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Deliverable 2.2

Report on use cases/scenarios

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List of Abbreviations

Term	Description
ADC	Analogue to Digital Converter
AI	Artificial Intelligence
AR	Augmented Reality
BBU	Baseband Unit
CapEx	Capital Expenditure
CEPT	European Conference of Postal and Telecommunications Administrations
CRAN	Cloud Radio Access Network
ECC	Electronic Communications Committee
eMBB	enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FWA	Fixed Wireless Access
GDP	Gross domestic product
HPC	High-Performance Computing
KPIs	Key Performance Indicators
KVIs	Key Value Indicators
IoT	Internet of Things
ISAC	Integrated Sensing And Communication
ITU	International Telecommunication Union
LoS	Line of Sight
m/eMTC	massive/enhanced Machine Type Communications
MIMO	Multiple Input Multiple Output
NAS	Network-Attached Storage
OpEX	Operational Expenditure
ORAN	Open Radio Access Network
PoC	Proof of Concept
PON	Passive Optical Network
PTMP	Point-to-Multipoint
PTP	Point-to-Point
QoS	Quality of Service
RRH	Remote Radio Head
SDGs	Sustainable Development Goals
SiGe-BiCMOS	Silicon Germanium – Bipolar Complementary Metal–Oxide–Semiconductor
SME	Small and Medium-sized Enterprise
SNS JU	Smart Networks and Services Joint Undertaking
UC	Use Case
URLLC	Ultra-Reliable Low Latency Communications
VR	Virtual Reality
WP	Work Package
XR	Extended Reality

Executive Summary

This document defines the use cases, requirements and KPIs, on a system level, of the solution proposed by TeraGreen that will drive the developments to be made within the project. The document starts by describing the approach of WP2 and its relation to the rest of the WPs. An introduction to the objectives and the technological advancements of TeraGreen is then presented, especially with respect to future 6G systems. The main part of the document consists of the description of the proposed scenarios for use cases, as well as the definition of the associated requirements and KPIs, taking into consideration different kinds of services aligned with 6G, and assuming both indoor and outdoor deployments. The document considers both reference use cases as well as project-specific ones. Convenient templates are used for the description of the project-specific use cases, requirements and KPIs for consistency purposes. From the aforementioned requirements and KPIs, the TeraGreen system specifications are extrapolated for the two types of THz links developed in TeraGreen, namely the medium range and the short range. Finally, the societal impact of the project innovations is described, together with relevant key value indicators (KVIs).

1. Introduction

TeraGreen is an EU funded project dedicated to THz wireless links. THz communications are becoming increasingly necessary due to several driving factors:

- **Bandwidth Demand**: The ever-growing demand for higher data rates and bandwidth in wireless communications, driven by applications like high-definition video streaming, virtual reality, and the Internet of Things (IoT).
- **Spectrum Congestion**: Lower frequency bands (like those used for 4G and 5G) are becoming congested. THz frequencies offer a vast, underutilized spectrum that can alleviate this congestion.
- **High-Speed Data Transfer**: THz communications can support ultra-high-speed data transfer rates, essential for future applications such as real-time data processing and support of future advanced 6G applications and services.
- **Short-Range Communications**: THz frequencies are ideal for short-range communications, such as in data centres or for chip-to-chip communications, where high bandwidth and low latency are crucial.
- **Technological Advancements**: Advances in materials, semiconductor technology, and signal processing have made it feasible to develop THz communication systems.
- **Security and Privacy**: THz waves have limited penetration through obstacles, which can enhance security and privacy in wireless communications by reducing the risk of signal interception.
- **Cost-Efficient and Rapid Deployment of Base Stations**: THz communications enables wireless fronthaul and backhaul, reducing the need for expensive fiber-optic infrastructure. In addition, THz-based wireless links can be set up much faster than fiber-optic links, enabling faster expansion of existing 5G networks and faster rollout of future 6G networks, particularly in areas where existing fiber is sparse or too costly to install.

The above factors drive the research and development of THz communications as a promising solution for future wireless networks [1].

TeraGreen develops a new disruptive technology path for sustainable and scalable commercial exploitation of the THz spectrum for energy efficient and Tbit/sec wireless communication links enabled by a unique combination of:

- Quasi-optical MIMO antennas where a record number of wide-band data signals are being transmitted in parallel through a point-to-point wireless link with an -unprecedented low level of radiated energy.
- Low-energy consumption and record wideband THz transmitters and receivers, in one of the most advanced silicon processes in the world with great commercialization potential.
- A novel baseband with zero-crossing modulation enabling energy-efficient wideband communication using 1-bit A/D conversion with temporal oversampling.

TeraGreen is expected to reduce the power consumption in future 6G base stations by a factor of at least 1000 in terms of energy per bit, while increasing the aggregated data rates by a factor of at least 10. TeraGreen will perform several wireless link demonstrations to showcase its commercial use for wireless backhaul and fixed wireless access. The success of TeraGreen will help Europe to be on the foremost frontier in the evolution of mobile networks towards 6G and beyond, bringing significant advances in the evolution of communications networks in 6G. TeraGreen will serve as a key enabler for this evolution in a long-term time horizon, i.e. 5-10 years from the end of the project.

Specifically, for 5G and future 6G networks TeraGreen can serve as a complete fronthaul - backhaul solution for small-cell dense urban networks and for purpose-built fixed wireless access applications where backhaul capacity will be in the range of 200-1000 Gbps. In particular, the THz wireless links proposed by TeraGreen can be used as an alternative to the wired, fibre or microwave backhaul link of small cells. In this way, TeraGreen will enable the densification of cells in a cost-effective manner, since it will downscale the need to deploy wired backhaul links only to those small-cell base stations that do not have a LoS connection. Thanks to the energy efficiency of the proposed technologies, this densification will also be possible in a power-friendly and eco-friendly manner.

The work and results described in this report was carried out in work package 2, “Use cases, system model and requirements”, and more specifically in Task 2.2 “Use cases, requirements and KPIs”.

WP2 specifies the use cases targeted by the TeraGreen concept deriving the corresponding system requirements as well as the associated KPIs. WP2 derives also system models for wideband THz communication including MIMO, as well as the final demonstrations to be conducted in WP6 providing the requirements for each component.

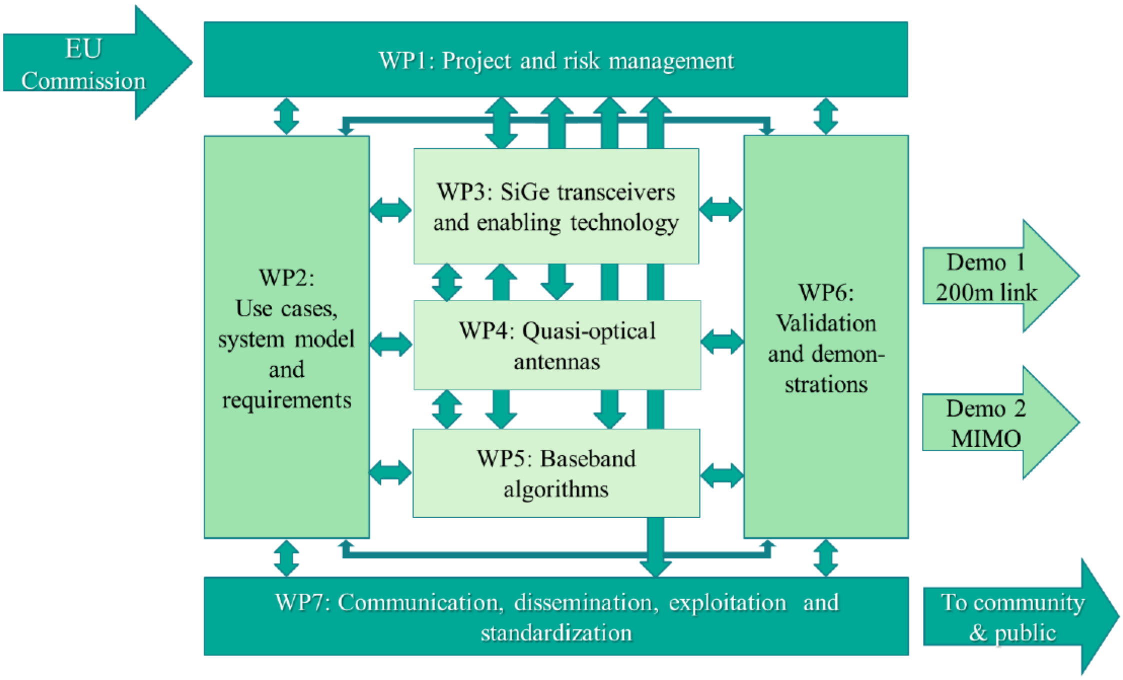

FIGURE 1. WP2 INTER-RELATIONS WITH THE OTHER WPS

As shown in Figure 1, WP2 is one of the most important work packages, since it relates with all the other work packages defining the user and system requirements, as well as the requirements and component interfaces for the final TeraGreen demos.

Task 2.2, in particular, will define the innovative technological solutions of TeraGreen through the detailed description of relevant use cases and scenarios. Based on the latter, the user and system requirements will be derived while the respective technologies will be explored. In addition, this task will identify and define the technical Key Performance Indicators (KPIs) that will be utilized for the validation of the TeraGreen technological objectives during the demos/pilots phase. These requirements will feed the technical WPs 3, 4 and 5. The use cases and the related KPIs defined in this task will also be utilised by T2.3 and T2.5 to define the relevant demos, as well as by WP6 for the execution of the final demonstrations.

TeraGreen proposes four use cases:

- Fronthaul in ultra-dense small cell networks,
- High throughput fixed wireless access (FWA),
- Live immersive XR in large-scale events, and
- Wireless data centres.

In the context of ultra-dense small cell networks, TeraGreen addresses the critical challenge of providing energy-efficient and high-capacity fronthaul solutions using terahertz (THz) communication. Small cells are essential for delivering high data rates and low latency in 6G networks, especially in dense urban environments. However, the fronthaul links must handle massive amounts of data traffic. TeraGreen's THz-based solutions offer ultra-high bandwidth for these fronthaul links, ensuring seamless communication while significantly reducing energy consumption.

TeraGreen's use case on high-throughput Fixed Wireless Access (FWA) focus on delivering ultra-fast, energy-efficient internet connectivity to homes, businesses, and remote areas using THz communication. By leveraging THz spectrum, TeraGreen enables multi-gigabit per second (Gbps) data rates, allowing users to experience fibre-like speeds wirelessly without the need for costly physical infrastructure like fiber optic cables.

TeraGreen's use case for live immersive extended reality (XR) in large-scale events focus on delivering seamless, high-bandwidth experiences that enable participants to interact in real time with virtual elements, no matter the scale of the audience. Using THz communication, TeraGreen provides the ultra-low latency and high data rates required to support immersive technologies such as augmented reality (AR) and virtual reality (VR) at events like concerts, sports games, or conferences.

Finally, TeraGreen's use case for wireless data centres aim to revolutionize the efficiency and scalability of next-generation data centres by utilizing THz communications. With the increasing demands of cloud computing, AI, and big data analytics, traditional wired infrastructure can become a bottleneck in terms of speed, flexibility, and energy consumption. TeraGreen offers ultra-high throughput, low-latency wireless links that can replace or complement fibre-optic connections within data centres, enabling faster data transmission between servers, storage units, and other critical components.

The deliverable is organized as follows:

In Chapter 2 we describe briefly the TeraGreen objectives and innovations. In Chapter 3 we summarize the most important 6G use cases and KPIs that have been proposed until now and can serve as a reference for our work. In Chapter 4 we describe in detail the TeraGreen use cases and their associated requirements. In Chapter 5 we summarize the system requirements that stem from TeraGreen’s use cases, and we assign specific KPIs. In Chapter 6 we analyse the societal impact of the TeraGreen innovations with specific key value indicators (KVIs). Finally, Chapter 7 provides a summary and conclusion of the work and results presented in this deliverable.

