MT Division, TEC

STUDY PAPER ON

TERAHERTZ (THz) COMMUNICATION & SENSING

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TELECOMMUNICATION ENGINEERING CENTRE
KHURSHID LAL BHAWAN, JANPATH
NEW DELHI - 110001
INDIA

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तृप्ति सकसेना,
TRIPTI SAXENA
वरिष्ठ उप महानिदेशक एवं प्रमुख
Sr. Deputy Director General & Head

भारत सरकार
दूरसंचार विभाग
दूरसंचार अभियांत्रिकी केंद्र
खुर्शीद लाल भवन, जनपथ, नई दिल्ली 110001
Govt. of India
Department of Telecommunications
Telecom Engineering Centre
Khurshid Lal Bhawan, Janpath, New Delhi-110001

Foreword

It gives me great pleasure to pen this foreword for the release of the study paper on **"Terahertz Communication and Sensing"**—a subject that holds tremendous promise for shaping the next frontier in advanced wireless communication and sensing technologies.

In my capacity as Senior Deputy Director General and Head of the Telecommunication Engineering Centre (TEC), I have had the privilege of witnessing the exceptional progress of telecommunications in India. From copper wires to optical fibres, from 2G to 5G and now towards the 6G vision—each leap has been driven by innovation, collaboration, and a deep commitment to pushing the boundaries of science. The emergence of terahertz (THz) frequencies offers yet another opportunity to redefine what's possible.

The THz spectrum, straddling the gap between the microwave and infrared bands, is expected to become a critical enabler for ultra-high-speed data transmission, beyond what current wireless systems offer. Its unique characteristics—such as ultra-wide bandwidth, low latency, and high spatial resolution—can unleash new applications in high-capacity communication, high-precision imaging, non-invasive sensing, security scanning, and even biomedical diagnostics.

This study paper is the result of comprehensive research and technical exploration carried out by domain experts under the aegis of TEC. It offers an insightful overview of the technical foundations, key challenges, and the evolving global ecosystem around terahertz technologies. More importantly, it offers a perspective rooted in India's aspirations for indigenous R&D and leadership in futuristic communication technologies.

As India forges ahead with its vision for Atmanirbhar Bharat in the telecommunications sector, harnessing the potential of emerging technologies becomes an essential part of our strategy. This paper is a commendable step in facilitating dialogue among academia, industry, and government stakeholders. It not only brings technical clarity to a complex domain but also encourages stakeholders to participate in building a robust roadmap for terahertz development in India.

I extend my appreciation to the contributors of this study paper for their diligence, expertise, and foresight. It is my firm belief that such knowledge initiatives will act as springboards to greater innovation, standardization, and deployment frameworks that benefit both our industry and citizens.

Let this paper serve not just as a reference document, but as a call to action—urging all of us to explore, invest, and collaborate in unlocking the transformative potential of terahertz communication and sensing.

(Ms. Tripti Saxena)

ISO 9001:2015
दूरभाषा/Tel.:+91-11-23320252
ई-मेल/E-mail: srddg.tec@gov.in वेबसाइट/Website : www.tec.gov.in

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Abstract

Overview of Terahertz Communication:

Communication forms the foundation of human civilization, allowing the sharing of ideas, information, and emotions that fuel advancement in many areas. From spoken language to advanced digital networks, the evolution of communication technologies has reshaped how individuals, industries, and societies interact. The RF spectrum has long been the backbone of communication, supporting various technologies from analog radio transmissions to sophisticated cellular networks. In the modern age, wireless communication is at the cutting edge, driving smooth connectivity and long-distance data transmission. With the emergence of data-intensive applications, demands for faster speeds and higher bandwidth continue to rise, particularly in applications such as real-time video streaming, virtual reality, and cloud computing, conventional radio frequency (RF) technologies bands—ranging from kilohertz to gigahertz frequencies—have become increasingly congested & face limitations in meeting these escalating needs. To address these challenges and unlock unprecedented capabilities in wireless transmission, researchers and engineers have turned their focus toward Terahertz (THz) communication, a promising frontier in electromagnetic spectrum utilization which has led to the exploration of terahertz frequencies

Terahertz (THz) communication is a cutting-edge wireless technology that utilizes electromagnetic waves within the 0.1–10 THz frequency range or wave lengths between 3 mm and 30 μm. The significance of this frequency range lies in its ability to support extremely high data rates, ranging from tens to hundreds of gigabits per second (Gbps), far surpassing the capabilities of current wireless technologies such as 5G. Positioned between microwave and infrared waves, THz communication enables ultra-high-speed data transfer, making it ideal to play a crucial role for next-generation wireless networks like 6G and beyond.

The transition to high-speed and high-capacity wireless communication is driven by the necessity of handling enormous amounts of data efficiently. As devices become smarter and interconnected through the Internet of Things (IoT) and Artificial Intelligence (AI)-driven networks, higher frequency bands, such as THz waves, provide the bandwidth required for handling vast data streams without bottlenecks. Additionally, the importance of data speed is evident in fields such as telemedicine, where ultra-fast communication facilitates remote surgeries and diagnostics, and in autonomous vehicles, where real-time traffic updates and sensor data require instantaneous transmission for safe navigation.

Although THz communication holds great transformative potential, it encounters numerous challenges such as significant atmospheric absorption, signal loss, and technological hurdles in the fabrication of THz devices. Unlike lower frequency bands, THz waves exhibit higher propagation losses, making efficient transmission over long distances difficult. Overcoming these obstacles necessitates advancements in signal processing, modulation techniques, and antenna designs to ensure reliable communication in diverse environments. Recent breakthroughs in graphene-based THz transceivers, metasurface antennas, and photonic-based signal generation have provided innovative solutions to mitigate these limitations, making THz communication more viable for future wireless applications.

1. Introduction

1.1 Evolution of Communication

Communication has been the foundation of human civilization, shaping social interactions, governance, economic progress, and technological advancements. From primitive methods of signaling to sophisticated high-speed networks, communication has evolved into an essential driver of global connectivity. While THz communication offers immense transformative potential, it is hindered by various challenges, including substantial atmospheric absorption, signal degradation, and technical difficulties in developing THz devices. As modern technology continues to progress, communication systems have transitioned from traditional analog exchanges to digital networks, revolutionizing the way individuals, enterprises, and governments interact. In recent years, innovations such as artificial intelligence, wireless networks, and high-speed data transmission have paved the way for the development of 6G, the next-generation communication system. The transformation from basic forms of interaction to ultra-fast, intelligent, and secure communication technologies highlights the ever-growing significance of communication.

The 19th and 20th centuries saw revolutionary progress in communication driven by the rise of electrical technologies. The invention of the telegraph in 1837 by Samuel Morse introduced long-distance messaging using coded signals transmitted via electrical wires. This advancement boosted global interactions, allowing swift business transactions and efficient diplomatic collaboration. The telephone, pioneered by Alexander Graham Bell in 1876, transformed interpersonal communication by allowing individuals to speak directly, eliminating the limitations of written correspondence. The invention of radio waves by Guglielmo Marconi in 1895 further expanded communication by introducing wireless transmission, leading to the emergence of radio broadcasting, emergency messaging systems, and entertainment networks. The rise of television in 1927 brought mass media communication into households, creating a global platform for news dissemination, cultural programming, and political broadcasts.

In the 1970s, the term "terahertz" was coined to refer to the range of spectral frequencies linked to instruments such as interferometers and diode detectors. Prior to the mid-1980s, the technologies for infrared and microwave waves, which flanked the terahertz band, were well-established, and their understanding was advanced. However, knowledge of the terahertz band itself was still limited. Additionally, because terahertz waves overlap both the millimeter wave band at the longer wavelengths and the infrared band at the shorter wavelengths, it represents a transitional zone—bridging macroscopic classical theory with microscopic quantum theory, as well as electronics with photonics. This area became known as the "terahertz gap" in the electromagnetic spectrum, though its boundaries were not clearly defined at the time.

The evolution of mobile networks progressed through different generations, each introducing innovations to enhance communication capabilities. 1G, developed in the 1980s, provided basic analog voice communication. 2G, introduced in the 1990s, integrated digital messaging (SMS) and improved call quality. 3G, emerging in the 2000s, enabled mobile internet, allowing users to browse websites and access digital services from portable devices. 4G, implemented in the 2010s, accelerated broadband connectivity, supporting video streaming, high-speed downloads, and seamless global communication. The introduction of 5G, in the 2020s, revolutionized wireless communication by offering ultra-fast data transmission, reduced latency, and enhanced connectivity for Internet of Things (IoT) applications.

Despite the remarkable advancements of 5G, the growing demand for instantaneous data exchange, immersive technologies, and intelligent automation has led to the development of 6G, the future generation of wireless communication. 6G is envisioned to deliver unprecedented data speeds, ultra-low latency, and AI-integrated networking, surpassing the capabilities of its predecessors. One of the defining characteristics of 6G is its utilization of Terahertz (THz) frequencies, enabling transmission speeds exceeding 100 Gbps, facilitating real-time communication and advanced computing applications. The integration of Artificial Intelligence (AI) in 6G networks will enable autonomous network optimization, predictive analytics, and seamless device interactions, enhancing efficiency and reliability.

The applications of 6G will redefine industries and societal functions, supporting advanced innovations such as smart cities, autonomous vehicles, precision healthcare, and immersive virtual experiences. High-speed connectivity in urban infrastructure will enable intelligent traffic systems, automated energy management, and interconnected sensors for environmental monitoring. In the healthcare sector, AI-assisted diagnostics, robotic surgeries, and remote patient care will benefit from instant data processing and high-resolution imaging supported by 6G connectivity. The evolution of augmented reality (AR) and virtual reality (VR) will expand interactive experiences, enabling holographic telepresence, realistic simulations, and immersive learning environments.

Despite its transformative potential, 6G faces challenges related to device fabrication, regulatory standardization, cyber security threats, and energy efficiency. The development of high-frequency transceivers requires innovations in graphene-based technologies, metasurfaces, and quantum-enhanced components to ensure optimal performance and signal integrity. The allocation of THz spectrum bands for public and commercial use must align with global regulatory policies to prevent interference and ensure network stability. Cyber security concerns, such as data breaches, AI-driven cyber-attacks, and privacy risks, must be addressed to protect sensitive information and maintain secure connectivity. Additionally, advancements in energy-efficient processing units and sustainable network architectures will be necessary to reduce environmental impact and enhance long-term viability.

