and channel performance impacting PHY layer performance and in turn causing some actions to compensate at the LINK layer.>*
Geometrical requirements	*Describe the positions of the antennas (e. g. top of the racks for rack to rack communication; at the boards for board to board communication;* *Distance between antennas;* *LOS or obstructed LOS* *A graphic describing the situation might be quite helpful*
Wireless data transmission requirements	*Expected data rate* *Expected max. allowed BER*
Non-functional requirements	*< list non-functional requirements for this use case>*
Coverage of Service Life-cycle phases	*<explain if and how this use case covers/matters to the following phases>* *Phase 1 [Service request / SLA negotiation]:* *Phase 2 [Planning / Design]:* *Phase 3 [Deployment]:* *Phase 4 [Operation and Monitoring]:* *Phase 5 [Billing]:* *Phase 6 [Decommissioning]:*

iii) Implementation, Evaluation and Impact

Implementation, Evaluation and Impact	
Prototyping/testbed	*<outline the plan for prototyping and testbed development>*
Benchmarking and validation/evaluation methodology	*<explain how to validate and evaluate the proposed use case, esp. compared with state-of-the-art in the given domain>*
Relevant standards	*<list relevant standards>*

Relevant open source projects	*<list relevant open source projects, esp. those components that could be reused/extended for this project>*
Relation to performance KPI(s)	*<explain which technical KPI(s) that this use case scenario is expected to contribute to>*
Relation to business KPI(s)	*<explain which business KPI(s) that this use case scenario is expected to contribute to>*
Technical innovation in the field	*<explain how this use case will advance the state-of-the-art in the technical/scientific domain>*
Business impact in the sector	*<present benefits, novelties and impact of the use case with respect to state-of-the-art in the given business sector for vertical businesses, operators, service providers, and/or other stakeholders>*
End user benefits	*<present expected added value for end users>*
Relation to relevant use cases in related H2020 and/or nationally funded projects	*<to be led by the T2.2 task leader and partners involved in relevant 5G-PPP WGs and other Beyond 5G projects>*

B.2 Appendix: Beyond 5G Requirements and Vision

The following text is taken from the H2020 ICT-09-2017 call text, to represent the requirements and vision of the "Beyond 5G" research.

Specific Challenge:

While 5G networks has an established roadmap towards technology validation, specifications and tests by industry, outstanding new scientific opportunities are blooming in the field of networking research, with the objective of bringing little explored technologies and system concepts closer to exploitation. The challenge is to support European scientific excellence notably in the DSP domain, and to bring the most promising long term research coming from the labs closer to fruition. This includes perspectives for the full exploitation of the spectrum potential, notably above 90 GHz, with new waves of technologies and knowledge, bringing wireless systems to the speed of optical technologies, and for new applications. It includes interaction with photonic systems as well as new cooperation networking and protocols, notably in the mobility context.

Development and exploitation of academic research through transfer and innovation towards industry with a particular focus on SMEs is an integral part of the challenge.

Scope:

Research and Innovation Actions

Proposals may cover one or more of the themes identified below.

- **Scientific and technology advances** for novel use of the spectrum potential, de-risking technological building blocks at frequencies above 90 GHz up to THz communications backed by innovative usage scenarios, address visible light communications and develop radically new approaches for spectrum efficiency.

- **Advanced signal processing**, antenna processing, information theory and coding to optimize and reach Tbit/s in wireless communications.
- **Demand-attentive and cooperation networking** alternative to 5G architectures, including HetNets, opportunistic networks novel architectures and protocols for routing, latency and caching in complex networks notably for mobility.

Expected Impact:

- Validation of disruptive communication concepts, technologies and architectures;
- Proof of applicability of challenging spectrum regions towards innovative and cost efficient applications;
- Advances in signal processing and information theory and scientific publication in world class journals;
- Industry competitiveness with exploitation of academic research through transfer and innovation towards industry, in particular SMEs or start ups.