2. TeraGreen Objectives and Innovations

The exponential demand on global wireless data streaming services is pushing current communication network technologies to their limits. To respond to this demand, future 6G networks will depend on Tbit/sec data rate transmission via easily deployable wireless links. The SNS Joint Undertaking (JU) initiative wants to foster Europe’s technological leadership to address the challenges to cope with this increasing demand in terms of high-data rate communications including the exploitation of new spectral bandwidths. Energy-efficient solutions are required since the current cellular network sector has become one of the major contributors to the emission of greenhouse gases because of its excessive energy consumption. Current 5G wireless systems, characterized by their small spectral bandwidths and high-power electronics are fundamentally limited in terms of achievable data rates vs energy consumption. One of the main objectives of the SNS JU is to accelerate the development of energy-efficient network technologies with the aim of significantly reducing the energy and resource consumption of the whole digital infrastructure by 2030. TeraGreen addresses these objectives by developing the fundamental technological ingredients to reach >Tbps capacities with an energy-efficient solution at THz frequencies for the first time. The TeraGreen concept is illustrated in Figure 2.

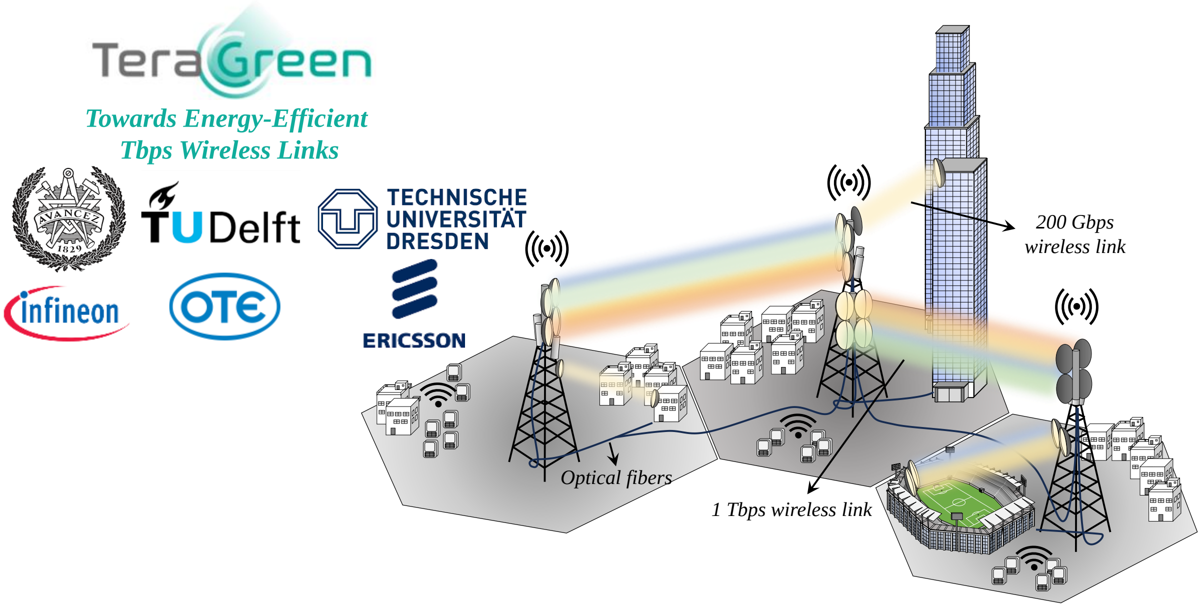

FIGURE 2: *TERAGREEN* CONCEPT: QUASI-OPTICAL MIMO ANTENNAS FOR THE FORMATION OF MULTIPLE NEAR-FIELD COMMUNICATION SPATIAL CHANNELS TO REACH TBPS CAPACITIES. EACH CHANNEL TRANSMITS >100GBPS SIGNAL WITH ZERO-CROSSING MODULATED WAVEFORMS. THE QO ANTENNA IS INTEGRATED WITH WIDEBAND SIGE-BICMOS TRANSCEIVERS OPERATING AT 300GHZ.

2.1 TeraGreen Objectives

TeraGreen will establish the foundations for future Tbit/sec communications systems by providing the understanding and proof-of-concept demonstrations of how the generation, detection and multiplexing of multiple ultra-wide band THz signals can be realized with highly energy-efficient and scalable technological solutions. The main objectives behind this concept are the following:

- **Objective 1:** TeraGreen develops lens integrated SiGe-BiCMOS transceivers in the THz band that can transmit and receive high-speed, energy-efficient pico-second signals.
    - **Sub-Objective 1.1:** TeraGreen develops transmitter and receiver architectures in the 300GHz band with a very high spectral RF bandwidth of 70GHz [2]. TeraGreen will use one of the most advanced silicon processes in the world, IFAG's latest 90nm SiGe-BiCMOS process, with maximum oscillation frequencies fmax exceeding 500GHz and copper metallization for mm-wave analog and mixed signal applications, which offers state-of-the-art performance at low power consumption.
    - **Sub-Objective 1.2:** TeraGreen develops wideband quasi-optical antennas in the 252-325GHz band that can operate in a radiative near-field link to reach over the air power spreading levels below 10dB. The quasi-optical antenna will be based on a dual-polarized integrated lens architecture to enable polarization multiplexing over the entire bandwidth and include steering capabilities for beam alignment.
    - **Sub-Objective 1.3:** TeraGreen develops zero-crossing modulation schemes suitable for energy-efficient wideband communication over a quasi-optical link using receivers with temporally oversampled 1-bit quantization. Moreover, baseband algorithms for efficient sequence-based modulation and receiver algorithms for channel estimation, receiver synchronization and sequence detection will be developed considering the characteristics of the quasi-optical channel.

- **Objective 2:** TeraGreen performs a proof of concept of high-speed and high-efficient wireless transmission for a medium range link distance at THz using silicon technology for the first time.
    - **Sub-Objective 2.1:** TeraGreen develops two integrated demonstrator units capable to transmit and receive, respectively, two simultaneous wideband data streams. The unit

will be able to adjust the transmit power, baseband bandwidth and modulation order. The unit will incorporate alignment techniques with accuracies below 1degree.
    - **Sub-Objective 2.2:** TeraGreen performs a demonstration of a 200Gbps wireless transmission capable to reach a medium range distance of 500m with a radiated energy efficacy of 8.000Tbit/Joule. Estimations of the baseband power consumptions will be done for this demonstration.

- **Objective 3:** TeraGreen develops quasi-optical MIMO array architectures to exploit the high degree of spatial multiplexing of the THz spectrum [3].
    - **Sub-Objective 3.1:** TeraGreen develops a simulation framework to evaluate the capacity and energy consumption in MIMO array architectures at THz combining high frequency electromagnetic techniques, THz silicon circuit performance estimations, and baseband signal models.
    - **Sub-Objective 3.2:** TeraGreen designs MIMO lens antenna arrays that can generate and detect simultaneously multiple wideband data streams in a near-field link with the goal of reaching Tbps aggregated capacities.
    - **Sub-Objective 3.3:** TeraGreen studies zero-crossing modulation for MIMO transmission. Due to the highly non-linear 1-bit quantization at the receiver, standard approaches for spatial equalization and substream separation in the digital domain cannot be applied. Thus, the robustness of zero-crossing modulation to substream interference as well as the application of transmitter side pre-equalization will be studied.

- **Objective 4:** TeraGreen performs the first proof of concept that Tbit/sec wireless transmission in the THz spectrum using near-field spatial multiplexing is possible.
    - **Sub-Objective 4.1:** TeraGreen characterizes a 2x2 dual-polarized lens array integrated with BiCMOS transmitters operating in the 300GHz band.
    - **Sub-Objective 4.2:** TeraGreen characterizes a 2x2 dual-polarized lens array integrated with BiCMOS receivers operating in the 300GHz band.
    - **Sub-Objective 4.3:** TeraGreen performs a short range (<10m) laboratory demonstration of the simultaneous transmission and detection of 8 data streams (8x8 MIMO) in the 300GHz band, with the potential to reach up to 100m, Tbit/sec capacities and a radiated energy efficacy of 40.000Tbit/Joule.

2.2 TeraGreen Innovations

TeraGreen aims to develop integrated THz transceivers for point-to-point wireless links capable of delivering terabit-per-second (Tbps) data rates. By leveraging a multi-disciplinary approach, the project will address critical challenges in the 300 GHz band through advancements in RF hardware, packaging, lens-antennas, and baseband signal processing technologies.

TeraGreen focuses on achieving ultra-fast wireless speeds (>200 Gbps) in the THz spectrum without excessive power consumption. This goal will be achieved through the following innovations:

- **Quasi-Optical Links:** Designing links that minimize energy spread in free space, reducing radiated energy levels by a factor of 1000 compared to existing 5G solutions. These links are based on quasi-optical antennas with ultra-high gain and precise alignment capabilities to mitigate the high free-space path loss inherent in THz frequencies. TeraGreen will also design MIMO lens arrays capable of generating and detecting multiple wideband data streams for near-field links, targeting Tbps aggregated capacities.
- **Silicon-Based Front-end Circuits**: Implementing silicon-based THz circuits to significantly lower DC power requirements. These circuits will have cut-off frequencies reaching 500 GHz to overcome the current lack of commercial THz solutions. TeraGreen will pioneer SiGe-BiCMOS electronics and optimized baseband designs to deliver Tbps wireless transmission at unprecedented energy efficiency. The project aims to increase wireless data rates by a factor of 100 while reducing energy consumption per bit by at least 1000 times compared to 5G solutions. The front-end will be enhanced to meet the demands of ultra-fast communications, including high

bandwidth, linearity, I-Q balance, LO rejection, low thermal noise, and minimal phase noise. These advancements will be achieved using innovative nm-scale SiGe-BiCMOS devices.
- **Energy-Efficient Modulation:** This will be achieved through development of wideband waveforms optimized for energy-efficient 1-bit analog-to-digital conversion (A/D) with temporal oversampling, enabling low-power utilization of large bandwidth signals. TeraGreen will invest on the robustness of zero-crossing modulation in handling substream interference in MIMO systems. Pre-equalization techniques will also be explored to overcome challenges posed by non-linear 1-bit quantization.
- **MIMO Array Architectures for THz Communication**: To exploit the high spatial multiplexing potential of the THz spectrum, TeraGreen will develop quasi-optical MIMO array architectures and an advanced simulation framework to assess capacity and energy efficiency [4], [5]. Creation of multi-beam MIMO architecture with lens antenna arrays enabling spatial multiplexing, marking the first step toward achieving Tbps links by simultaneously supporting multiple wideband data streams.

3. 6G Reference Use Cases and KPIs

The journey from 5G to 6G represents a significant leap in mobile communication technology, building on the foundational advancements of 5G while addressing new and emerging demands for connectivity [6]. The path to 6G will be marked by the exploration of new spectrum ranges, including the use of terahertz (THz) frequencies, which will enable unprecedented bandwidth and communication capacity. In addition, 6G will prioritize sustainability with energy-efficient designs, and introduce revolutionary concepts like integrated sensing and communication (ISAC), connected intelligence, and digital twins.

Defining new use cases for 6G involves extensive global collaboration between research institutions, industry leaders, and standardization bodies like the ITU and 3GPP. Governments, universities, and private sector stakeholders are conducting large-scale research initiatives, such as 6G Flagship [7] and Hexa-X [8], exploring the technological requirements and societal needs that 6G must address. These efforts are focused on understanding the limitations of 5G and envisioning new applications that go beyond current capabilities.

The use cases and their associated capabilities (key performance indicators (KPIs)) considered below will serve as reference for the TeraGreen use cases, requirements and KPIs. The technological innovations proposed in TeraGreen will be inline and able to support all related capabilities required for the next generation mobile communications system.

3.1 IMT-2030 Usage Scenarios

As an initial step to the definition of 6G use cases and KPIs, IMT-2030 [9] mentions a list of so called “usage scenarios”, which, essentially, correspond to different use case groups and network capabilities as a means to separate between different objectives/target domains. The IMT-2030 usage scenarios evolve from and expand on the IMT-2020 5G Service Classes/scenarios (ITU-R Recommendation ITU-R M.2083 [10]), namely on: enhanced Mobile BroadBand (eMBB) (3GPP TR 22.863, [11]), massive/enhanced Machine Type Communications (m/eMTC) (3GPP TR 22.861, [12]) and Ultra Reliable Low Latency Communications (URLLC) (3GPP TR 22.862, [13]).