As 6G technology progresses, interdisciplinary collaborations among scientists, engineers, policymakers, and industry leaders will drive innovations in quantum communication, AI-powered security, and ultra-fast wireless infrastructure. The integration of quantum cryptography in 6G networks will enhance security protocols, ensuring encrypted data exchanges resistant to cyber threats. The convergence of AI-driven predictive analytics with edge computing will enable real-time decision-making capabilities, optimizing digital interactions and reducing processing delays.

The future of communication continues to evolve, shaping interconnected societies and fostering technological progress. From ancient cave paintings to AI-enhanced wireless communication, the transformation of information exchange has defined human history. The emergence of 6G represents the next chapter in telecommunication, promising global integration, intelligent automation, and secure digital networking. As researchers and developers continue to refine 6G capabilities, communication will remain a fundamental force driving innovation, collaboration, and societal growth in the digital age.

2. Fundamentals of Terahertz Waves

2.1 Electromagnetic Spectrum Overview

The electromagnetic (EM) spectrum refers to the range of all possible frequencies of electromagnetic radiation. Electromagnetic waves are oscillations of electric and magnetic fields that propagate through space and carry energy. The classification of the EM spectrum is as follows:

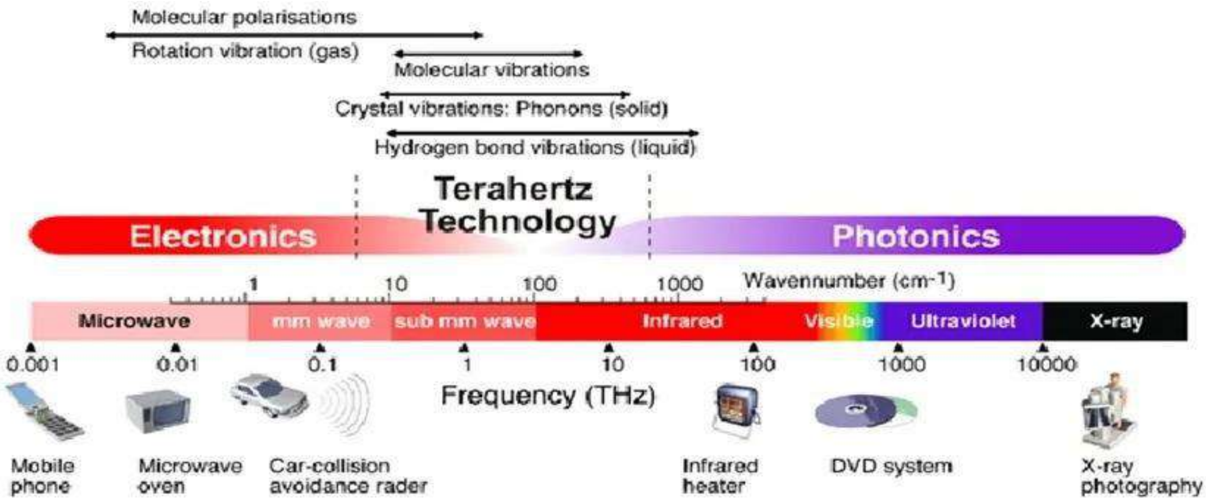


Figure 2: Classification of EM wave

2.2 Introduction to Terahertz Communication

The band above 275 GHz is the main part of terahertz band. Terahertz waves, also known as Submillimetre radiation usually refers to the frequency band between 0.1 THz-10 THz with the corresponding wavelength of 0.03 mm-3 mm, making THz waves shorter than microwave frequencies but longer than infrared radiation. Positioned between microwave and infrared frequencies, THz waves offer a unique combination of high data transmission rates and low latency, making them a promising candidate for next-generation communication systems.

The THz spectrum has garnered significant interest for applications in high-speed communication, sensing, and imaging due to its ability to support very high data transfer rates. For example, THz waves can potentially enable data transmission rates of tens of gigabits per second (Gbps). Additionally, THz frequencies exhibit unique properties, such as being sensitive to materials and providing non-invasive imaging capabilities, making them valuable for scientific and medical research.

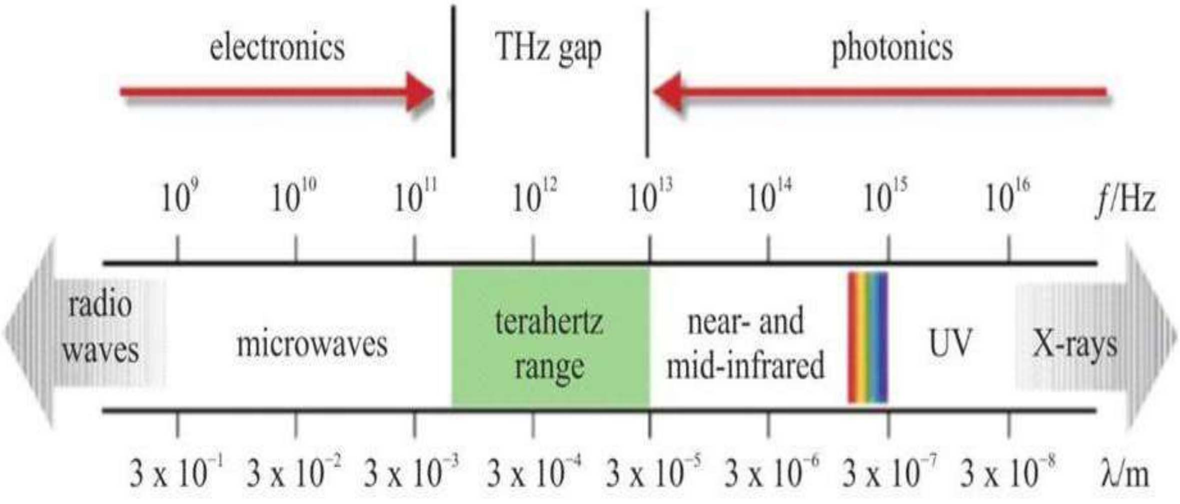


Figure1: Position of terahertz band in the radio spectrum[Report ITU-R SM.2352-1]

Comparison of Terahertz Waves with Radio Waves and Infrared waves are given in Table 1 below:-

Table 1 :- Comparison of THz waves with radio waves and infrared radiation

Property	**Radio Waves (3 kHz – 300 GHz)**	**Terahertz Waves (0.1 THz – 10 THz)**	**Infrared Radiation (0.3 THz – 430 THz)**
Frequency Range	3 kHz to 300 GHz	0.1 THz to 10 THz	0.3 THz to 430 THz
Wavelength	1 mm to 100 km	30 µm to 3 mm	1 mm to 1.3 µm
Position in Spectrum	Low-frequency, below microwaves	Between microwave and infrared	Between terahertz and visible light
Applications	Radio broadcasting, TV signals, Wi-Fi, cellular networks	High-speed wireless communication, imaging, spectroscopy, sensing	Thermal imaging, remote sensing, communication
Propagation Characteristics	Can travel long distances, less attenuation	Limited range due to atmospheric absorption	Limited range, mostly absorbed by water vapor
Data Transfer Rate	Low to moderate (up to a few Gbps)	Extremely high (up to tens of Gbps)	Moderate to high (up to several Gbps)
Penetration Ability	Can penetrate buildings, walls	Limited penetration (e.g., blocked by walls)	Limited penetration (e.g., absorbed by water)
Atmospheric Absorption	Low	High, especially due to water vapor	Moderate to high (strong absorption by water vapor)
Technology Maturity	Well-established, widely used	Emerging, experimental phase	Well-established, used in thermal imaging

2.3 Transmission Characteristics of Terahertz Waves:-

a) **High Permittivity: -** The higher frequencies in the terahertz range have a high penetration ability compared with visible light. Hence, terahertz electromagnetic waves have lower transmission losses in the atmosphere and can penetrate many non-metallic materials, such as paper, plastics, fabrics, etc. This makes the terahertz band have a wide range of applications in the fields of non-destructive testing, safety inspection and medical imaging. Additionally, because their wavelengths exceed the size of airborne dust or dirt particles, these signals experience minimal transmission loss in dusty or smoky environments. This makes them ideal for imaging in challenging conditions such as fire rescue operations or desert windstorms.

b) **High Spatial Resolution**: - Electromagnetic waves in the terahertz band have high resolution. The terahertz band has a wavelength range from millimeter to micron, which is shorter than the RF and microwave bands, so it has higher resolution. This makes the terahertz band very important for high-resolution imaging and spectral analysis.

c) **Short wavelength and good directivity: -** Compared with the microwave, the frequency is higher which could be used as the communication carrier to carry more information in a unit of time. With shorter wavelength and good directivity, it is very promising to be used in certain wireless communication application scenarios.

d) **Safety:-** Terahertz radiation has photon energy in the milli-electron volt range, which is much lower than the energy required to break chemical bonds. As a result, it doesn't cause ionization, making it especially suitable for examining biological samples and conducting human body scans. Moreover, because water strongly absorbs terahertz waves, these signals can't penetrate human skin, ensuring their safety for medical applications like detecting skin-related conditions.

e) **Rapid attenuation in water: -** Radio signals exceeding 275 GHz are heavily absorbed by water, a characteristic that holds potential for medical use. Since tumor tissues contain water levels that differ notably from those of healthy cells, analyzing this water content can help identify and locate cancerous growths.

2.4 Advantages of using Terahertz Wave:-

The terahertz band is between microwave and infrared light, and has many unique features. The main Advantages of THz communication include the following aspects: -

a. **Wide bandwidth:** Terahertz band has a wide range of spectrum resources, which can provide a data transmission rate as high as several hundred Gbps, far exceeding the traditional wireless communication technology.

b. **Low energy consumption:** The electromagnetic wave used in terahertz communication requires low energy, and has little impact on the human body and the environment, which can also save energy.