Appendix C Lean Business Model Canvas

Table 2 Lean Business Model Canvas

PROBLEM List your customers top 1-3 problems.	SOLUTION Outline a possible solution for each problem.	UNIQUE VALUE PROPOSITION Single, clear, compelling message that turns an unaware visitor into an interested prospect.	UNFAIR ADVANTAGE Something that can't be easily copied or bought.	CUSTOMER SEGMENTS List your target customers and users.
EXISTING ALTERNATIVES	KEY METRICS List the key numbers that tell you how your business is doing.	HIGH LEVEL CONCEPT List your X and Y analogy (e.g. YouTube = Flickr for videos)	CHANNELS List your path to customers.	EARLY ADOPTERS List the characteristics of your ideal customers.
COST STRUCTURE List your fixed and variable costs.			REVENUE STREAMS List your sources of revenue.	

Appendix D WIT Test License ES1170

Commission for
Communications Regulation

Ref: ES 1170

Dr. Alan Davy,
Netlabs Building,
WIT West Campus,
Carriganore
Co. Waterford.

14th March 2018

<u>Re: Research and Development (Test) Licence</u>

Dr Davy,

Further to you recent request, please find enclosed your Wireless Telegraphy (Research and Development) Licence and accompanying documentation (issued under S.I. 113 of 2005):

This licence is valid for the period: **1st April 2018 to 31st March 2019**.

The radio system must be operated in accordance with the conditions as stipulated in the licence and the attached standard conditions which are laid down in the Licensing Legislation. Non-compliance with these conditions is an offence under the Wireless Telegraphy Act 1926 and may lead to withdrawal of the licence.

Yours Sincerely,

N.B. PLEASE RETAIN THESE DOCUMENTS FOR FUTURE REFERENCE.

Tara Kavanagh

Tara Kavanagh
Licensing Operations Manager

An Coimisiún um Rialáil Cumarsáide
Commission for Communications Regulation
One Dockland Central, Guild St., Dublin 1, D01 E4X0.
1 Lárcheantar na nDugaí, Sráid na nGildeanna, BÁC 1, D01 E4X0.
Tel | Teil +353 1 804 9600 Suíomh | Website: www.comreg.ie

WIRELESS TELEGRAPHY ACT, 1926
WIRELESS TELEGRAPHY (Research and Development Licence) REGULATIONS, 2005
LICENCE

Licence No: ES-1170

Licence under section 5 of the Wireless Telegraphy Act, 1926, to keep, have possession of, install, maintain, work and use apparatus for wireless telegraphy for the provision purpose of Research and Development.

The Commission, in exercise of the powers conferred on it by section 5 of the Wireless Telegraphy Act, 1926 (No. 45 of 1926) and section 4 of the Telecommunications (Miscellaneous Provisions) Act, 1996 (No. 34 of 1996) and section 9(1) of the Communications Regulation Act, 2002 (No. 20 of 2002) hereby grants to the Licensee specified authorisation to keep, have possession of, install, maintain, work and use apparatus as specified in the Second Schedule (Part 2) of this licence and subject to the terms and conditions as set out in the Wireless Telegraphy (Research and Development Licence) Regulations, 2005 (S.I. No. 113 of 2005).

The Commission for Communications Regulation, grants the following Licence to:

Name: **Waterford Institute of Technology**
Address : **Cork Road, Waterford.**

1. This Licence comes into effect on the **1st April 2018** and, subject to revocation, expires on the **31st March 2019.**

2. The Licensee will ensure that it complies with the geographical and technical conditions contained within Parts 1 - 4 to this Licence:

   Part 1 : Places at which the Licensee is authorised by this Licence to keep and have possession of the Apparatus (as per Page 2)

   Part 2 : The apparatus for wireless telegraphy to which this Licence applies (as per Page 2)

   Part 3 : Radio frequency channels on which the Apparatus is authorised by this Licence to be used (as per Page 2)

   Part 4 : Specific Provisions (not applicable).