The usage scenarios of IMT-2030 are illustrated in Figure 3 and include:

Immersive Communication

This usage scenario extends the enhanced Mobile Broadband (eMBB) of IMT-2020 and covers use cases which provide a rich and interactive video (immersive) experience to users, including the interactions with machine interfaces.

Typical use cases of this scenario include:

- communication for immersive XR
- remote multi-sensory telepresence
- holographic communications

Required capabilities include enhanced spectrum efficiency and consistent service experiences, higher data rates and increased mobility in various environments, high reliability and low latency for responsive and accurate interaction with real and virtual objects, as well as larger system capacity for simultaneously connecting numerous devices.

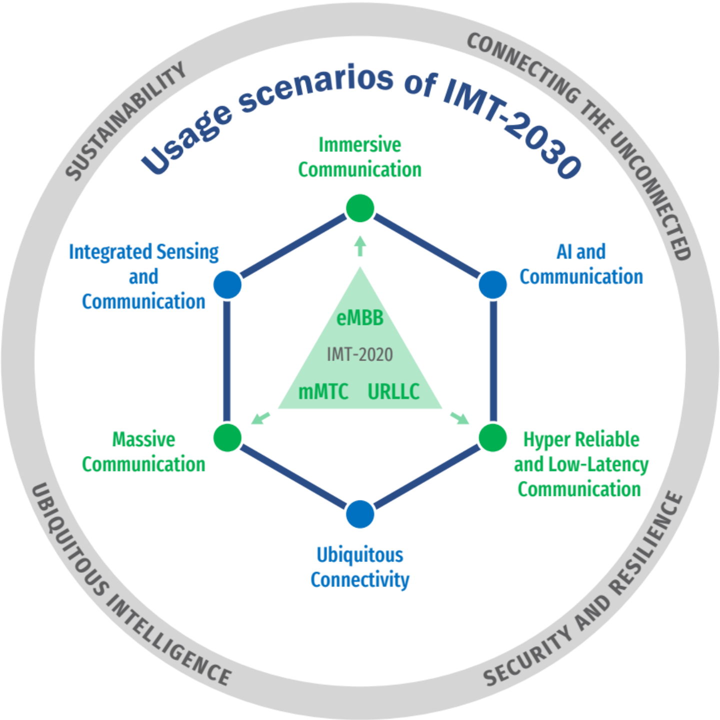

FIGURE 3. USAGE SCENARIOS AND OVERARCHING ASPECTS OF IMT-2030 [9]

Hyper Reliable and Low-Latency Communication

This usage scenario extends the Ultra-Reliable and Low-Latency Communication (URLLC) of IMT-2020 and covers specialized use cases that are expected to have more stringent requirements on reliability and latency.

Typical use cases of this scenario include:

- communications in an industrial environment for full automation, control and operation
- emergency services
- tele-medicine
- monitoring for electrical power transmission and distribution

Required capabilities include enhanced reliability and low latency, and depending on the use case, precise positioning, and connection density.

Massive Communication

This usage scenario extends massive Machine Type Communication (mMTC) of IMT-2020 and involves connection of massive number of devices or sensors for a wide range of use cases and applications.

Typical use cases include expanded and new applications in:

- smart cities
- transportation
- logistics
- health
- energy
- environmental monitoring
- agriculture

Required capabilities include high connection density, different data rates, low power consumption, mobility, extended coverage, and high security and reliability.

Ubiquitous Connectivity

This usage scenario is intended to enhance connectivity with the aim to bridge the digital divide. Connectivity should be enhanced to address presently uncovered or scarcely covered areas, particularly rural, remote and sparsely populated areas.

Typical use cases include:

- IoT
- mobile broadband communications

Artificial Intelligence and Communication

This usage scenario would support distributed computing and AI applications.

Typical use cases include:

- IMT-2030 assisted automated driving
- autonomous collaboration between devices for medical assistance applications
- offloading of heavy computation operations across devices and networks
- creation of and prediction with digital twins

Required capabilities include high area traffic capacity and user experienced data rates, low latency and high reliability, data acquisition, preparation and processing from different sources, distributed AI model training, model sharing and distributed inference across IMT systems, and computing resource orchestration and chaining.

Integrated Sensing and Communication

This usage scenario facilitates new applications and services that require sensing capabilities. It makes use of IMT-2030 to offer wide area multi-dimensional sensing that provides spatial information about unconnected objects as well as connected devices and their movements and surroundings.

Typical use cases include:

- IMT-2030 assisted navigation
- activity detection and movement tracking
- environmental monitoring
- provision of sensing data/information on surroundings

Required capabilities include high-precision positioning and sensing, including range/velocity/angle estimation, object and presence detection, localization, imaging and mapping.

3.2 IMT-2030 Capabilities (KPIs)

IMT-2030, defined by the International Telecommunication Union, sets the global framework for 6G, outlining the performance, technical requirements, and key use cases that this next-generation mobile network must achieve. IMT-2030 envisions capabilities that surpass 5G, including ultra-low latency (as low as sub-millisecond), extremely high data rates (up to 1 Tbps), and the ability to support a massive number of devices in highly dense environments. These capabilities are crucial to facilitate advanced technologies such as holographic communications, immersive extended reality, autonomous systems, and precision-driven industries like healthcare and manufacturing. IMT-2030 also emphasizes network intelligence, security, and Energy Efficiency, ensuring 6G networks can dynamically adapt to varying user demands while minimizing environmental impact.

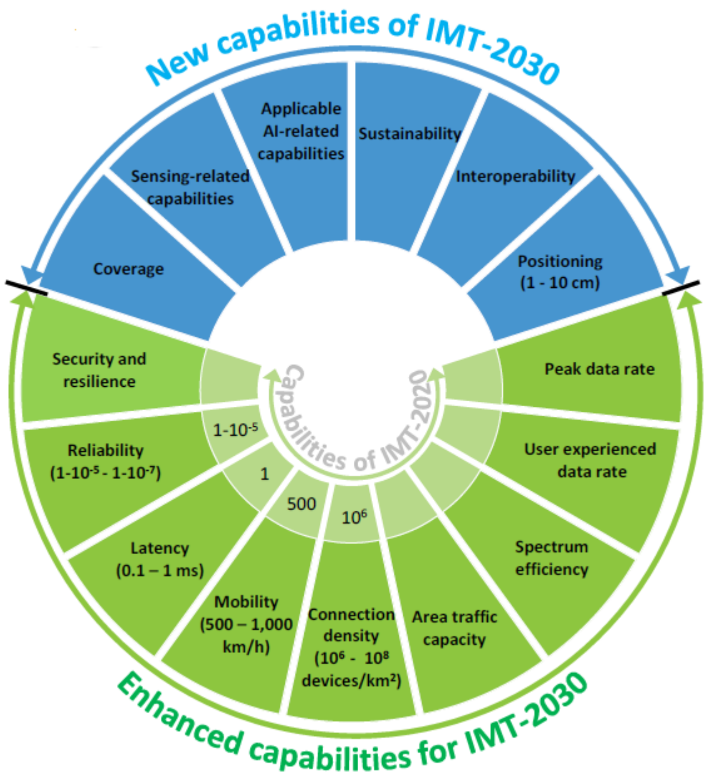

FIGURE 4. CAPABILITIES OF IMT-2030 (KPIS) [9]

IMT-2030 will provide enhanced capabilities compared to those described for IMT-2020 in Recommendation ITU-R M.2083, as well as new capabilities to support the expanded usage scenarios of IMT-2030, as depicted in Figure 4. The range of values provided for these capabilities are estimated targets for research and investigation of next generation mobile telecommunications. These values may further depend on certain parameters and assumptions including, but not limited to, frequency range, bandwidth, and deployment scenario. Further these values for the capabilities apply only to some of the usage scenarios and may not be reached simultaneously in a specific usage scenario.

IMT-2030 capabilities are vital to research projects like TeraGreen because they provide a comprehensive framework and technical benchmarks for developing sustainable, high-performance communication technologies. TeraGreen, which develops a technology path for sustainable and scalable commercial exploitation of the THz spectrum for energy-efficient and Tbit/sec wireless communication links, try to meet the ultra-high data rates, low latency, and Energy Efficiency targets set by IMT-2030, and design systems that meet the demands of 6G networks while minimizing environmental impact. The project's goal to enhance the Energy Efficiency of THz communication aligns with IMT-2030's emphasis on sustainability, pushing researchers to innovate in areas such as energy-harvesting techniques, smart resource allocation, and green network architectures. This alignment ensures that TeraGreen contributes to the global goals for 6G by addressing both performance and environmental challenges.

The IMT-2030 Capabilities are presented in tabular form in Table 1.

TABLE 1. IMT-2030 CAPABILITIES (KPIS) OVERVIEW [9]

IMT-2030 Capability	Definition	Value
Peak data rate	Maximum achievable data rate under ideal conditions per device	50, 100, 200 Gbit/s
User experienced data rate	Achievable data rate that is available ubiquitously across the coverage area to a mobile device.	300 Mbit/s and 500 Mbit/s
Area traffic capacity	Total traffic throughput served per geographic area	30 Mbit/s/m^2 and 50 Mbit/s/m^2

Connection Density	Total number of connected and/or accessible devices per unit area	$10^6 – 10^8$ devices/km^2
Spectrum efficiency	Spectrum efficiency refers to average data throughput per unit of spectrum resource and per cell	1.5 and 3 times greater than that of IMT-2020
Mobility	Maximum speed, at which a defined QoS can be achieved	500 – 1.000 km/h
Latency over the air interface	Contribution by the radio network to the time from when the source sends a packet of a certain size to when the destination receives it	0.1 – 1 ms
Reliability	Capability of transmitting successfully a predefined amount of data within a predetermined time duration with a given probability	$1\text{-}10^{-5}$ to $1\text{-}10^{-7}$
Positioning	Ability to calculate the approximate position of connected devices. Positioning accuracy is defined as the difference between the calculated horizontal/vertical position and the actual horizontal/vertical position of a device	1 – 10 cm
Sensing-related capabilities	Ability to provide functionalities in the radio interface including range/velocity/angle estimation, object detection, localization, imaging, mapping, etc.	These capabilities could be measured in terms of accuracy, resolution, detection rate, false alarm rate, etc.
Sustainability	Sustainability, or more specifically environmental sustainability, refers to the ability of both the network and devices to minimize greenhouse gas emissions and other environmental impacts throughout their life cycle. Important factors include improving Radiated Energy Efficiency, minimizing energy consumption and the use of resources, for example by optimizing for equipment longevity, repair, reuse and recycling.	Energy Efficiency is a quantifiable metric of sustainability. It refers to the quantity of information bits transmitted or received, per unit of energy consumption (in bit/Joule).
Security and resilience	Security refers to the preservation of confidentiality, integrity, and availability of information, such as user data and signalling, and protection of networks, devices and systems against cyberattacks such as hacking, distributed denial of service, man in the middle attacks, etc. Resilience refers to capabilities of the networks and systems to continue operating correctly during and after a natural or man-made disturbance, such as the loss of primary source of power, etc.	No quantifiable metrics are associated with this capability.
Applicable AI-related capabilities	Applicable AI-related capabilities refer to the ability to provide certain functionalities throughout IMT-2030 to support AI enabled applications. These functionalities include distributed data processing, distributed learning, AI computing, AI model execution and AI model inference, etc.	No quantifiable metrics are associated with this capability.
Interoperability	Interoperability refers to the radio interface being based on member-inclusivity and transparency, so as to enable functionalities between different entities of the system.	No quantifiable metrics are associated with this capability.

4. TeraGreen Use Cases

The following template is used for the description of the project-specific use cases, for consistency purposes.