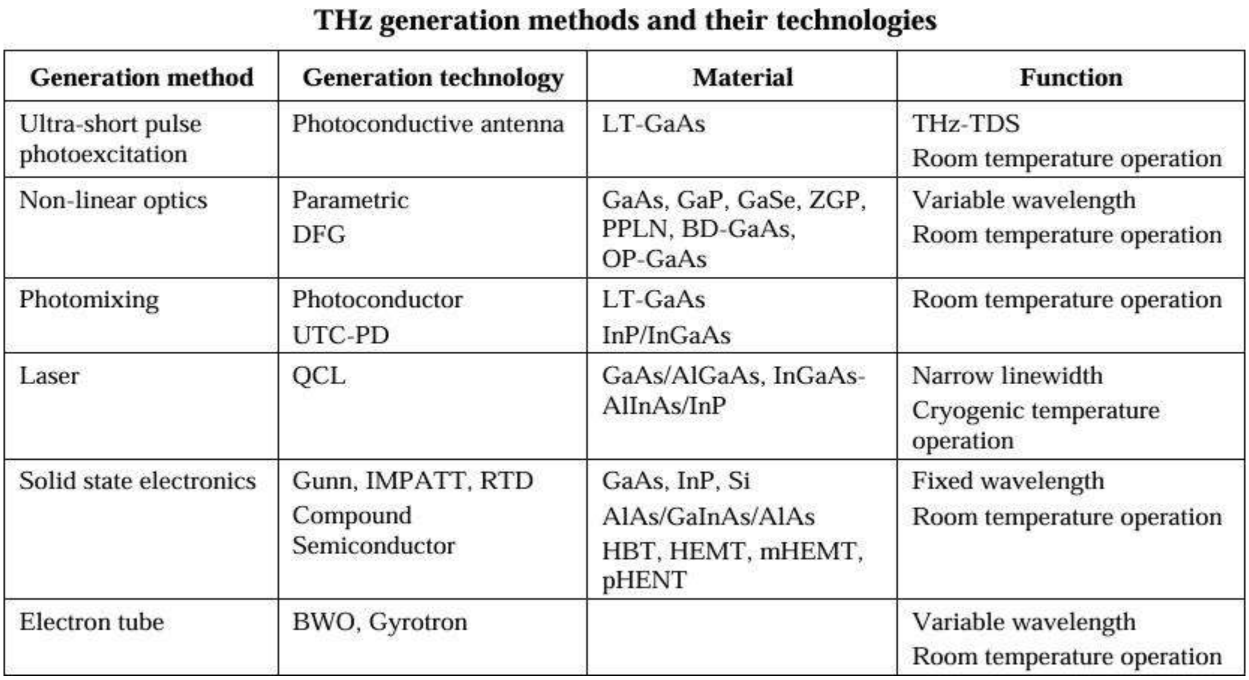
c. **Strong penetration:** Terahertz waves can penetrate many non-metallic materials, such as paper, Plastic, cloth, etc. But the penetration of metals and water and other materials is poor. This makes terahertz communication have advantages in some special environments, such as medical imaging and security detection.

d. **High security:** Terahertz waves are easily disturbed during transmission, and it is difficult to be eavesdropped and disturbed. This makes THz communications have potential in fields with high security requirements, such as military communications, security monitoring and so on.

2.5 Generation and detection of terahertz waves:

There are several methods for generating terahertz waves, with optical excitation and electron excitation being the most prevalent. Optical excitation involves using a laser source to produce terahertz waves. In this process, a strong laser beam is directed onto a nonlinear optical crystal or gas, where the light's frequency is either doubled or mixed. By selecting the right material, the frequency can be converted into the terahertz range. This approach can generate high-power terahertz waves, but it requires complex equipment and technology. Electron excitation, on the other hand, involves generating terahertz waves through electron beams. A high-energy electron beam is accelerated and directed through a metal or semiconductor thin film. As the electron beam interacts with the thin film, terahertz waves are produced. While this method generates high-frequency terahertz waves, it demands high-energy electron beams and sophisticated accelerator systems.

Following figure summarizes various THz wave generation methods and corresponding technologies:-



THz generation methods and their technologies

Generation method	Generation technology	Material	Function
Ultra-short pulse photoexcitation	Photoconductive antenna	LT-GaAs	THz-TDS Room temperature operation
Non-linear optics	Parametric DFG	GaAs, GaP, GaSe, ZGP, PPLN, BD-GaAs, OP-GaAs	Variable wavelength Room temperature operation
Photomixing	Photoconductor UTC-PD	LT-GaAs InP/InGaAs	Room temperature operation
Laser	QCL	GaAs/AlGaAs, InGaAs-AlInAs/InP	Narrow linewidth Cryogenic temperature operation
Solid state electronics	Gunn, IMPATT, RTD Compound Semiconductor	GaAs, InP, Si AlAs/GaInAs/AlAs HBT, HEMT, mHEMT, pHENT	Fixed wavelength Room temperature operation
Electron tube	BWO, Gyrotron		Variable wavelength Room temperature operation

Figure3: Terahertz Generation Method and their technologies.[Report ITU-R SM.2352-1]

When it comes to detecting and receiving terahertz waves, various techniques are used, with terahertz wave detectors being the most common. These detectors generally rely on either the photoelectric or thermal effect. Photoelectric detectors work by converting the energy from terahertz waves into electrons, which are then detected based on their movement. Thermal detectors, conversely, convert the energy into heat, and the change in heat energy is used to detect the presence of terahertz waves. Additionally, terahertz wave antennas, typically made from metal or semiconductor materials, can also be employed to capture terahertz waves and convert them into electrical signals.

2.6 Need of Terahertz Communication and sensing: -

At WRC-19, ITU-R assigned a total of 13.5GHz spectrum (which also has frequency from higher frequency band) for mm Wave communication in 5G. But, since the data requirement is growing exponentially, this assigned spectrum may not be sufficient to fulfill the bandwidth requirements for the emerging technologies and application. Although, there is ample amount of bandwidth available in the higher side of the Electromagnetic spectrum, but that was unutilized for cellular technology due to hardware limitations. But, now, with advanced antenna design and technology once unfeasible spectrum may become feasible spectrum for cellular technology.

Based on these considerations, THz band seems to be suitable for huge data rate communications (in Tbps) as current advancement in the hardware technologies are able to support this band.

In addition to THz communications, THz sensing (including positioning, imaging, and spectroscopy) exploits the tiny wavelength on the order of micrometers and the frequency-selective resonances of various materials over the measured environment to gain unique information based on the observed signal signature.

The reasons for exploration in the THz bands are given below: -

a. **Spectrum scarcity of the sub-6GHz band:** The favorable propagation characteristics of sub-6GHz frequencies facilitate the use of sophisticated transmission technologies such as massive multi-input multioutput (MMIMO), non-orthogonal multiple access (NOMA) , and high-order modulation like 1024-ary quadrature amplitude modulation (1024QAM) to achieve high spectral efficiency. However, spectrum scarcity and non-continuity pose a significant challenge to achieving higher rates. Even if the sub-6GHz band ultimately determines a bandwidth of 1GHz for International Mobile Telecommunications (IMT) services, a Tbps link can only be realized under the extreme spectral efficiency of 1000bps/Hz, as suggested by the Shannon capacity $R = B \log_2(1 + S/N)$. However, such high performance is impractical in the foreseeable future. The peak spectral efficiency for IMT-2020 is 30bps/Hz (in ideal conditions).

b. **Insufficient mmWave bandwidth below 100GHz:** At WRC-19, the mmWave spectrum in 24.25-27.5 GHz, 37 43.5 GHz, 45.5-47 GHz, 47.2-48.2 GHz and 66–71 GHz, was assigned to IMT services. mmWave technologies below 100GHz can support a single RF transceiver with a maximal bandwidth of 10GHz due to the nonlinearity of RF components. Thus, Tbps can only be reached with spectral efficiency of 100bps/Hz. This is currently infeasible for high-frequency signal transmission, which is prone to the use of low-order modulation and single carrier techniques due to the constraints of mmWave components. Therefore, it is argued that the potential for realizing Tbps communications relies on massively abundant frequencies above 100GHz.

c. **Constraint of optical sensing:** Like THz frequencies, the application of optical wireless communications (OWC) faces some challenges, such as eye-safety constraints, atmospheric (fog, rain, dust, or pollution) absorption, high diffusion loss, low optical-emitter output power, photonic phase noise, line-of-sight (LoS) reliance, and beam misalignment. Nevertheless, lightwave does not exhibit comparable sensing, imaging, and positioning capabilities as THz signals. From the perspective of integrated sensing and communications, the THz band is considered a suitable option to efficiently realize a dual-functional 6G system.

d. **Non-ionizing nature of THz frequencies:** Unlike ionizing radiation, THz frequencies are non-ionizing because their photon energy is not sufficient (0.1 to 12.4meV, which is over three orders of magnitude weaker than ionizing photon energy levels) to release an electron from an atom or a molecule, where typically 12eV is required for ionization. The THz band offers abundant spectral resources, ranging from tens of gigahertz to several terahertz, depending on the transmission distance. This makes the available bandwidth more than ten times greater than that of mmWave bands, while the operating frequency is at least one order of magnitude below the optical bands. This implies that THz sensing is generally considered safe for biological samples and humans, allowing for non-destructive and non-invasive imaging and diagnosing.

e. **High resolution and penetration capabilities:** Although low-frequency signals are able to sense, detect, and localize objects, as the radar and Global Navigation Satellite System (GNSS), THz sensing/positioning can improve the resolution due to the small wavelength, even for objects hidden from direct view. THz waves are able to penetrate a variety of non-conductive materials, e.g., plastics, fabrics, paper, ceramics, and dielectric substances. This allows THz sensing to detect hidden objects, structural defects, and layers beneath surfaces, making it useful in security screening, quality control, process monitoring, and material characterization.

f. **Low environmental interference:** In contrast to visible or IR radiation, THz waves are less vulnerable to environmental factors such as ambient light, fog, or smoke. It allows THz sensing for outdoor environments or adverse conditions, expanding its usability in fields such as remote sensing, atmospheric monitoring, and outdoor stand-off security screening of dangerous items like firearms, bombs, and explosive belts hidden beneath clothing.

g. **Spectroscopic analysis:** THz waves interact with molecules in a characteristic manner, leading to unique spectral fingerprints. THz spectroscopy provides valuable information about molecular vibrations and rotational transitions, enabling the identification and analysis of chemical substances, including explosives, drugs, and biomolecules. It is particularly effective for identifying substances with distinct THz absorption or reflection properties.