3. The Licensee will ensure that it makes payments of the fees as outlined in the Regulations.

Signed: Tara Ka
on behalf of the Commission for Communications Regulation

Date: 14th March 2018 **Official Stamp** Commission for Communications Regulation

Part 1: Location Details:		Part 2: Equipment Details:	
LICENSEE :	Waterford Institute of Technology	EQUIPMENT MANUFACTURE :	M-sequence UWB mm-Wave Reail-Time MIMO Channel Sounding
ADDRESS:	Cork Road, Waterford.		
PURPOSE OF TEST :	Ultra High Band Tests at 300GHz	ANTENNA TYPE :	Standard Gain Horns 25 dB(Flann Microwave) Cross Polarisation Height; .5 - 2.5 metres a.g.l. Gain; 25 dBi
DURATION :	01/04/2018 to 31/03/2019		
LICENCE REF # :	ES 1170		

Part 3: Radio Frequency Channels (on which the Apparatus may be used)

Transmit Site/s	Receive Site/s	Base Station Transmit Carrier Frequency (GHz)	Base Station Receive Carrier Frequency (GHz)	Channel Bandwidth (MHz)	Maximum ERP (dBW)	Comments
Dell EMC Ireland Ovens Co. Cork 51°52'38.6"N 8°38'40.7"W	Dell EMC Ireland Ovens Co. Cork 51°52'38.6"N 8°38'40.7"W	304.2	304.2	8000	-30	(1) System must be adequately isolated from other radio systems. (2) Effective Radiated Power(dBm) must not exceed the designated limit. (3) Licence is granted on a non-interfering/non-protected basis.

Wireless Telegraphy (Research and Development Licence) Regulations, 2005
Licence Conditions

It shall be a condition of a Licence that:

(1) the Licensee will ensure that it complies with the geographical and technical conditions contained within Parts 1 to 4 of the licence;

(2) the Licensee will ensure that it makes payments of the fees as outlined in Regulation 9 of these regulations;

(3) the Licensee shall not provide an electronic communications network or an electronic communications service to third parties using, directly or indirectly, apparatus licensed under these Regulations;

(4) where the Licensee uses apparatus for wireless telegraphy of a class or description set out in an order(s) under Section 3(6) of the Act of 1926 which provides an exemption from licensing, the Licensee shall use such apparatus in accordance with such orders;

(5) During major disasters the Licensee shall comply with any decisions, determinations, requirements, specifications, notifications and directions issued by the Commission from time to time to ensure communications between emergency services and authorities and broadcasts to the general public;

(6) the Licensee may not, without the consent of the Commission (which shall not be unreasonably withheld) assign the Licence or any of the powers, duties or functions conferred by it or otherwise transfer any of the rights or obligations conferred by it;

(7) the Licensee will ensure that non-ionising radiation emissions from each radio installation operated by the Licensee for the purposes of the Service are within the limits specified by the guidelines published by the International Commission for Non-Ionising Radiation Protection ("ICNIRP"). and that it complies with any Radiation emission standards adopted and published from time to time by ICNIRP, any standards of the European Committee for Electrotechnical Standards and any standards which may from time to time be specified by the European Union and that the wireless telegraphy apparatus operated by the Licensee is not installed or operated at a location in a manner such as to be the cause of the aggregate non-ionising radiation emissions exceeding the limits specified by the guidelines published by the ICNIRP and that it complies with any radiation emission standards adopted and published by ICNIRP or its successors from time to time, any radiation emission standards of the European Committee for Electrotechnical Standards and any radiation emission standards specified by national and EC law;

(8) if the address of the Licensee changes, the Licensee shall, as soon as possible, notify the Commission in writing of the change;

(9) the Licensee complies with any special conditions imposed under section 8 of the Act of 1972 and subject to which this Licence is deemed by subsection (3) of that section to be issued;

(10) the Licensee shall ensure that its licensed apparatus and parts thereof shall be designed, constructed, installed, maintained, operated and used so as not to cause harmful interference with the lawful use or operation of any electronic communications network or other authorised apparatus for wireless telegraphy;

(11) the Licensee shall comply with any decisions, determinations, requirements, specifications, notifications and directions issued by the Commission from time to time regarding the maintenance of the integrity of the apparatus and in connection with spectrum management considerations or investigations by the Commission into cases of interference with the operation of electronic communications networks or other authorised apparatus for wireless telegraphy;

(12) the Licensee shall reimburse the Commission for any costs reasonably incurred in the investigation of harmful interference relating to the licensed apparatus;

(13) the Licensee complies with obligations under relevant international agreements relating to the use of apparatus or the frequencies to which they are assigned.