TABLE 2. TERAGREEN USE CASES TEMPLATE

UC#: Title
Stakeholders:
Description, current status and limitations, and advantages of THz communications:
Service flows:
Associated PoC:

Stakeholders are the entities that will be involved and/or benefited by the particular use case. The consortium has identified five target groups which can benefit from the TeraGreen outcomes:

- **Mobile/wireless industry and society** (**TG1**): Telecom equipment vendors, Telecom operators, Pure-play service providers over mobile networks, OTTs, App developers, Consumers/mobile end users
- **Microelectronics sector & community** (**TG2**): Semiconductor and packaging technology providers, Vendors/equipment providers, Chipset/ASIC manufacturers & suppliers
- **European society** (**TG3**): Partnership and networking between relevant segments
- **Academic community** (**TG4**): Universities, Research Institutes
- **Regulatory authorities, policy makers & standardization bodies** (**TG5**): European Commission, Regulators, e.g., ECC, ETSI, CEPT, National authorities on wireless communications

The proof of concept (PoC) for the above use cases will be performed through two demonstrations that will confirm the suitability of the TeraGreen innovations in facilitating these use cases. The two demonstrations are mentioned as Demo 1 and Demo 2 in the use case descriptions that follow.

Demo 1 is a medium-range demonstration aiming at supporting >200Gbps data rate over ~100 meters, with a future capability to reach 500m, with a radiated energy efficiency of 8000Tbps per Joule. This demonstration will take place at CHALMERS and EAB premises.

Demo 2 is a short-range demonstration focusing on capacity and targets an over-the-air laboratory demonstration to reach an aggregated Tbps capacity using MIMO near-field multiplexing. The over the air demonstration will consist of a short distance (i.e., up to 10 meters) link validation of a 8x8 QO-MIMO system with the potential to reach up to 100m. This demo will be performed in the TUDELFT Earl McCune Laboratories.

The following sections identify use cases that leverage the energy-efficient, high-capacity point-to-point, and wide-bandwidth capabilities of the TeraGreen solution. It begins with a detailed explanation of the use cases, followed by an overview of the KPIs used to characterize them. Finally, these KPIs are consolidated and presented in Table 7 for clarity and reference.

In this context, four use cases have been considered that share the same characteristic of wireless solution through point-to-point links delivering high capacity with low latency and highly reliable communication:

- UC1: Fronthaul in ultra-dense small cell networks
- UC2: High throughput fixed wireless access (FWA)
- UC3: Live immersive XR in large-scale events
- UC4: Wireless data centres

4.1 UC1: Fronthaul in ultra-dense small cell networks

In the context of ultra-dense small cell networks, TeraGreen addresses the critical challenge of providing energy-efficient and high-capacity fronthaul solutions using terahertz (THz) communication. Small cells are essential for delivering high data rates and low latency in 6G networks, especially in dense urban environments. However, the fronthaul links must handle massive amounts of data traffic. TeraGreen's THz-based solutions offer ultra-high bandwidth for these fronthaul links, ensuring seamless communication while significantly reducing energy consumption and latency. This is particularly beneficial for supporting real-time applications in crowded areas, where data demands are intense. By integrating sustainable energy-efficient designs, TeraGreen enables scalable small cell deployment without overwhelming the network's energy resources.

TABLE 3. UC1: FRONTHAUL IN ULTRA-DENSE SMALL CELL NETWORKS

UC1: Fronthaul in ultra-dense small cell networks
Stakeholders: TG1, TG2, TG3, TG4
Description, current status and limitations, and advantages of THz communications: The cloud radio access network (CRAN) has been proposed as a promising architecture for meeting the needs and goals of 5G and beyond networks. However, the provisioning of cost-efficient connections between a large number of remote radio heads (RRHs) in the cell sites and the baseband unit (BBU) pool (see Figure 5) in the central location, known as the fronthaul, has emerged as a new challenge. Many wired and wireless solutions have been proposed to address this bottleneck [14]. Specifically, optical technologies presented by passive optical networks (PONs) are today considered to be the best suitable solution for 5G and beyond network fronthaul due to their properties of providing high capacity and low latency. Nevertheless, fiber in dense urban areas, while extremely expensive, is not always available and can sometimes be impossible to install. Advantages of THz communications for fronthaul include the following: High Data Rates: THz frequencies handle massive data loads, ideal for ultra-dense urban areas with heavy user demand. Support for 6G: THz links meet the high traffic demands of 6G applications like high-resolution video, AR/VR, and holograms. Cost Efficiency: Wireless THz fronthaul reduces relience on expensive fiber, cutting installation and maintenance costs. Rapid Deployment: THz links enable faster network expansion compared to fiber. Small Cell Densification: Short-range THz links efficiently connect small cells to BBUs without interference. Scalability: THz links allow dynamic deployment and easy scaling to support growing networks. Low Latency: THz fronthaul minimizes delays, crucial for real-time applications like autonomous driving and industrial automation. Edge Computing Support: THz links enable low-latency communication between small cells and edge nodes for real-time processing. Directional Beamforming: Ensures high spectral efficiency and minimizes interference, optimizing spectrum usage in crowded areas. Spatial Reuse: The short-range nature of THz links improves spectrum efficiency, avoiding congestion. Energy Efficiency: THz links are energy-efficient for short distances, reducing operational costs.

Sustainability: Lower infrastructure needs and reduced power consumption make THz fronthaul more sustainable.

Enhanced Security: Directional THz signals resist eavesdropping and enhance privacy.

Reduced Interference: Short-range and directional links ensure reliable communication in dense urban settings.

Improved QoS: Lower interference leads to consistent, high-quality fronthaul connections.

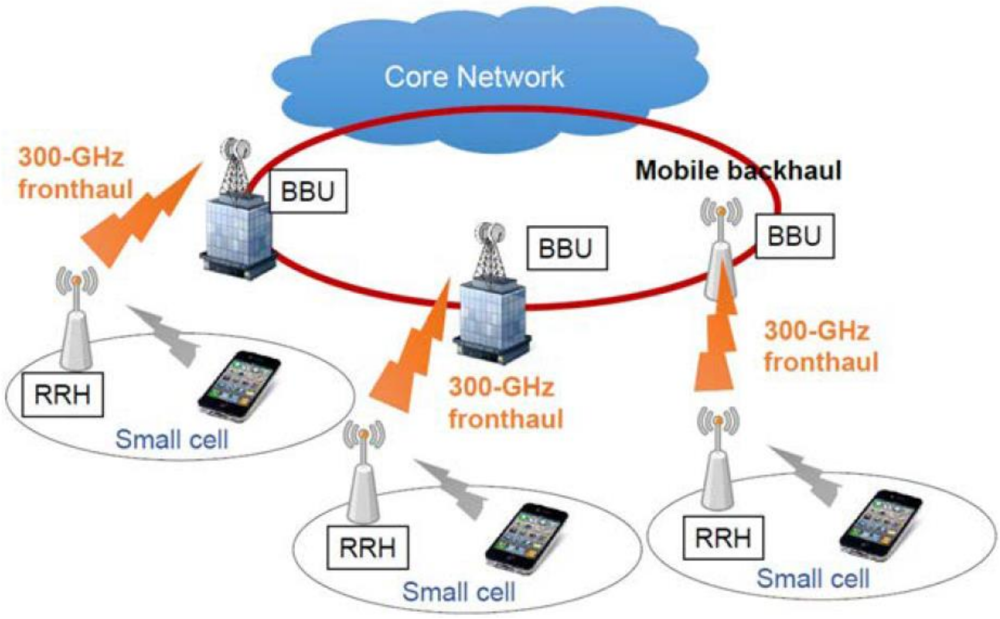

FIGURE 5. USING TERAGREEN FOR FRONTHAUL ACCESS [10]

Service flows:

User Devices (smartphones, tablets, IoT devices) initiate a connection to the nearest RRH in the respective small cell. This could involve handover from another cell or a new connection.

The small cell receives user data, such as internet requests, streaming content, or IoT sensor data.

The small cell processes this data locally if possible, or it forwards the data to a Baseband Unit (BBU) via a THz fronthaul link.

The THz fronthaul link transmits the aggregated data from multiple users to the BBU.

The BBU processes the incoming data, performing functions such as user scheduling, resource allocation, and data aggregation.

The processed data is sent back to the small cells via the THz fronthaul link, ready for delivery to the user devices.

The BBU connects to the core network for further data processing and access to broader services (internet, cloud applications, etc.).

Return paths are established for responses from the core network to the user devices, maintaining the cycle of communication.

Use Case Scenarios:

High-Density Urban Area Service Provision

In a bustling downtown district, a high concentration of users accesses the network for services like social media, video streaming, and IoT device management.

Event Venue Connectivity

During a large event, such as a concert or sports game, thousands of attendees use their devices to share experiences in real time. Small cells deployed around the venue connect to user devices. **Smart Transportation Systems** In an urban area with smart traffic lights and connected vehicles, small cells enable communication between vehicles, infrastructure, and the control center. **Public Safety Applications** During emergencies, first responders rely on rapid communication and data sharing. Emergency vehicles and personnel equipped with devices can connect to small cells deployed throughout the area.
Associated PoC: Demo1, Demo2

4.2 UC2: High throughput fixed wireless access (FWA)

TeraGreen's use case on high-throughput Fixed Wireless Access (FWA) focus on delivering ultra-fast, energy-efficient internet connectivity to homes, businesses, and remote areas using terahertz (THz) communication. By leveraging THz spectrum, TeraGreen enables multi-gigabit per second (Gbps) data rates, allowing users to experience fiber-like speeds wirelessly without the need for costly physical infrastructure like fiber optic cables. This is particularly beneficial for bridging the digital divide in rural or underserved areas, providing high-speed connectivity where traditional broadband deployment is challenging. With an emphasis on Radiated Energy Efficiency, these high-throughput FWA solutions not only enhance connectivity but also minimize environmental impact, aligning with sustainability goals for 6G networks.

TABLE 4. UC2: HIGH THROUGHPUT FIXED WIRELESS ACCESS (FWA)

UC2: High throughput fixed wireless access (FWA)
Stakeholders: TG1, TG2, TG3, TG4
Description, current status and limitations, and advantages of THz communications: Fixed Wireless Access (FWA) using Terahertz (THz) communications represents a cutting-edge approach to providing high-speed broadband wirelessly, particularly for the "last mile" of internet access. This use case leverages the ultra-high-frequency spectrum of the THz band to deliver fiber-like speeds without the need for physical cabling, especially in areas where fiber installation is difficult or cost-prohibitive. FWA is widely used today to deliver broadband, primarily through lower-frequency bands such as sub-6 GHz or millimeter waves (24-100 GHz). Traditional FWA technologies provide a competitive alternative to fiber in certain areas, but they come with limitations, especially in terms of bandwidth and speed. Current FWA systems typically offer speeds ranging from 100 Mbps to 1 Gbps, depending on the frequency band, distance, and interference conditions. While these speeds are adequate for basic broadband services, they fall short of the growing demand for multi-gigabit internet speeds. While FWA technologies, particularly those based on 5G, have reduced latency, they still can’t match the low latency required by highly interactive applications like real-time gaming or augmented reality (AR). Lower-frequency bands used in FWA are often crowded, leading to interference issues and congestion, particularly in densely populated urban environments. THz communications offer a new horizon for FWA by addressing many of the current limitations. THz frequencies provide enormous bandwidth capacity, enabling data rates that could potentially reach terabits per second (Tbps). This allows THz-based FWA to deliver fiber-like or even better-than-fiber

speeds wirelessly, supporting high-definition video streaming, virtual and augmented reality, cloud-based gaming, and other data-intensive services.

THz communications promise extremely low latency, often below 1 millisecond (ms), making them suitable for real-time applications. This ultra-low latency supports critical applications such as remote healthcare (e.g., telesurgery), autonomous vehicle networks, industrial automation, and interactive AR/VR experiences.

THz frequencies are largely unoccupied compared to the sub-6 GHz and even mmWave bands. This results in less interference and congestion in the spectrum. The abundance of THz spectrum allows for cleaner, more stable connections, especially in dense urban environments where many devices are competing for bandwidth.

The highly directional nature of THz beams offers enhanced security by making it difficult for eavesdroppers to intercept the signal. THz signals are confined to narrow beams and are easily blocked by obstacles, reducing the risk of hacking. Enhanced physical layer security is crucial for sensitive applications, such as military communications, financial transactions, and secure data transfers.