3. Use Case of Terahertz Communication and Sensing

3.1 Use Case of Terahertz Communication

The terahertz (THz) frequency spectrum provides vast bandwidth, enabling ultra-fast wireless communication and offering unprecedented flexibility in mobile system design. Its capacity supports the development of wireless backhaul links between network nodes, which is essential for creating ultra-dense network architectures. This not only speeds up network deployment but also lowers the cost of site acquisition, installation, and maintenance. The extremely short wavelengths at THz frequencies allow for the development of miniature antennas, paving the way for advanced applications such as nanoscale communications among nanodevices, on-chip data transfer, and the Internet of Nano-Things. Furthermore, THz waves are highly suitable for non-communication functions like high-resolution sensing, imaging, and environmental positioning, enabling seamless integration of communication and sensing systems. The Terahertz communication applications are: -

A. Integrated sensing and communication (ISAC) in a radio access network:-

Radio Access Networks (RANs) were initially built to support wireless communication between base stations and user devices. However, with the increasing demand for location-based services—like targeted ads using device location—modern RANs are being adapted to provide basic positioning functions by leveraging system reference signals to sense the environment. Looking ahead, future RANs are likely to move toward higher frequency ranges, including the terahertz (THz) band, which offers abundant spectrum. This shift would not only enhance data transmission capabilities but also enable advanced sensing functions, making RANs more comparable to traditional radio localization systems. Research into integrating sensing with communication in RANs is actively underway.

Figure below illustrates a scenario where integrated sensing and communication are deployed within a radio access network, highlighting THz-capable links with blue circles. Both base stations and user devices can analyze received RF signals to gather environmental details—such as object presence, distance, velocity, shape, and orientation. This data supports various applications including localization, tracking, environmental mapping, reconstruction, and activity or gesture recognition. Additionally, it can enhance the efficiency of communication services. The RF signals used for this sensing can originate from standard communication transmissions or from specialized sensing signals.

It is worth mentioning that resolution in sensing or imaging is inversely proportional to the wavelength of the signal—shorter wavelengths (like those in the THz range) can resolve smaller objects and finer details because they can distinguish between points that are closer together in space.

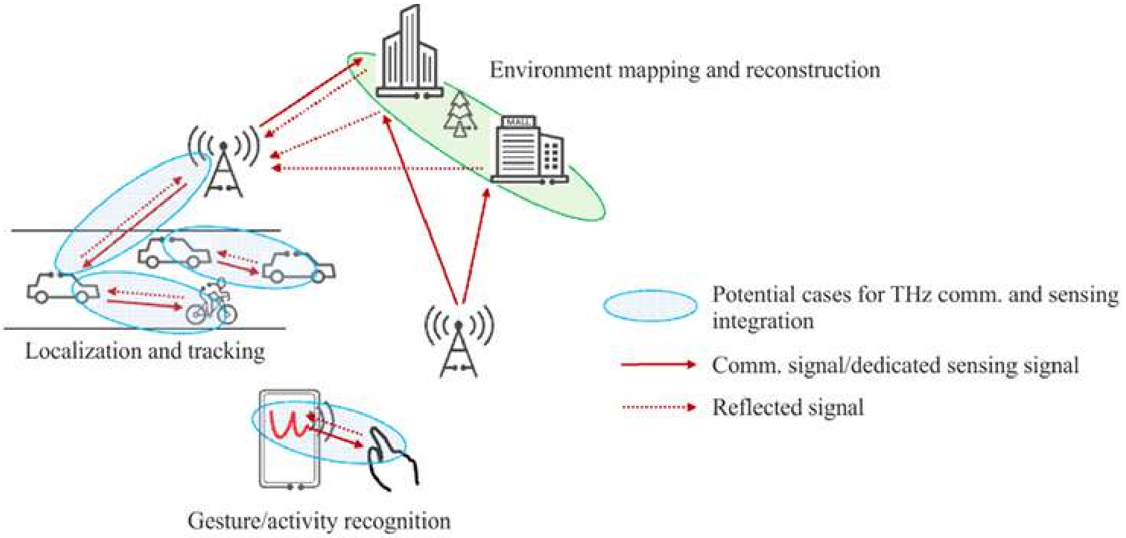
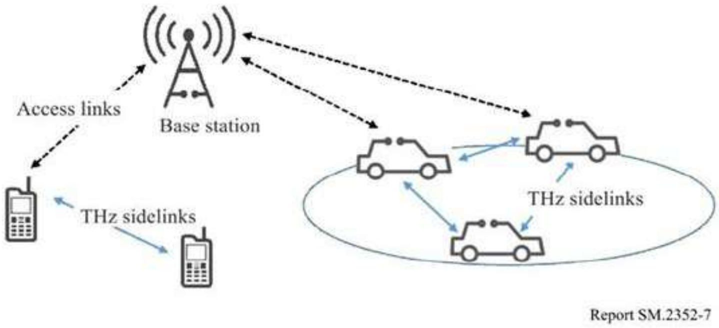
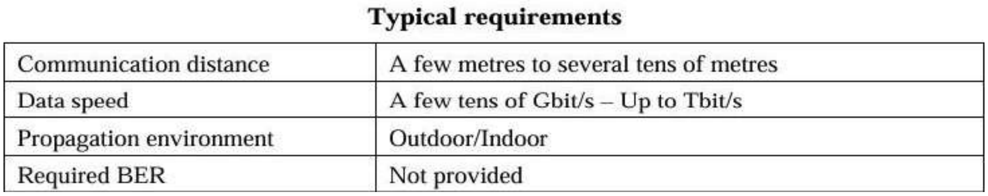


Figure4:- Use case of THz integrated sensing and communication in a radio access network [Report ITU-R SM.2352-1]

B. Super-Sidelink in short range communication environment: -

Super-sidelink refers to a direct peer-to-peer communication link that can leverage essential features of conventional radio access networks. Together with mesh networking capabilities, it is envisioned to become a fundamental component of future mobile network architectures. This technology allows mobile devices to connect and exchange data directly with nearby devices over short distances, bypassing the need to route traffic through a base station. As a result, it helps in reducing the data load on the base station while also minimizing latency in communication between the devices, leading to more efficient and responsive mobile interactions Device-to-Device (D2D) and Vehicle-to-Everything (V2V) are two representative of super side link.




Typical requirements

Communication distance	A few metres to several tens of metres
Data speed	A few tens of Gbit/s – Up to Tbit/s
Propagation environment	Outdoor/Indoor
Required BER	Not provided

Figure5:- Super-sidelink in short range communication environment [Report ITU-R SM.2352-1]

In D2D communication, THz links can facilitate ultra-fast, low-latency data exchange between nearby devices without relying on central infrastructure. This is particularly beneficial in dense environments such as stadiums, factories, or campuses where real-time sharing of high-resolution media, augmented reality content, or collaborative data is critical.

For V2V communication, THz technology provides the high throughput and low latency required to support autonomous vehicles, enabling real-time transmission of sensor data such as LIDAR and high-definition video for cooperative driving, safety alerts, and navigation. Additionally, the narrow beam width of THz signals enables precise, directional communication and enhanced localization capabilities, essential for collision avoidance and lane coordination. However, challenges such as high path loss, atmospheric absorption, and line-of-sight dependency must be addressed through solutions like intelligent reflecting surfaces and multi-band hybrid systems.

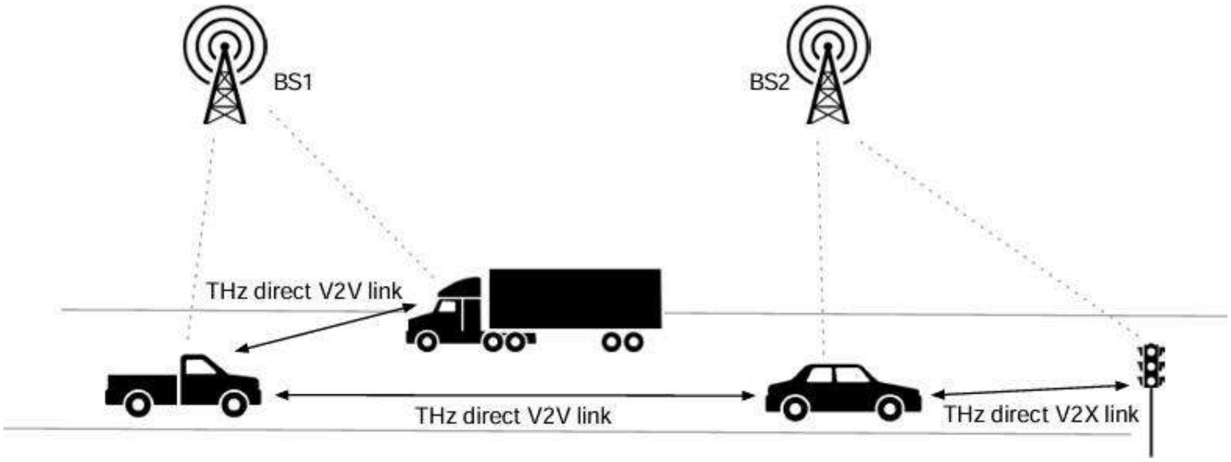
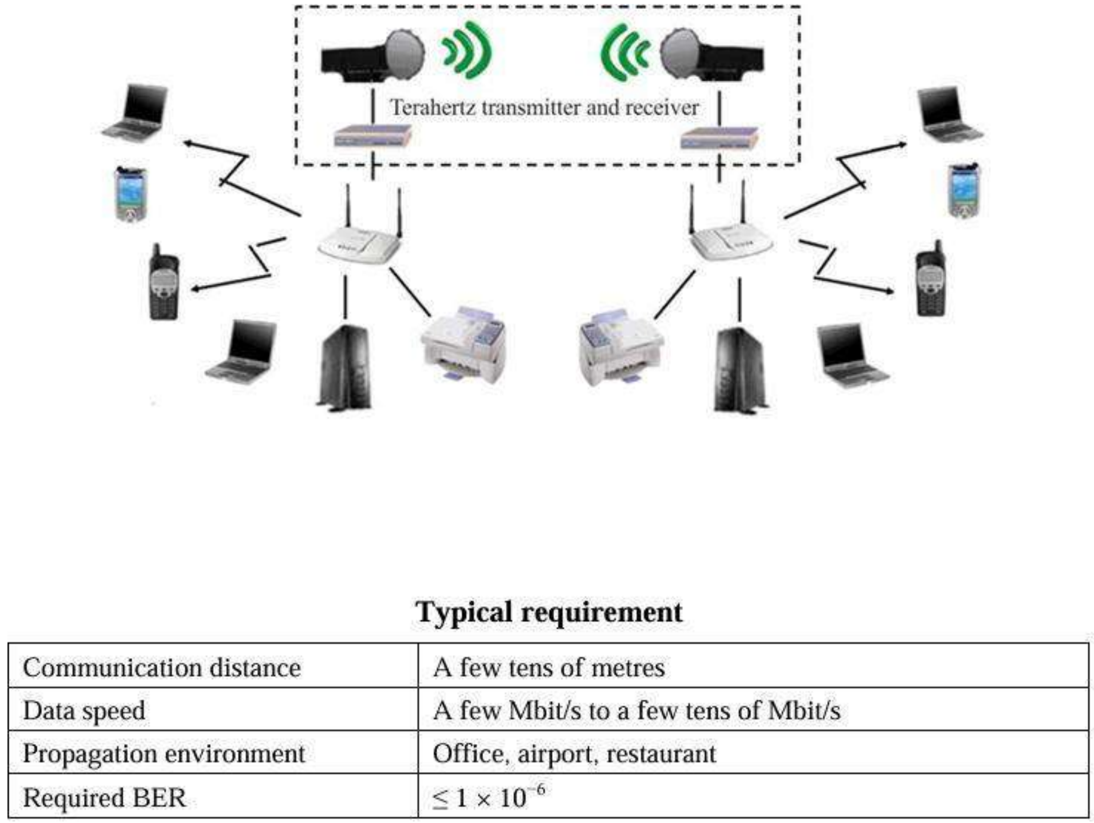


Figure6:- V2V and V2X local collaboration[ETSI GR THz 001 V1.1.1]

C. Terabit Campus/Private Networks/ THz WLAN:

Terahertz (THz) communication enables Terabit-per-second (Tbps) data rates, making it ideal for campus and private network deployments requiring ultra-high-speed, low-latency connectivity. In environments such as universities, research labs, smart factories, Industry 4.0, Tactile Internet and enterprise campuses, THz links support seamless data transfer for bandwidth-intensive applications like 8K video streaming, real-time digital twins, and collaborative AR/VR. The short-range, high-capacity nature of THz also enhances data security and reduces interference, making it well-suited for localized, high-density environments. These capabilities facilitate the deployment of industrial networks, linking a vast number of sensors and actuators within a factory, and campus networks providing high data-throughput, low-latency, and high-reliability connections for equipment and machine. The frequency of THz is 1-4 order of magnitude, which is higher than microwave, and its data rate can be 10 Gbit/s. Considering the characteristics of high speed, wide band, compact structure, small size, low radiation damage and strong anti-interference of THz WLAN, it can be used in commercial.



Typical requirement

Communication distance	A few tens of metres
Data speed	A few Mbit/s to a few tens of Mbit/s
Propagation environment	Office, airport, restaurant
Required BER	$\leq 1 \times 10^{-6}$

Figure7:- Use case of THz WLAN [Report ITU-R SM.2352-1]

D. Use case on remote surgery:

Terahertz (THz) communications enable remote surgery by allowing surgeons to operate medical robots from afar with support from technologies like augmented reality and haptic feedback. With ultra-high-speed, low-latency data transmission, THz enhances imaging, sensing, and real-time video streaming. This allows medical interventions in underserved areas, reduces infection risk, and improves healthcare quality. In remote surgery service flows, a medical robot at a distant facility gathers advanced sensory data and high-resolution video of the surgical site. This information is transmitted over a high-speed, low-latency network to the surgeon, who uses sensory feedback tools and video to guide the robot in real time through a closed-loop control system.

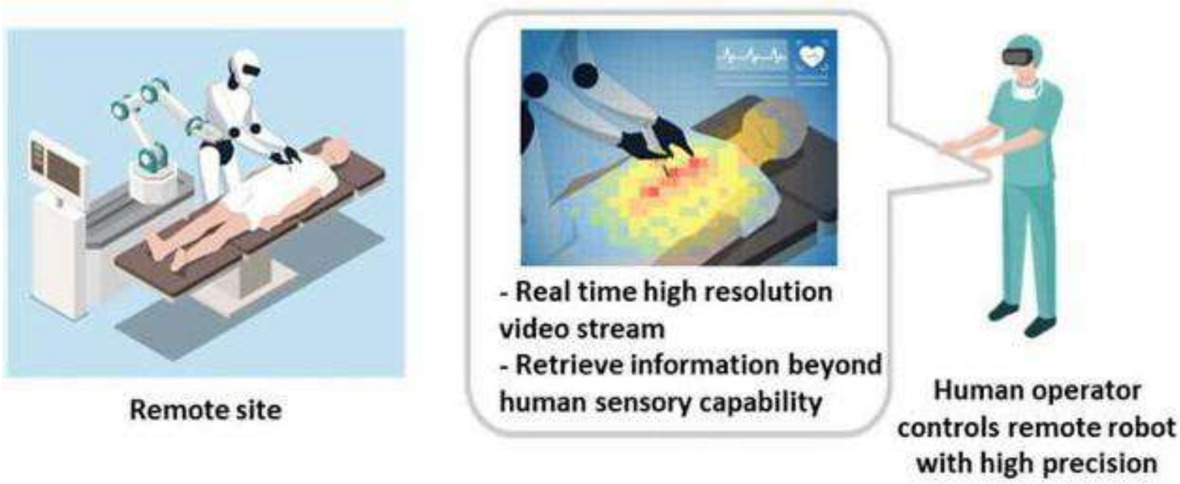
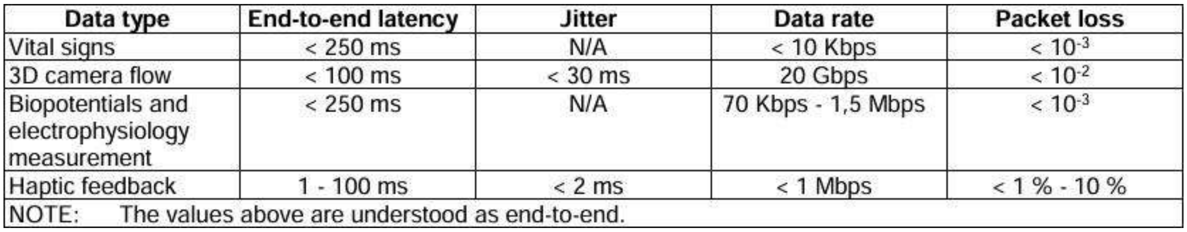


Figure8:- Use case of Remote Surgery [ETSI GR THz 001 V1.1.1]



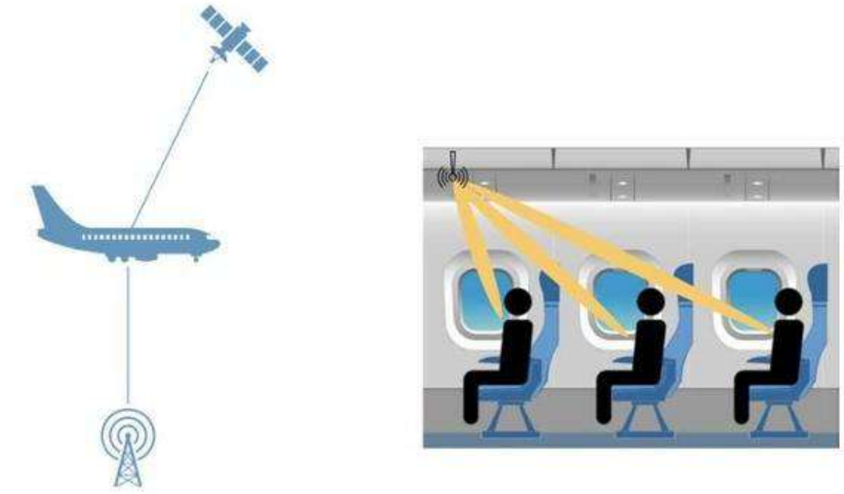
Data type	End-to-end latency	Jitter	Data rate	Packet loss
Vital signs	< 250 ms	N/A	< 10 Kbps	$< 10^{-3}$
3D camera flow	< 100 ms	< 30 ms	20 Gbps	$< 10^{-2}$
Biopotentials and electrophysiology measurement	< 250 ms	N/A	70 Kbps - 1,5 Mbps	$< 10^{-3}$
Haptic feedback	1 - 100 ms	< 2 ms	< 1 Mbps	< 1 % - 10 %
NOTE: The values above are understood as end-to-end.				

Figure:- KPIs for remote surgery [ETSI GR THz 001 V1.1.1]

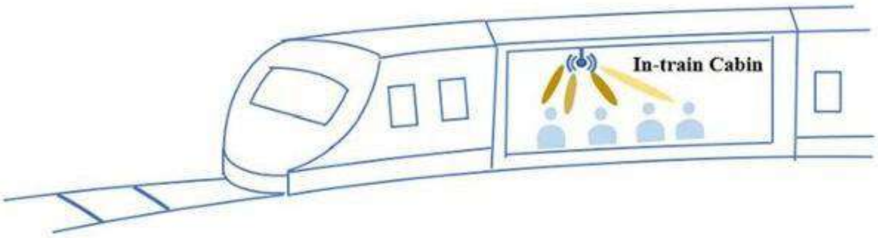
E. Use case on in-airplane or train cabin entertainment: -

Modern airplane and train cabins require high-speed, low-latency connectivity for services like streaming, gaming, and real-time updates. With rising passenger density and bandwidth demands, THz technology offers a superior alternative to Wi-Fi, enabling higher data rates and capacity. A THz-based hotspot installed in the cabin can provide localized entertainment and communication, supported by ground stations or satellite backhaul. Local servers reduce transmission load, and devices may interact directly using THz links. Preconfigured, directional beams to each seat ensure secure, interference-free communication, while additional beams or frequency layers can extend coverage across the entire cabin for seamless service.

In THz-enabled in-cabin networks, user devices detect and connect to a THz hotspot, registering with the cellular network to access the internet. For local communication, traffic is managed directly through the hotspot, with optional external routing. This setup supports high-bandwidth, low-latency activities like video streaming, conferencing, and online gaming during travel.