THz communications can be deployed with massive MIMO (multiple-input, multiple-output) and beamforming techniques to ensure high-performance connectivity even in densely populated areas. THz-based FWA can scale efficiently in urban environments, providing high-speed connectivity to thousands of users and devices without physical fiber infrastructure.

While the hardware for THz communications (antennas, amplifiers, etc.) is currently more expensive, the ability to bypass fiber optic deployment can lead to overall cost savings. Especially in areas where laying fiber is expensive or physically impractical (e.g., remote or mountainous regions), THz FWA can reduce infrastructure costs while still delivering ultra-high-speed connectivity.

THz communications are expected to play a significant role in 6G networks. As a result, investing in THz FWA provides future-proof infrastructure that can evolve to support emerging technologies like holographic communications, immersive AR/VR, and the Internet of Things (IoT). Early adoption of THz FWA allows network operators to position themselves for the future, meeting the escalating bandwidth and latency requirements of 6G applications.

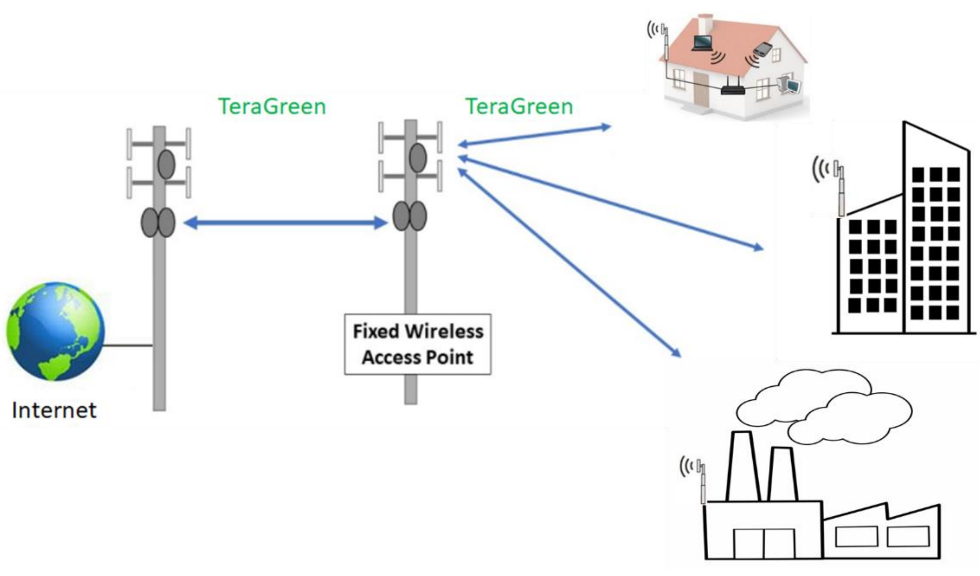

FIGURE 6. USING TERAGREEN FOR FIXED WIRELESS ACCESS (FWA)

Service flows:

A THz base station or hub is installed at a strategic location, often on a tower or rooftop in urban environments, or in rural areas with clear line-of-sight to the surrounding properties. The base station serves as the central node for wireless communication, connecting the end-users to the broader network backbone. The backhaul for the base station can be provided by fiber-optic links or other high-capacity wireless technologies like millimeter-wave communications, satellite links, or even THz wireless links.

The base station establishes highly directional THz communication links to customer premises equipment (CPE) located at fixed locations, such as homes, businesses, or offices. These links can provide high-capacity wireless data channels over relatively short distances (typically up to 100 - 500 meters due to atmospheric absorption at THz frequencies).

Advanced beamforming and massive MIMO technologies are used to focus narrow beams on individual users or devices, ensuring maximum signal strength and minimizing interference. This step is crucial to counter the high path loss inherent to THz frequencies and to deliver high data rates to end-users.

At the customer's end, a CPE is installed, which consists of a receiver (often integrated with an antenna) that can capture the high-frequency THz signal and convert it into usable internet service for the home or office. This CPE can connect to the user's devices through a wired Ethernet connection or a Wi-Fi router for local wireless distribution, or even through indoor THz links.

Once the FWA THz link is established, high-speed data transmission flows between the base station and the CPE. The service flow allows the transmission of:

- High-speed internet access
- Video streaming (8K, 16K, VR content)
- Real-time applications like online gaming or cloud-based services
- IoT data transmission for smart homes or businesses

The network infrastructure prioritizes different types of traffic (e.g., video, voice, data) using Quality of Service (QoS) management techniques. Since THz communications offer extremely low latency and high bandwidth, they can easily accommodate real-time services like teleconferencing, gaming, and AR/VR, which demand strict QoS guarantees.

Use case scenarios:

Urban Broadband Access

In densely populated cities, where installing fiber is costly or takes a lot of time and resources to install, THz FWA can offer ultra-high-speed broadband as an alternative. This is particularly useful in multi-tenant buildings (e.g., apartments, office towers) where each unit requires high bandwidth for streaming, video conferencing, cloud computing, and other bandwidth-heavy applications.

Example: A large apartment complex in a metropolitan area is underserved by existing broadband providers. THz FWA can provide gigabit speeds to each unit without the need for disruptive fiber installation, offering a faster deployment solution for high-speed internet.

Enterprise Connectivity

For businesses requiring high-capacity, low-latency networks for cloud services, real-time data analytics, and high-definition video conferencing, THz FWA can provide reliable connections. Enterprises can use THz FWA as their primary or backup link to ensure continuous, high-speed access without relying on physical fiber connections.

Example: A corporate campus needs to connect multiple buildings with secure, ultra-fast communication links. Deploying THz FWA between the campus buildings allows the company to avoid laying fiber underground and provides a robust network for data-intensive business operations.

Rural and Remote Areas

In rural regions, where laying fiber-optic cables is often cost-prohibitive, THz FWA can provide a viable alternative to deliver high-speed internet. While the range of THz signals is shorter, strategic placement of base stations can serve rural homes or businesses where the last mile of connectivity is a significant barrier.

Example: A small rural community located in hilly terrain struggles with slow broadband options. THz FWA base stations deployed on elevated structures can provide high-speed internet access to homes, offering high-quality services like streaming, online education, and telemedicine without the high cost of running fiber through difficult terrain.

5G and 6G Network Extensions

THz FWA is ideal for extending 5G and future 6G networks into high-demand areas such as smart cities, stadiums, or densely packed event spaces. These areas require high data rates and low latency for services like AR/VR, IoT, and autonomous vehicles, where physical infrastructure may not be feasible.

Example: During a major event in a stadium or city square, THz FWA can provide temporary high-capacity networks to support the thousands of users accessing 4K streams, live VR experiences, and cloud-based services simultaneously. The FWA links can be deployed on drones or rooftop base stations to extend 5G/6G services during the event.

Disaster Recovery and Emergency Networks

THz FWA can be rapidly deployed to provide high-speed broadband in emergency situations where physical infrastructure is damaged or non-existent, such as after natural disasters.

Example: After a natural disaster disrupts existing communication lines, THz FWA is quickly deployed to provide critical internet access to emergency responders and displaced residents, supporting real-time coordination, medical data transmission, and satellite connectivity.

Smart Home and IoT Connectivity

In a smart home or smart building environment, THz-based FWA can deliver the ultra-high bandwidth required to connect a wide range of IoT devices (sensors, cameras, thermostats) in real-time, enabling seamless automation, security, and data sharing.

Example: In a smart city district, residential and commercial buildings use THz FWA to wirelessly connect thousands of IoT devices, from traffic lights to security cameras, to a centralized cloud system, enabling real-time data analysis for traffic management, public safety, and Radiated Energy Efficiency.

Associated PoC:

Demo 1, Demo 2

4.3 UC3: Live immersive XR in large-scale events

TeraGreen's use case for live immersive extended reality in large-scale events focus on delivering seamless, high-bandwidth experiences that enable participants to interact in real time with virtual elements, no matter the scale of the audience. Using terahertz (THz) communication, TeraGreen provides the ultra-low latency and high data rates required to support immersive technologies such as augmented reality (AR) and virtual reality (VR) at events like concerts, sports games, or conferences. This allows attendees, both on-site and remotely, to experience rich, interactive environments, such as live holographic performances or virtual meet-and-greets, without interruptions. The energy-efficient design of TeraGreen solutions ensures that these immersive experiences can be delivered sustainably, even with the massive data demands of large-scale events. This unlocks new possibilities for entertainment, education, and business, revolutionizing how people engage with live events.

TABLE 5. UC3: LIVE IMMERSIVE XR IN LARGE-SCALE EVENTS

UC3: Live immersive XR in large-scale events
Roles - Stakeholders: TG1, TG2, TG3, TG4
Description, current status and limitations, and advantages of THz communications: Large-scale events, like concerts or football matches, gather up to 100,000 people in compact areas. Ultra-HD cameras capture multiple viewing angles, while audiences use devices like AR/VR headsets

and smartphones for immersive real-time experiences. Users can switch angles, enjoy 360° video, and share live streams.

Current status and limitations:

Throughput Issues: Traditional networks (4G, Wi-Fi, and even 5G) struggle to handle the massive data demands of XR, causing lag, resolution drops, and service interruptions.

Latency Challenges: XR requires sub-10ms latency for real-time interaction; traditional systems cause delays that disrupt immersion and can induce motion sickness.

Network Congestion: Dense user environments overwhelm infrastructure, leading to packet loss and degraded XR performance.

Processing Demands: Centralized processing adds latency, while local devices lack the power for real-time rendering.

Device Limitations: XR devices face short battery life and overheating, limiting their practicality for long sessions.

Positioning Issues: Existing tech struggles with accurate tracking and synchronization in crowded settings, breaking XR immersion.

Advantages of THz Communications:

High Data Rates: Enables seamless streaming of 360° video, real-time holograms, and 3D models, ensuring smooth, high-quality XR experiences.

Ultra-Low Latency: Sub-millisecond delays ensure real-time interactions, eliminating motion sickness and enhancing immersion.

Congestion Mitigation: THz small cells serve localized traffic, supporting thousands of users without interference or slowdowns.

Edge Integration: Processing offloaded to edge nodes reduces latency, improves responsiveness, and enhances XR quality.

Improved Device Performance: Efficient communication reduces battery drain and heat generation, allowing longer immersive sessions.

Accurate Localization: Beamforming ensures precise tracking and synchronization, enhancing realism in XR environments.

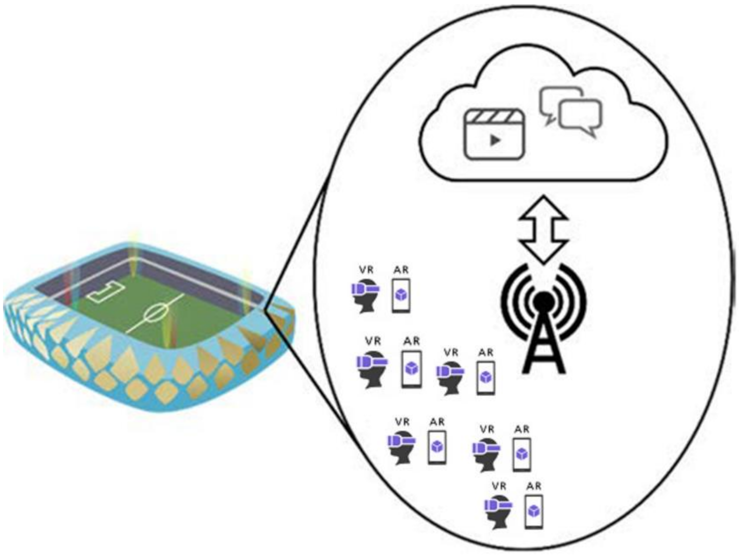

FIGURE 7. LIVE IMMERSIVE XR IN LARGE-SCALE EVENTS

Service flows:

As attendees enter the venue, their XR-capable devices (such as smartphones, AR glasses, or VR headsets) automatically connect to the event's network, powered by THz access points. Upon connection, the system identifies each device and user, authenticates them, and assigns them to a network slice that matches the quality of service required for XR interactions.

Using network slicing capabilities, the system allocates distinct bandwidth slices for XR-related services (such as live holograms or AR overlays) and standard network services (such as messaging, calls, or social media use). This ensures that XR services receive priority in terms of speed, latency, and reliability.

Real-time data (such as live video feeds, sensor data from performers or athletes, and crowd interactions) is collected, processed, and rendered into XR content at nearby edge computing nodes.

High-speed, directional THz links provide the main backbone, transmitting large volumes of XR data from the edge servers to distribution points within the venue. These links operate as point-to-point (P2P) connections between processing hubs and localized distribution nodes.

THz links can be also utilized to carry the customized content to access points distributed strategically throughout the venue, each covering small clusters of users. These nodes can be equipped to deliver user-specific streams from edge servers with minimal delay.

The last hop to user devices is typically served by mmWave in 5G or 6G networks. These access points, covering a broader area and being able to tolerate moderate obstacles, provide a reliable, high-bandwidth connection for the final delivery to individual devices.

Users can receive personalized or contextualized XR content, tailored to their location within the venue. For example, a user near the stage at a concert could see detailed holograms of the performer, while a user farther back might receive a 360-degree live feed of the event or an AR-enhanced view of the stage.

Use case scenarios:

Immersive Concert Experiences

Concert attendees could experience live performances not only on stage but also as 3D holographic projections displayed across different sections of the venue. Attendees in the back rows or remote sections would feel as though they're right in front of the performer, with the holograms displayed via AR glasses. Attendees could also engage with XR elements such as interactive lighting or customized visual effects that respond to their movements or actions. For example, they might choose different visual themes for the concert (e.g., fire, water, or space themes), which could influence the appearance of holograms and augmented reality visuals around them. Fans could use AR or VR to virtually interact with holographic representations of the performers in real time. These interactions could be personalized, allowing fans to ask questions or take virtual photos with the artists.

Sports Events with Enhanced AR/VR

At stadiums or arenas, fans wearing AR glasses or using AR-enabled smartphones can see real-time player statistics, performance metrics, and strategic overlays projected onto the field or court. These data points would be updated continuously as the game progresses, providing deep insights into team strategies or player performance. In addition, fans could instantly switch between different camera angles using VR headsets or AR devices, enabling them to see key moments from any perspective, including a 360-degree view or close-up replays. THz communications would ensure that high-resolution video is delivered seamlessly without any lag. Large-scale fan engagement games could also be deployed, where attendees participate in virtual challenges or contests, visible in real time through their AR devices. For instance, in soccer, fans could "kick" a virtual ball by physically moving their phones, with results being projected on a stadium-wide AR interface.

Trade Shows and Expos

At large-scale trade shows, companies can use XR to provide attendees with immersive, holographic product demonstrations. Products too large to display physically (e.g., industrial machinery, cars, or airplanes) could be projected as interactive 3D models. Users could manipulate, assemble, or test these virtual models through their AR or VR devices. THz communications would also allow remote participants to join the event virtually in real time. Attendees could interact with exhibitors and other participants through immersive avatars or holograms, enabling remote networking as though they were physically present.

Health and Safety Management

Event organizers could use AR to monitor crowd movements and density in real time, using data collected from THz-connected devices throughout the venue. This data could be visualized through AR glasses to security staff, allowing them to manage crowd safety and avoid congestion or bottlenecks. In case of emergencies, THz-powered XR systems could guide attendees through evacuation procedures using real-time AR instructions displayed on their devices. For example, AR overlays could show the safest exit routes or direct medical personnel to the exact location of incidents.

Hybrid Events with Remote XR Participation

THz communication could support fully immersive participation from remote attendees using VR headsets. Remote participants would feel as though they are physically present at the event, experiencing live performances, keynote speeches, or exhibitions in a 3D virtual environment. Hybrid events could facilitate collaboration between onsite and remote attendees. For example, an XR-based design conference could allow remote participants to work alongside physical attendees to create 3D models, artwork, or prototypes, which are visible to both groups in real time.

Associated PoC:

Demo 2

4.4 UC4: Wireless data centres

TeraGreen's use case for wireless data centers aim to revolutionize the efficiency and scalability of next-generation data centers by utilizing terahertz (THz) communications. With the increasing demands of cloud computing, AI, and big data analytics, traditional wired infrastructure can become a bottleneck in terms of speed, flexibility, and energy consumption. TeraGreen offers ultra-high throughput, low-latency wireless links that can replace or complement fiber-optic connections within data centers, enabling faster data transmission between servers, storage units, and other critical components. By eliminating the need for extensive cabling, TeraGreen's wireless solutions not only reduce operational complexity and costs but also enhance the flexibility and scalability of data centers to quickly adapt to evolving workloads. Additionally, the energy-efficient nature of these THz communications aligns with the sustainability goals of modern data centers, reducing their overall carbon footprint while supporting ever-growing data demands.

TABLE 6. UC4: WIRELESS DATA CENTRES

UC4: Wireless data centres
Roles - Stakeholders: TG1, TG2, TG3, TG4
Description, current status and limitations, and advantages of THz communications: In today's data centers, interconnections are primarily handled through fiber-optic cables and high-speed Ethernet. These networks provide high data transfer rates and low latency but come with several challenges and limitations. Wired connections require extensive infrastructure, including racks of fiber-optic cables, switches, and physical interfaces. This setup leads to high installation costs, complex management, and maintenance challenges. The large volume of cables can make scaling difficult, limiting the flexibility of server arrangements. It can also complicate cooling solutions due to restricted airflow. As data centers grow, adding or reconfiguring servers requires manual handling of cabling, making expansion time-consuming and costly.

Despite improvements in fiber-optics and Ethernet, the growing demand for data processing from AI, big data, and edge computing is putting pressure on existing interconnect solutions. The need for sub-millisecond latency in real-time applications is becoming harder to meet as workloads increase. Data centers are energy-intensive, partly due to the cooling required for densely packed servers and cabling systems. The heat generated by cables and switches adds to this problem.

THz communications offer significant advantages for wireless data centers. THz communications can support data rates in the terabits-per-second range. This is significantly faster than current fiber-optic and Ethernet connections, which typically reach gigabit or low terabit levels. This will allow data centers to handle data-intensive workloads like AI model training, real-time analytics, and cloud computing efficiently.

THz communication allows for wireless connections between servers, storage, and switches, reducing the need for physical cabling. This can simplify data center design, allowing for more flexible server configurations and easier management. In addition, new servers can be added wirelessly without the need for extensive rewiring or restructuring, making scaling faster and cheaper.

THz communication can provide sub-millisecond latency, which is crucial for real-time applications such as cloud gaming, edge computing, and high-frequency trading. Current wired solutions struggle to meet such low latency demands, especially as traffic volumes grow. Low latency reduces delays in data processing and transmission, improving the performance of distributed computing and real-time analytics.

Wireless data centers based on THz technology will enable dynamic network reconfiguration, where servers and network elements can be rearranged without the need for physical reconnections. This will allow for faster scaling in response to increased workloads. For example, data center resources can be scaled up or down based on demand without downtime.

Removing cables and switches helps to optimize cooling by allowing for better airflow between servers. This leads to more efficient temperature management and reduces the overall energy consumption of the data center. In addition, THz communication's high spectral efficiency allows more data to be transferred per unit of energy compared to traditional cabling.

THz wireless links can reroute data dynamically in case of link failures or congestion. This enables more resilient data center operations, as it avoids the single points of failure that can occur with wired connections. Also, automatic load balancing and redundancy become easier to implement, improving uptime and reducing the risk of outages.

Eliminating cables opens new possibilities for designing compact and highly efficient data centers. With no physical wires to manage, the space can be better optimized for server and storage placement. Smaller, more modular designs can be created, making data centers more efficient in terms of space usage.

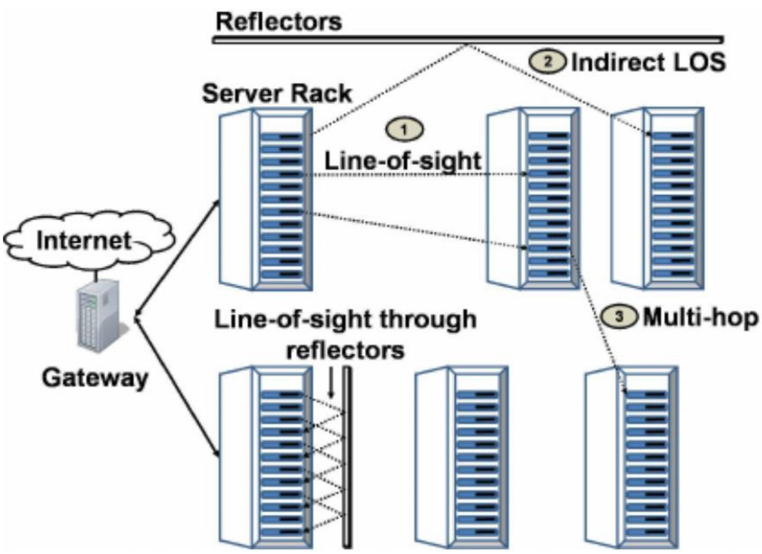

FIGURE 8. WIRELESS DATA CENTER [19]

Examples of communication within data centers:

Server-to-Server Communication

Servers need to communicate frequently to share data, replicate services, and perform distributed computing tasks.

Server-to-Storage Communication

High-performance computing (HPC) and big data analytics require rapid access to large volumes of data stored in networked storage systems. THz links enable low-latency wireless communication between servers and storage units.

Server-to-Edge Communication

Data centers often interact with edge devices to offload compute tasks or provide low-latency services. THz communication can enable high-speed, wireless connections between central servers and edge computing devices.

Intra-Rack and Inter-Rack Communication

In wireless data centers, THz communications can be used for both intra-rack (within the same server rack) and inter-rack (between different racks) data transfer. This allows for modular, cable-free designs that improve scalability and reduce physical complexity.

Use Case Scenarios:

Artificial Intelligence and Machine Learning

Data centers running AI workloads require rapid access to large datasets for training models. THz communications facilitate quick data retrieval and processing.

Example: A machine learning algorithm needs to process vast amounts of data stored across multiple servers. Using THz links, data can be transferred at high speeds, allowing the model to be trained more efficiently and effectively.

Big Data Analytics

Businesses analyze massive datasets to extract insights. THz communications enable quick data access and real-time analysis.

Example: A retail company aggregates sales data from various sources. With THz wireless links, the data center can swiftly analyze the data and provide insights for inventory management, marketing strategies, and customer trends.

IoT and Edge Computing

IoT devices generate massive amounts of data that need to be processed quickly. THz communication enables efficient server communication with edge devices.

Example: A smart home system collects data from various sensors (temperature, motion, etc.). THz links connect the edge devices to the data center for processing, allowing for real-time automation and user notifications.

Data Center Disaster Recovery and Backup Solutions

Data centers need robust backup and disaster recovery solutions. THz communication facilitates fast and efficient data transfer between data centers for backup.

Example: In the event of a system failure, a data center quickly restores data from a backup stored in another facility. THz communication enables rapid data transfer, minimizing downtime and data loss.

Telecommunication Network Management

Telecommunication providers require data centers to manage network traffic efficiently. THz communication can enhance internal communication for network management.

Example: Network traffic management systems analyze data flow and usage patterns. THz links enable real-time communication between data centers and remote base stations, optimizing resource allocation and improving service quality.
Associated PoC: Demo2

5. TeraGreen Requirements and KPIs

In this chapter, we present the requirements stemming from the TeraGreen's use cases. We then assign target values for the quantifiable parameters, as well as success criteria for the non-quantifiable ones for each use case in a tabular form.

5.1 TeraGreen Requirements

The TeraGreen requirements that result from the considered use cases are the following:

Sufficient LoS Link Distance: The LoS distance that the wireless link can cover must be large enough in order to be able to be used as a backhaul/midhaul/fronthaul solution.

Ultra-High Peak Data Rates: The THz LoS links must be able to provide ultra-high data rates comparable or exceeding those of fiber connections. The maximum achievable data rate will be measured in ideal conditions (line of sight, no interference, good environmental conditions).