In-airplane or train cabin entertainment



In-train cabin entertainment

Figure9:- Use case on in-airplane or train cabin entertainment [ETSI GR THz 001 V1.1.1]

F. **Military communications**

Terahertz communication has a very high application value, which is highly valued by governments and research institutions, including national defense security and military fields. Terahertz communication can be used in terahertz radar and other military fields, because the terahertz wavelength is very short, so it can detect more tiny targets and obtain more accurate positioning. Terahertz frequency band has a rich band of frequencies, hence it can emit a large number of pulses and detect the enemy's stealth technology since it has a good pass rate for absorbing materials, can ignore coatings, and has strong anti-stealth capabilities. Compared with microwave radar, it has high resolution, strong anti-jamming ability and strong anti-stealth ability. Compared with infrared radar and LiDAR, it has lower attenuation in suspended particulates and in dust, smoke and battlefield pollution conditions, so terahertz radar has a stronger ability to penetrate dust and smoke than infrared and LiDAR, and can achieve all-weather work.

G. Use case on cooperative mobile robots:

Automation has significantly advanced society, and cooperative mobile robots offer further benefits in productivity and sustainability. These include various guided vehicles like AGVs, drones, and laser-guided units, which can function autonomously or via remote control. For tasks such as cooperative carrying or dynamic manufacturing, robots must interact with each other and with humans in real time. Flexible software-defined manufacturing allows adaptation to changing demands, supported by mobile robots sharing tasks and data. This approach needs multi-tasking capability, real-time learning, and easy redeployment of modular systems. However, current systems face delays and reliability issues due to limited radio resources and communication queuing. Terahertz (THz) communication presents a promising solution, offering abundant spectrum to reduce contention and enable ultra-reliable, low-latency coordination between robots. This enhances intra-group collaboration and supports the rapid, flexible deployment essential for modern, efficient manufacturing and logistics systems.

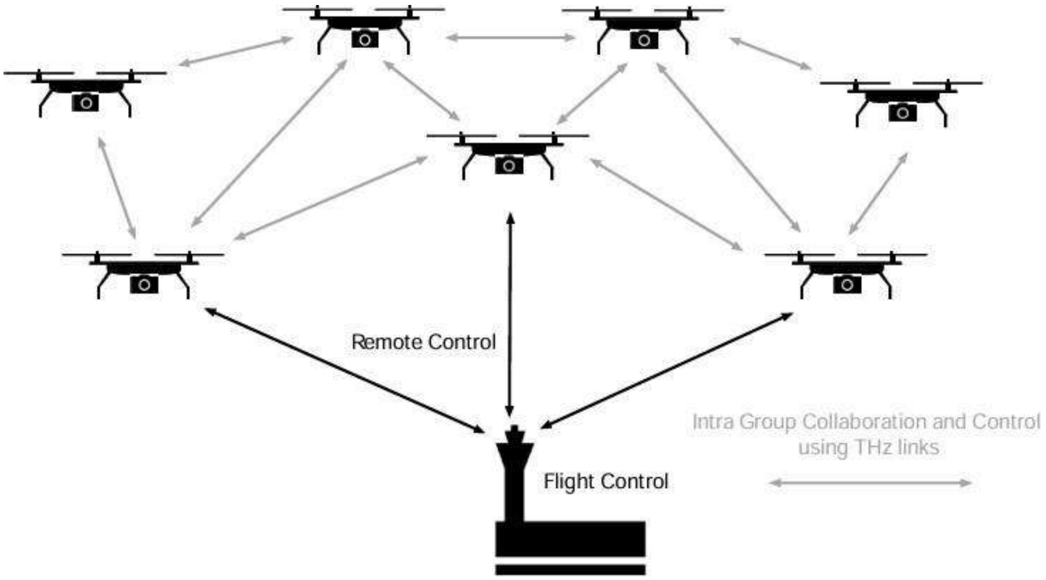


Figure10:- Drone remote control and intra group collaboration [ETSI GR THz 001 V1.1.1]

Communication among mobile robots and with networks involves high-resolution sensor data and control commands, demanding ultra-high data rates, reliability, capacity, and low latency—all achievable with terahertz (THz) spectrum. These capabilities ensure the safe and efficient operation of mobile robots like AGVs. In distributed systems, robots may make autonomous decisions or rely on network instructions, requiring bidirectional data exchange. THz communication also supports high-precision sensing and localization, essential for dynamic environments. In scenarios like flexible manufacturing, cooperative robots must coordinate closely—often with humans or other machines—to execute shared tasks, making real-time, accurate spatial awareness critical to success.

H. Use case on hazardous material work: -

Robots are essential for handling hazardous materials such as radioactive, toxic, or explosive substances, protecting humans from dangerous exposure. Designed for extreme environments, they offer precision and access to data beyond human capability. Terahertz (THz) technology enhances these systems by enabling advanced sensing through spectroscopy for chemical, pollutant, and antibiotic detection. Additionally, THz supports real-time, high-resolution video streaming for remote operation, surpassing current system capabilities. This combination of robotics and THz communication significantly improves safety and efficiency in industrial settings. Overall, it contributes to public health protection and optimization of complex processes in high-risk environments. Here, a remotely operated robot collects advanced hazard monitoring data and high-resolution video from dangerous sites. This sensory information is securely transmitted over a high-speed, low-latency network. At the control center, a human operator receives the video feed and remotely pilots the robot, enabling safe and efficient oversight of hazardous environments.

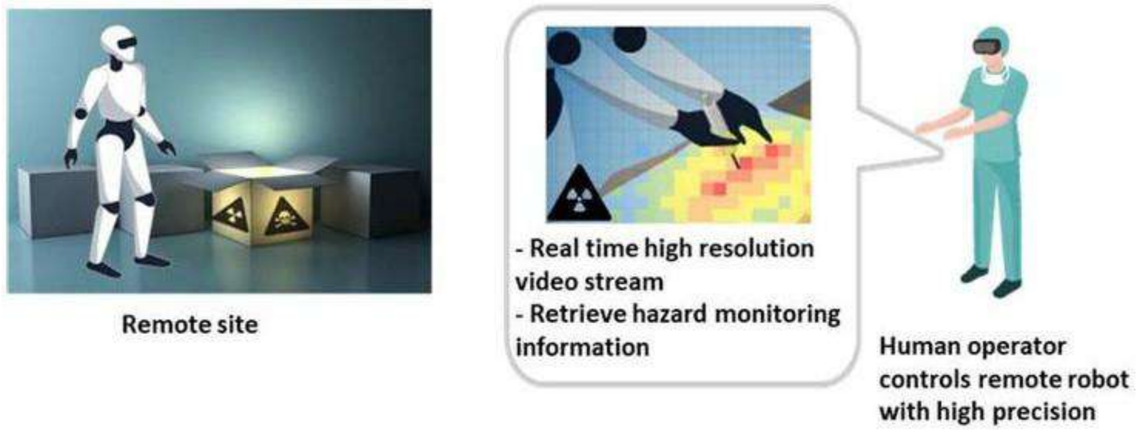
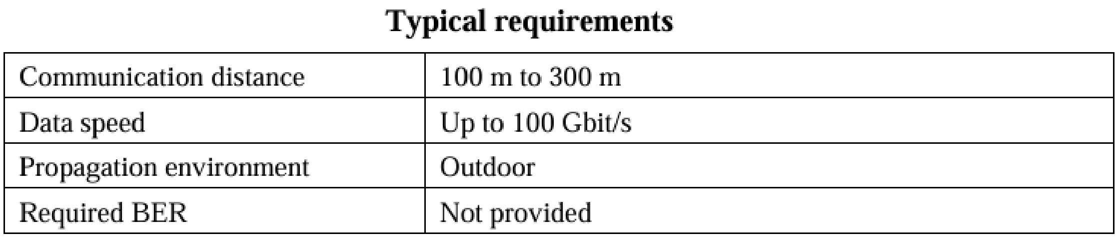


Figure11:- Use case on hazardous material work [ETSI GR THz 001 V1.1.1]

I. Terabit Wireless Backhaul: -

The installation of fiber optical connections is typically time-consuming and costly, and it may not always be feasible to deploy public optical networks within certain buildings or areas due to property owner objections. However, the next-generation mobile network is expected to be highly heterogeneous, requiring high-throughput backhaul or front haul connectivity between network elements such as macro base stations, small cells, relays, and distributed antennas. Highly directive THz links can provide ultra-high-speed wireless backhaul or front haul reducing the time and cost of installation and maintenance while enabling greater flexibility in network architecture and communications mechanisms. As a wireless backhaul extension of the optical fiber, THz wireless links can work well as an essential building block to guarantee a universal telecommunications service with high-quality, ubiquitous connections everywhere.



Typical requirements

Communication distance	100 m to 300 m
Data speed	Up to 100 Gbit/s
Propagation environment	Outdoor
Required BER	Not provided

Figure12:- Typical requirement of Wireless Backhauling [Report ITU-R SM.2352-1]

J. Use case on mission critical XR: -

Mission critical XR is designed for high-stakes scenarios like public safety, demanding greater reliability and lower latency than standard XR applications. A typical use case involves rescue personnel wearing XR helmets connected via a centralized commanding vehicle using THz links. These helmets transmit sensory data and receive critical instructions—such as debris locations or victim vital signs. If direct links to the command center are unavailable, team members can relay communication among themselves. Alternatively, when a site is too hazardous, XR-equipped responders can operate remotely, guiding rescue robots or drones dispatched from the command vehicle. These autonomous agents rely on XR user perspectives and commands to navigate and collect data. They may also act as relays, expanding communication coverage. THz communication and sensing play a pivotal role in enabling real-time data exchange, autonomous coordination, and situational awareness, ensuring effective response in dynamic and dangerous environments where human access is limited or unsafe.