Low BER: The Bit Error Rate must be equal or lower than this of fiber connections. BER is defined as the ratio of the number of bits received in error to the total number of bits transmitted during a given time interval.

Low Latency: The system must provide extremely low latency, defined as the time required for a data packet of a specified size to travel from the source to the destination.

High Availability: The system must provide high availability defined as the percentage of time during which the system is working correctly meeting the expected QoS requirements.

High Radiated Energy Efficiency: The system must exhibit very high radiated energy efficiency measured as the number of information bits that are transmitted per unit energy consumed.

High System Energy Efficiency: The system must exhibit very high total energy efficiency, taking into consideration also the energy consumed by the analogue frontends and the digital baseband processing that have the ability to minimize the overall energy consumption (e.g., with the use of 1-bit ADC).

High Spectral Efficiency: The system must provide high spectral efficiency defined as the number of information bits that are transmitted per second per Hz.

Support for 6G: The system must be able to support the anticipated capacity and latency demands of future 6G networks, fulfilling the needs and capabilities of Table 1 especially with respect to the user needs.

Reduced Interference: THz links must exhibit reduced interference compared to lower-frequency wireless solutions like mmWave. This is something to be expected, since with their short transmission range and high directionality, THz links are less prone to interference compared to lower-frequency wireless solutions like mmWave.

Narrow Beamforming: The system must exhibit highly directional beamforming, which allows for efficient spectrum use and reduced interference.

Sustainability: The system must be sustainable resulting in an environmentally friendly installation and operation in the long run, particularly in urban areas where power and space are at a premium. By reducing the need for physical infrastructure and improving spectral efficiency, THz wireless links contributes to a more sustainable network architecture.

Cost Efficiency: The system must be able to be installed and operated in a cost-efficient manner compared to fiber. THz communications enable wireless connections, reducing the need for expensive fiber-optic infrastructure. Fiber deployment in urban areas is costly due to the complexity of laying cables and dealing with physical obstructions (roads, buildings, etc.).

Rapid Deployment: The system must be able to be deployed rapidly, possibly within hours. In any case, THz-based wireless links must be able to be set up much faster than fiber-optic links. Of course, in areas where existing fiber is sparse or too costly to install, the only option will be the use of THz links, provided that their coverage will be adequate.

Security and Privacy: Security and privacy must by guaranteed. This requirement is associated mainly with the highly directional antennas that need to be utilized, which reduce the risk of eavesdropping and enhances privacy and security in the fronthaul.

High QoS: The system must provide high quality of service, which in the case of TeraGreen will be based mostly on a combination of sufficient coverage and high data rates.

5.2 TeraGreen KPIs

Based on the above requirements and the use cases considered, the TeraGreen KPIs are summarized in Table 7. The lower half of the table contains the requirements that are not associated with quantifiable metrics.

TABLE 7. TERAGREEN KPIS

KPIs	UC1	UC2	UC3	UC4
LoS link distance [m]	50-200	50-1000	Up to 100	Up to 100
Peak data rate [Tbps]	up to 1 (< 100m) up to 0.2 (>100m)	Up to 1 (< 100m) up to 0.2 (>100m)	up to 1	up to 1
Radiated energy efficiency [Tbit/Joule]	Up to 40.000(<100m link) up to 8.000 (>100m link)	Up to 40.000(<100m link) up to 8.000 (>100m link)	up to 40.000	up to 40.000
BER	10^{-12}	10^{-12}	10^{-12}	10^{-12}
Spectral efficiency [bits/s/Hz]	up to 14 (< 100m link) up to 2,9 (>100m link)	up to 14 (< 100m link) up to 2,9 (>100m link)	up to 14	up to 14
Availability	99,999% [15]	99,9% [15]	99% [15]	99,999% [15]
Antenna Alignment accuracy	< 1 degree	< 1 degree	< 1 degree	< 1 degree
Latency	<100µs [15]	1ms-50ms [15]	up to 1ms* [15]	<100µs [15]
Reduced Interference	Short transmission range and high directionality			
Narrow beamforming	Development of new MIMO architectures based on quasi-optical beamforming antennas that can work well in the THz spectrum			
Sustainability	Minimizing energy use through efficient hardware and reducing the reliance on fiber. Fiber cables are coated with plastics for protection, which contributes to plastic pollution if the cables are not properly recycled.			

Cost efficiency	Eliminating the need for expensive fiber-optic infrastructure and improving spectral efficiency.
Rapid deployment	Achieving faster set up times than the ones relating to fiber-optic links
Security and privacy	Development of highly directional links which reduce the risk of eavesdropping
High QoS	High data rates and reduced interference will result in improved quality of service (QoS)

* In case of two-way real-time interaction (e.g. high-definition video stream to AR glasses of onsite participants showing different angles of the grand event in real-time)

6. Societal Impact and Key Value Indicators (KVIs)

6.1 UN Sustainable Development Goals (SDGs)

The United Nations Sustainable Development Goals (SDGs) are a set of 17 global goals established in 2015 as part of the 2030 Agenda for Sustainable Development [16]. They are intended to provide a comprehensive blueprint for addressing the world's most pressing social, economic, and environmental challenges. Each goal is designed to foster peace, prosperity, and equity while protecting the planet and addressing the needs of current and future generations. Here is an overview of the goals:

1. **No Poverty**: This goal aims to eradicate poverty worldwide, ensuring access to essential resources, financial services, and social protection for all, particularly the most vulnerable.
2. **Zero Hunger**: Focused on ending hunger, achieving food security, and promoting sustainable agriculture, this goal seeks to ensure that everyone has sufficient, safe, and nutritious food year-round.
3. **Good Health and Well-being**: This goal promotes healthy lives and well-being for all at all ages, addressing preventable diseases, universal health coverage, and support for mental health and maternal health.
4. **Quality Education**: This goal advocates for inclusive, equitable, and quality education, with a focus on lifelong learning opportunities for all, reducing educational disparities.
5. **Gender Equality**: This goal aims to empower women and girls, advocating for equality across political, economic, and social realms while combating discrimination and violence against women.
6. **Clean Water and Sanitation**: Recognizing the importance of water, this goal seeks universal access to clean water and sanitation, while also improving water management practices to protect ecosystems.
7. **Affordable and Clean Energy**: This goal promotes universal access to affordable, reliable, and modern energy services, emphasizing renewable energy sources and improved energy efficiency.
8. **Decent Work and Economic Growth**: This goal supports inclusive and sustainable economic growth, productive employment, and decent work for all, emphasizing the reduction of informal work and unemployment.
9. **Industry, Innovation, and Infrastructure**: Focused on building resilient infrastructure, promoting inclusive industrialization, and fostering innovation, this goal is essential for sustained economic growth and development.
10. **Reduced Inequalities**: This goal addresses income and opportunity disparities within and among countries, promoting social, economic, and political inclusion for all.
11. **Sustainable Cities and Communities**: With urbanization on the rise, this goal promotes inclusive, safe, resilient, and sustainable urban living, with access to housing, transportation, and green spaces.
12. **Responsible Consumption and Production**: This goal emphasizes sustainable consumption and production patterns, encouraging efficient resource use and reducing waste and pollution.
13. **Climate Action**: This goal underscores the need for urgent action to combat climate change and its impacts, including adaptation and resilience measures.
14. **Life Below Water**: Aimed at conserving oceans, seas, and marine resources, this goal addresses pollution, overfishing, and biodiversity loss in marine environments.

15. **Life on Land**: This goal seeks to protect, restore, and promote sustainable use of terrestrial ecosystems, combat desertification, and halt biodiversity loss.
16. **Peace, Justice, and Strong Institutions**: This goal advocates for inclusive societies with strong institutions, promoting peace, justice, and accountability at all levels.
17. **Partnerships for the Goals**: This goal calls for strengthening global partnerships to achieve the SDGs, including financial, technological, and capacity-building support for developing countries.

The SDGs are interconnected, and achieving one often contributes to progress in others, fostering an integrated approach to sustainable development. Together, they serve as a roadmap for nations, organizations, and individuals to work towards a better and more equitable world.

The 17 Sustainable Development Goals include a total of 169 targets and 231 unique indicators that break down as follows:

- **Targets**: There are 169 targets that serve as specific objectives within each SDG, outlining the precise achievements needed to realize each goal by 2030. These targets cover various dimensions, such as specific policy actions, measurable outcomes, and essential support mechanisms.
- **Indicators**: There are also 231 unique indicators [17] designed to measure progress toward each target. These indicators provide a framework for countries to collect, track, and report data, allowing for an assessment of global progress across diverse areas, from reducing poverty rates to increasing renewable energy use and promoting gender equality.

Each SDG has multiple targets and indicators, ensuring a comprehensive approach that considers economic, social, and environmental aspects of sustainable development. The framework is overseen by the UN Statistical Commission, which regularly reviews and refines indicators to improve accuracy and relevance, ensuring they are robust enough to guide global progress towards the SDGs.

The UN statistics division metadata repository [18] provides metadata on the global SDG indicators, with detailed descriptions of each indicator's methodology, measurement criteria, and data sources. This is particularly useful for understanding how progress is tracked and measured.

6.2 Societal Impact of TeraGreen’s Innovative Technologies

TeraGreen’s THz wireless links promise a broad social impact by advancing core societal values such as digital inclusion, environmental sustainability, public safety, economic development, and quality of life.

Digital Inclusion and Access

By offering affordable high-speed connectivity, TeraGreen’s proposed wireless links will help ensure that all communities—urban, rural, and even attendees at large events—have access to the internet and the myriad benefits of digital connectivity. This fosters a more inclusive digital society, empowering people with access to information, services, and economic opportunities.

Environmental Responsibility

Reducing reliance on fiber infrastructure and promoting wireless data solutions lowers environmental impact by minimizing resource consumption and land disturbance. TeraGreen’s proposed solution for energy-efficient data transmission supports the EU’s sustainability goals, promoting responsible use of resources across telecommunications.

Public Health and Safety

The high-speed, low-latency nature of THz links can support telemedicine in rural areas and reliable communication for emergency response teams. Enhanced connectivity can improve access to healthcare and public safety services, especially in remote or underserved areas.

Economic Growth and Workforce Development

The deployment of THz wireless links will spur growth in telecommunications, support remote work and learning, and create job opportunities, including training for new technology-focused roles. This technological shift aligns with workforce development needs, supporting an economy that is both innovative and inclusive.

Enhanced Quality of Life

With immersive XR, reliable broadband, and responsive data centers, THz links create new ways for individuals to experience entertainment, engage in online activities, and enjoy the benefits of digital society. The quality-of-life improvements that come from inclusive, accessible digital experiences enhance social cohesion and cultural participation.

6.3 TeraGreen KVIs

TeraGreen's THz links are being developed for use cases that reflect pressing societal needs: supporting small cell deployments, enabling fixed wireless access, enhancing immersive extended reality experiences at large events, and optimizing data centre operations through wireless infrastructure. Each of these applications not only improves network efficiency and affordability but also carries significant societal benefits. By examining the key value indicators (KVIs) associated with each use case, we can appreciate the broader social impact of TeraGreen's innovations.

We need to stress-out that our intention in the following description of Key Value Indicators (KVIs) and their alignment with UN Sustainable Development Goals (SDGs) is to provide a **theoretical framework** on the KVIs that can be associated with the TeraGreen proposed solutions, and on the methods that can be used to evaluate certain metrics and success criteria, based on which these KVIs could be assessed, when the TeraGreen proposed solutions are widely used. Actual evaluation of the following KVIs is impossible within a limited-budget and limited-time research project like TeraGreen.

6.3.1 KVIs for UC1: Fronthaul in ultra-dense small cell networks

Key Value: Facilitating Dense Urban Connectivity

In dense urban environments, the demand for high-capacity, low-latency mobile networks are surging, driven by 5G and future 6G applications. Small cells, which provide localized coverage in high-traffic areas, require efficient backhaul/fronthaul solutions. Fiber, while reliable, faces challenges related to deployment costs and urban disruptions. THz links offer a viable alternative, enabling rapid, cost-effective deployment with high performance.