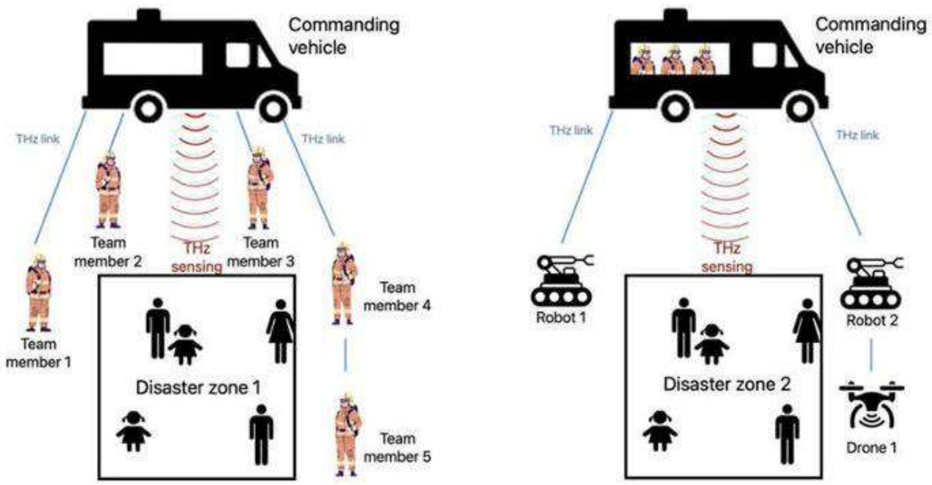
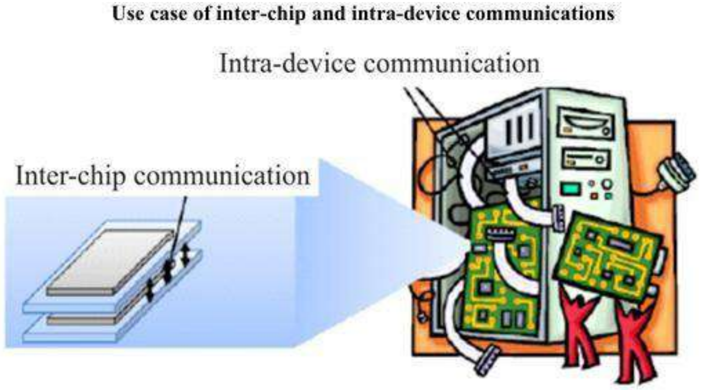


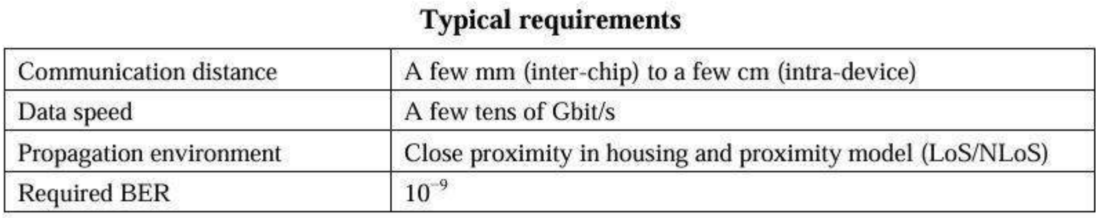
Figure13:- Use case on mission critical XR [ETSI GR THz 001 V1.1.1]

In mission-critical XR operations, the commanding vehicle acts as a central hub, collecting real-time data from XR helmets, robots, and various sensors. Team members connect directly or via relays, transmitting video, audio, motion, and vital signs. The vehicle processes this input and sends back essential updates like commands, victim status, debris risks, and real-time maps to guide the team effectively.

K. Inter-chip and intra-device communications: -

Inter-chip and intra-device communication using wireless technologies aims to reduce physical wiring and enable more compact circuit board and device designs. These connections typically span a few millimeters to several centimeters within the same housing, such as between stacked or closely arranged integrated circuits (ICs). With established data rates already reaching 10 Gbit/s for USB 3.1 and up to 2 Tbit/s via PCI Express 4.0 using multiple lanes, future systems are expected to handle at least tens of gigabits per second through terahertz (THz) wireless links. While not all applications demand terabit speeds, ultra-high-speed transmission is becoming essential. Propagation in these close-proximity environments involves both line-of-sight (LoS) and non-line-of-sight (NLoS) paths, often within metallic enclosures that cause strong reflections. This setup requires careful consideration of multipath effects from nearby components and reflections off internal housing surfaces, as THz waves can penetrate substrates and introduce complex transmission paths.


Use case of inter-chip and intra-device communications


Typical requirements

Communication distance	A few mm (inter-chip) to a few cm (intra-device)
Data speed	A few tens of Gbit/s
Propagation environment	Close proximity in housing and proximity model (LoS/NLoS)
Required BER	10^{-9}

Figure14:- Use case of inter-chip and intra-device communications [Report ITU-R SM.2352-1]

L. Use case on remote education: -

Immersive education using remote presence technologies like XR, robotics, and holographic telepresence is transforming global learning by enabling natural interaction with distant environments. Terahertz (THz) communication plays a key role by offering ultra-fast, low-latency data transfer and precise sensing. This approach enhances access to high-quality educational resources and fosters engaging, real-time collaboration across geographically dispersed learners—overcoming limitations of conventional video-based remote learning.

Immersive classrooms can be implemented in two formats: partially remote (hybrid), where the teacher is onsite and students join from various remote locations, and fully remote, where all participants connect virtually. Interaction styles include co-presence, simulating a shared physical space, and digital twin, allowing remote collaboration on group projects or experiments via virtual or physical environments.

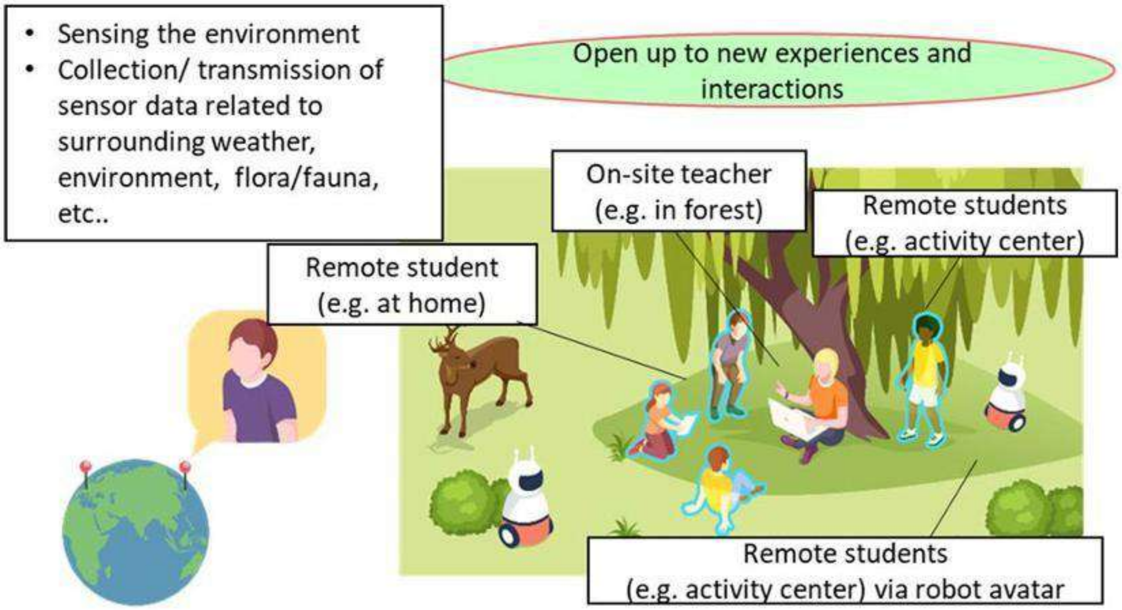


Figure15:- An example of remote education [ETSI GR THz 001 V1.1.1]

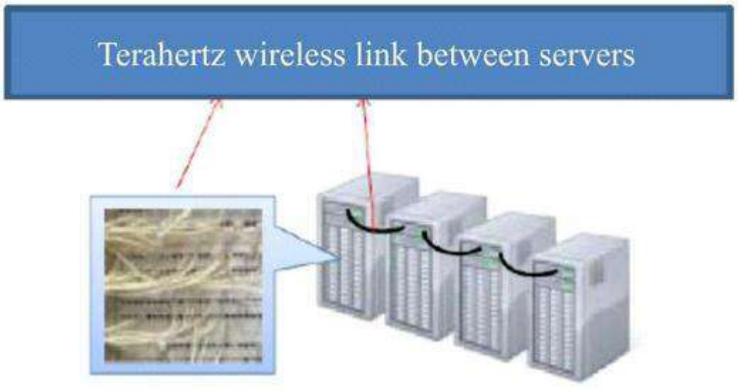
In immersive educational or recreational settings, sensors gather data from participants and their environment to track positions, gestures, viewpoints, and avatar movements. This data is partially processed locally, with more complex tasks sent to the cloud. High-speed two-way links enable remote users to both control interactive avatars and appear virtually on-site through avatar projection and sensor data exchange.

M. Wireless links between servers inside a data centre: -

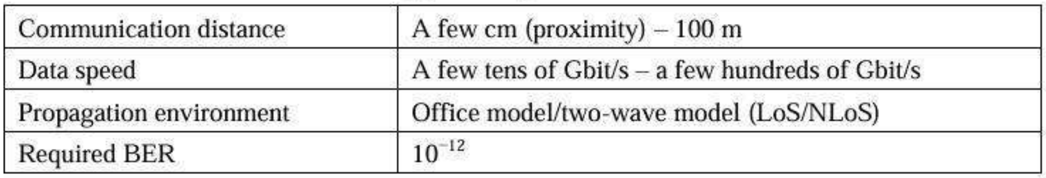
A potential application of terahertz (THz) communication is enabling wireless data transfer between servers within a data center. With the rapid expansion of cloud-based services driving the need for more data centers, replacing traditional cabling between servers and racks with wireless links is becoming increasingly desirable. Server racks typically contain a mix of storage and switching components, and THz communication can simplify interconnections within and between these racks. Communication distances can range from just a few centimeters (for vertically stacked servers) up to 100 meters (for links between separate racks). In terms of signal propagation, both line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios must be considered, particularly in office-like environments with reflective surfaces. In specific setups—such as server racks positioned against a wall and rear-panel connections being replaced by THz links—a two-ray propagation model becomes relevant due to reflections off the wall surfaces.