Key Value Indicators (KVIs)

1. **Network Throughput (Gbps)**: Measures the capacity of small cells supported by THz links compared to fiber.
2. **Deployment Cost Savings (€)**: Quantifies the reduction in costs achieved by using wireless links instead of laying fiber.
3. **Time to Deployment (Days)**: Assesses how quickly THz links can be installed and operational compared to traditional methods.

Social Impact

- **Enhanced Network Performance**: THz links improve urban connectivity, supporting critical services like IoT, autonomous vehicles, and smart city infrastructure.
- **Affordable Expansion**: Cost-efficient solutions enable network operators to expand coverage without significantly increasing service costs for consumers.
- **Reduced Urban Disruption**: Wireless deployment avoids road excavations and minimizes environmental and societal inconvenience.

Alignment with UN SDGs

1. **SDG 9 (Industry, Innovation, and Infrastructure)**: Indicator 9.c.1 (Population covered by mobile networks) reflects the increased reach and efficiency of urban connectivity.
2. **SDG 11 (Sustainable Cities and Communities)**: Indicator 11.3.1 (Inclusive urbanization) aligns with reduced urban disruption and improved access to services.
3. **SDG 12 (Responsible Consumption and Production)**: Indicator 12.2.1 (Resource efficiency) relates to reduced material usage compared to fiber deployments.

Broader Impacts

This use case also promotes **economic development** by enabling high-speed mobile connectivity, a foundational driver of digital business and innovation in urban spaces. By fostering connectivity in dense areas, TeraGreen supports urban communities, local businesses, and innovation hubs, contributing to a more inclusive urban economy.

6.3.2 KVIs for UC2: High throughput fixed wireless access (FWA)

Key Value: Bridging the Digital Divide

Access to high-speed internet is essential for modern life. However, rural and underserved urban areas often face connectivity gaps due to the high cost and logistical challenges of fiber installation. THz-based FWA provides a scalable, cost-effective solution, offering high-speed broadband without the need for extensive physical infrastructure.

Key Value Indicators (KVIs)

1. **Percentage of Underserved Areas Connected (%)**: Measures the geographical reach of FWA deployments.
2. **Guaranteed Average Internet Speed Delivered (Mbps)**: Quantifies the guaranteed quality of service provided to end-users.
3. **Adoption Rate Among Low-Income Households (%)**: Tracks how effectively FWA services reach economically disadvantaged populations.

Social Impact

- **Rural Connectivity**: FWA enables rural communities to access online education, telemedicine, and e-commerce opportunities, addressing systemic inequalities.
- **Urban Last-Mile Access**: In dense cities, FWA bridges gaps where fiber deployment is impractical or expensive.
- **Economic Empowerment**: Affordable, reliable internet fosters innovation and entrepreneurship, particularly in underserved regions.

Alignment with UN SDGs

1. **SDG 4 (Quality Education)**: Indicator 4.a.1 (Schools with internet access) reflects the potential for FWA to transform educational opportunities.
2. **SDG 3 (Good Health and Well-being)**: Indicator 3.8.1 (Access to essential health services) highlights the role of connectivity in supporting telemedicine.
3. **SDG 10 (Reduced Inequalities)**: Indicator 10.2.1 (Empowerment of marginalized groups) aligns with the equitable distribution of digital resources.

Broader Impacts

TeraGreen's high throughput fixed wireless access solutions will drive sustainable economic development by connecting local businesses to wider markets and resources. By empowering individuals to participate fully in digital services, FWA enhances social and economic integration in rural communities, promoting regional stability and growth.

6.3.3 KVIs for UC3: Live immersive XR in large-scale events

TeraGreen's THz links enable immersive XR experiences, such as VR and AR, at live events. Large-scale events, like concerts and sports games, benefit from high-speed, low-latency connectivity, allowing real-time XR interactions that make events more engaging and accessible.

Key Value: Enhancing Cultural Participation

Live XR experiences revolutionize how audiences engage with cultural, sports, and entertainment events. The THz links proposed by TeraGreen will enable the real-time delivery of personalized, high-resolution immersive content, overcoming bandwidth limitations that restrict traditional wireless technologies.

Key Value Indicators (KVIs)

1. **Event Engagement Rate (%)**: Measures attendee interaction with immersive XR content.
2. **Infrastructure Cost Savings (€)**: Evaluates the reduction in event setup costs enabled by wireless solutions.
3. **Accessibility Score for People with Disabilities (%)**: Assesses the inclusivity of XR experiences for diverse audiences.

Social Impact

- **Democratization of Cultural Experiences**: Immersive XR makes cultural and entertainment events accessible to remote and physically challenged audiences.
- **Economic Growth in Creative Industries**: Innovative XR experiences boost revenue streams for artists, event organizers, and related industries.
- **Inclusivity and Personalization**: Tailored XR content allows users to experience events in unique, personalized ways.

Alignment with UN SDGs

1. **SDG 11 (Sustainable Cities and Communities)**: Indicator 11.4.1 (Cultural heritage preservation) highlights the role of XR in enhancing cultural appreciation.
2. **SDG 10 (Reduced Inequalities)**: Indicator 10.3.1 (Reduction in discrimination) relates to accessibility features in XR technology.
3. **SDG 8 (Decent Work and Economic Growth)**: Indicator 8.9.1 (Tourism and cultural promotion) underscores the economic benefits of immersive XR.

Broader Impacts

XR experiences enable public events to reach wider audiences, offering inclusive cultural experiences and promoting tourism. By increasing social cohesion through shared experiences, TeraGreen contributes to community building, enhancing the sense of connectedness and belonging within diverse populations.

6.3.4 KVIs for UC4: Wireless Data Centers

Key Value: Sustainable and Scalable Infrastructure

As data demand surges, data centers face increasing challenges related to scalability, cost, and environmental impact. TeraGreen's THz wireless links will replace traditional wired interconnects, providing flexible, energy-efficient solutions that support modular growth and reduced resource consumption.

Key Value Indicators (KVIs)

1. **Reduction in Cable Use (%)**: Measures the decrease in physical cabling due to wireless deployment.
2. **Energy Efficiency (Watts/bit)**: Tracks the reduction in energy consumption for data transmission.
3. **Modular Scalability Index**: Evaluates the adaptability of data center capacity to changing demands.

Social Impact

- **Environmental Sustainability**: Wireless links reduce material waste and lower energy consumption, contributing to greener operations.
- **Cost-Effective Scalability**: Flexible deployment allows data centers to adapt to increasing demand without significant overhauls.
- **Support for Digital Services**: Improved data center efficiency enhances the reliability and affordability of cloud-based services.

Alignment with UN SDGs

1. **SDG 12 (Responsible Consumption and Production)**: Indicator 12.5.1 (Waste reduction) aligns with minimized cabling and material use.
2. **SDG 13 (Climate Action)**: Indicator 13.2.2 (Emission reductions) reflects energy-efficient operations.
3. **SDG 9 (Industry, Innovation, and Infrastructure)**: Indicator 9.4.1 (Upgrade to sustainable processes) relates to scalable, efficient infrastructure.

Broader Impacts

TeraGreen's wireless THz solutions address environmental sustainability by reducing the need for physical infrastructure and improving energy efficiency in data centers. As data centers are major energy consumers, this approach contributes to climate action and responsible consumption, supporting global sustainability goals by making digital infrastructure less environmentally taxing.

6.3.5 Cross-Cutting KVIs

There are certain key values that are common to all use cases. These are mainly the affordability and the sustainability of the solution, which are described in the following paragraphs.

Key Value: Affordability

Affordability refers to the reduction in costs for deploying, maintaining, and accessing high-speed communication networks enabled by THz wireless links. The elimination of extensive fiber installations and reduced reliance on expensive infrastructure makes TeraGreen's solutions particularly appealing in cost-sensitive environments, such as underserved rural areas or budget-constrained urban neighborhoods.

Key Value Indicators (KVIs)

1. **Reduction in Per-User Connectivity Costs (€)**: Tracks the average cost savings per user, reflecting the economic efficiency of THz-based solutions compared to traditional fiber services.
2. **Cost Efficiency of Infrastructure Deployment (€ per km)**: Measures the expense of deploying THz wireless links compared to laying fiber over a similar distance.
3. **Adoption Rates in Cost-Sensitive Regions (%)**: Monitors how effectively these affordable solutions are implemented in economically disadvantaged areas.

Social Impact

- **Economic Inclusion**: Affordable connectivity enables greater access to essential services like education, healthcare, and e-commerce, bridging the gap for underserved populations.
- **Business Innovation**: Reduced costs empower small and medium-sized enterprises (SMEs) to access advanced digital tools and compete in global markets.
- **Government and Policy Support**: The affordability of THz deployments attracts public investment and policy incentives to expand connectivity.

Alignment with UN SDGs

1. **SDG 1 (No Poverty)**: Affordable communication helps alleviate poverty by enabling access to education and economic opportunities.
2. **SDG 10 (Reduced Inequalities)**: Promotes equity by ensuring cost-effective connectivity for marginalized populations.
3. **SDG 9 (Industry, Innovation, and Infrastructure)**: Encourages the construction of cost-efficient digital infrastructure to support inclusive industrialization.

Key Value: Sustainability

Sustainability addresses the environmental benefits of THz communications, including reduced material use, lower energy consumption, and minimized physical disruption during deployment. Unlike fiber networks that require extensive civil engineering works, THz wireless links offer a greener alternative.

Key Value Indicators (KVIs)

1. **Reduction in Carbon Footprint (kg CO_2/connection)**: Measures the environmental impact of THz deployment versus fiber networks.
2. **Resource Utilization Efficiency (Material Usage per Connection)**: Tracks the reduction in physical materials like copper and plastics due to wireless deployment.
3. **Energy Efficiency in Data Transmission (Watts/bit)**: Monitors how much energy is consumed per unit of data transmitted, ensuring greener operations.

Social Impact

- **Environmental Protection**: Wireless deployment reduces ecological disruption caused by fiber installation, such as deforestation, land excavation, and waterway interference.
- **Climate Action**: The energy-efficient TeraGreen solutions will support global efforts to mitigate climate change by reducing greenhouse gas emissions.
- **Circular Economy**: Lower resource utilization promotes recycling and reduces e-waste in the long term.

Alignment with UN SDGs

1. **SDG 13 (Climate Action)**: THz communications contribute to global efforts to reduce emissions and promote sustainable technology adoption.
2. **SDG 12 (Responsible Consumption and Production)**: Reduces waste and promotes efficient resource use.
3. **SDG 15 (Life on Land)**: Avoids the environmental degradation often caused by physical cable installations.

7. Summary and conclusions

This deliverable presented TeraGreen's objectives, innovations, use cases, requirements, KPIs and KVIs. We started with a general presentation of the TeraGreen project, which is advancing the potential of terahertz (THz) wireless communications as a sustainable and cost-efficient alternative to fiber optics. We then presented briefly TeraGreen's objectives which centre on reducing deployment costs, promoting environmental sustainability, and extending connectivity while supporting future demands from data-intensive applications. Next, we summarized the project's innovations, which include high-capacity transceivers, dynamic beamforming and energy-efficient designs, that enable THz links to overcome propagation challenges and achieve terabit-per-second (Tbps) data rates. By focusing on critical use cases—small cell fronthaul, Fixed Wireless Access (FWA), immersive Extended Reality (XR) at large-scale events, and wireless data centers—we then presented the ways that the project addresses the growing need for high-speed, low-latency, and energy-efficient connectivity. From these use cases we extracted the associated requirements, and we assigned specific Key Performance Indicators (KPIs) that will be used to assess the proposed solutions. TeraGreen's innovations directly contribute to global goals like the UN Sustainable Development Goals (SDGs) by fostering equitable access to technology, minimizing carbon footprints. Therefore, by integrating technical performance with societal value, TeraGreen establishes a roadmap for THz technology to transform telecommunications while addressing critical global challenges. As the digital landscape evolves with the advent of 6G, TeraGreen stands as a key enabler of a connected, sustainable future, bridging the gap between cutting-edge research and real-world societal benefits.

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