FIGURE 4

Wireless links between servers inside a data centre



Typical requirements

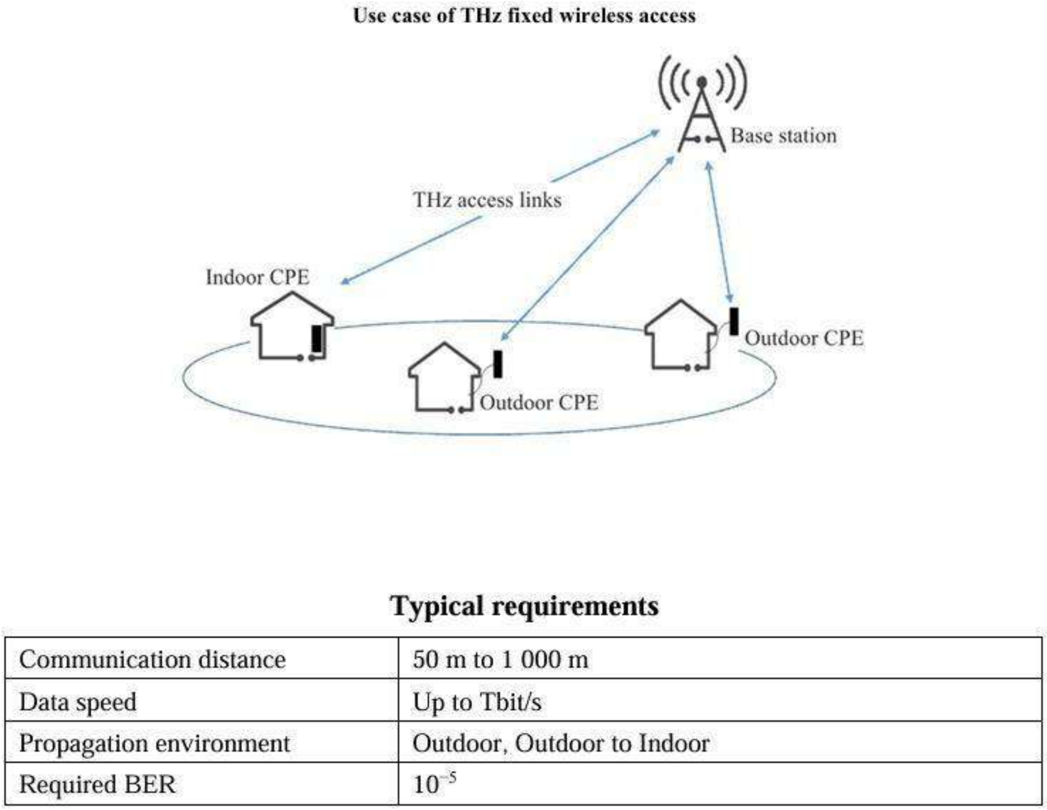


Communication distance	A few cm (proximity) – 100 m
Data speed	A few tens of Gbit/s – a few hundreds of Gbit/s
Propagation environment	Office model/two-wave model (LoS/NLoS)
Required BER	10^{-12}

Figure16:- Use case of Wireless links between servers inside a data centre [Report ITU-R SM.2352-1]

N. Terahertz FWA:-

Fixed Wireless Access (FWA) delivers dependable broadband connectivity to homes and businesses in areas where fiber infrastructure is unavailable or prohibitively expensive. Thanks to its quick deployment and affordability, FWA has gained widespread adoption globally. With the rising demand for ultra-high-speed data—reaching hundreds of gigabits per second—THz frequency bands have become a promising solution. In a typical THz FWA setup, multiple users connect to a base station via Customer Premise Equipment (CPE), which may be mounted outdoors to minimize signal loss through building materials. Communication ranges can vary from several meters to a few kilometers.



Typical requirements

Communication distance	50 m to 1 000 m
Data speed	Up to Tbit/s
Propagation environment	Outdoor, Outdoor to Indoor
Required BER	10^{-5}

Figure17:- Use case of Terahertz FWA [Report ITU-R SM.2352-1]

O. Application in molecular detection:-

All matter exhibits internal molecular motion, even when appearing still, and this motion generates radiation. Each molecule emits electromagnetic radiation at characteristic frequencies, known as its ―spectral fingerprint.‖ Many of these fingerprints occur in the infrared and above 275 GHz (terahertz) range. Terahertz solid-state lasers can detect vibrational signals from small molecules that infrared sensors may miss.

P. Application in Security Inspection:-

Many explosive substances and drugs have molecular rotational levels within the terahertz band. Terahertz spectroscopy enables body scans for detecting such substances, as well as identifying weapons and biological macromolecules. Unlike X-rays or ultrasound, terahertz imaging captures both object shapes and material composition by comparing signals against a known hazardous substance spectrum database. Its low energy ensures it doesn't cause ionization, making it safer for the human body. Moreover, it can detect non-metallic threats that metal detectors miss, highlighting its promising use in security screenings.

Q. Application in biomedicine: -

Signals above 275 GHz are strongly absorbed by polar molecules such as water and oxygen. Because different molecules absorb at different frequencies, this spectral data aids in diagnosing early skin cancers and other surface-level tissue abnormalities. During surgery, terahertz imaging provides real-time feedback on cancerous tissue removal with higher clarity than ultrasound. Furthermore, terahertz time-domain spectroscopy (THz-TDS) helps analyze biological macromolecules, supporting both pharmaceutical development and medical research.

R. Use case on grand events with ultra-high throughput: -

Large-scale events like concerts or sports games can attract over 100,000 attendees, requiring advanced communication systems. Numerous 8K cameras capture dynamic scenes, allowing spectators—both on-site and online—to interactively switch viewing angles via AR/VR or mobile devices for immersive experiences. These scenarios demand ultra-high data rates and massive link density in a confined area. Terahertz (THz) communication is ideal for meeting these high bandwidth and capacity needs. Bidirectional service stream between the local/cloud server and base stations, and between base stations and users are established.

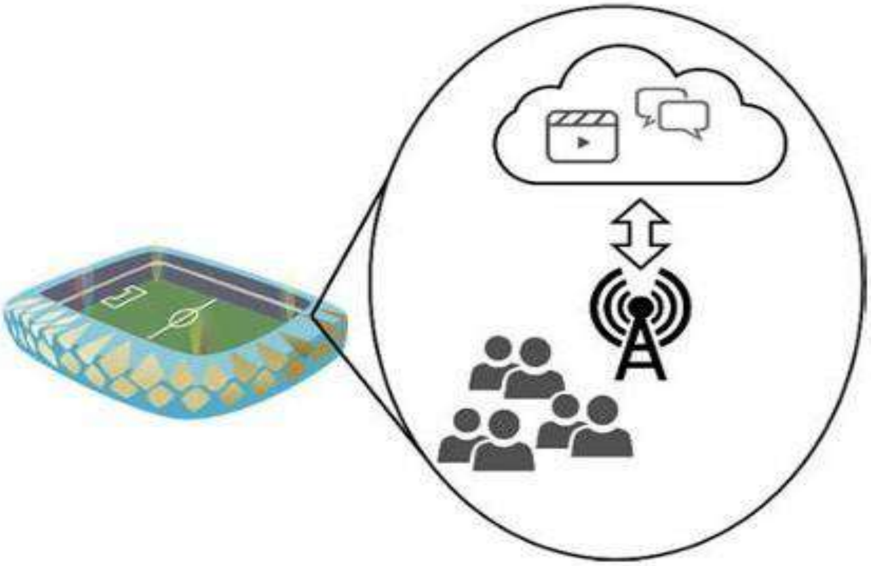


Figure18:- Grand Event with Ultra High Throughput [ETSI GR THz 001 V1.1.1]

3.2 Use Case of Terahertz Sensing

Terahertz (THz) sensing is a rapidly emerging technology that leverages electromagnetic waves in the terahertz frequency range (0.1 to 10 THz) for non-invasive measurement and imaging applications. As technology advances, THz sensing is poised to revolutionize industries, including telecommunications, biomedicine, and manufacturing. Terahertz (THz) sensing operates at frequencies where signal resolution is significantly enhanced due to the extremely short wavelengths. This allows for precise spatial differentiation at a high definition. THz sensing methods utilize the distinct frequency-dependent resonances of various materials in the environment, along with the small wavelengths—typically in the micrometer range—to extract unique data based on signal characteristics. These waves can penetrate a variety of materials, including clothing, packaging, and biological tissues, making THz sensing valuable for security, medical diagnostics, and material characterization. Unlike X-rays, THz radiation is non-ionizing and safer for biological tissues. THz sensors can detect chemical compositions, detect defects in materials, and monitor environmental conditions with high precision. However, their penetration is limited when interacting with metallic objects or environments where water significantly reduces their radiation power. By analyzing the variations in signal strength and phase—caused by differences in material thickness, density, or chemical composition—THz sensing enables the accurate identification of physical objects.

A. Terahertz Imaging: -

Terahertz (THz) imaging offers several advantages over microwave and visible light imaging, primarily due to its high spatial resolution, which stems from its smaller wavelengths and broad bandwidth. Unlike infrared and visible light, THz waves can penetrate various common materials, rendering them relatively transparent to THz signals. This capability has been leveraged for security screening applications, such as inspecting postal packages for concealed objects or scanning parcels and bags to detect potential threats. Additionally, THz radiation is non-ionizing, meaning it poses no significant health risks to biological cells beyond minor heating effects. This safety aspect has driven its use in medical imaging, where harmful ionizing radiation—such as ultraviolet, X-ray, and Gamma-ray—cannot be employed due to associated health risks. Furthermore, THz imaging is effective for stand-off detection of hidden weapons or explosives beneath clothing, making it a valuable tool in security checkpoints at airports, train stations, and border crossings.

B. Terahertz positioning: -

Future 6G and beyond systems are expected to deliver highly precise positioning and localization capabilities in both indoor and outdoor environments, addressing the limitations of traditional localization methods. Integrating THz sensing and imaging into these systems could enable centimeter-level localization in virtually any setting. THz imaging stands out by offering unique advantages in localization, particularly in non-line-of-sight (NLoS) scenarios where signal paths may undergo multiple reflections before reaching the base station. However, high-frequency localization faces attenuation challenges due to the emission characteristics of isotropic antennas, with THz antennas struggling to capture sufficient radiation power because of their small apertures.

C. THz radar applications:-

Compared to microwave, THz wave has narrower pulse width, smaller antenna size, narrower beam width and better directivity, which make THz radar be able to detect smaller targets and achieve more accurate positioning than microwave radar. Furthermore, with the advantage of imaging through material, THz radar can detect objects which are hidden in the cover or smoke.

(i) Radar Active Imaging: -

According to whether the radar is moving or not, the imaging can be divided into SAR imaging and inverse synthetic aperture radar (ISAR) imaging. By using the ultra-broad bandwidth, ultra-narrow pulse width and the better directivity of THz wave, THz SAR and ISAR radar can achieve very high imaging resolution compared to traditional microwave radar. Depending on the methods generating THz waves, the THz imaging radars could be divided into electronics and photonics. Due to the implementation difficulties of photonics radars, more THz imaging radars are developed based on the electronics method. This section mainly describes the electronics THz imaging radars.

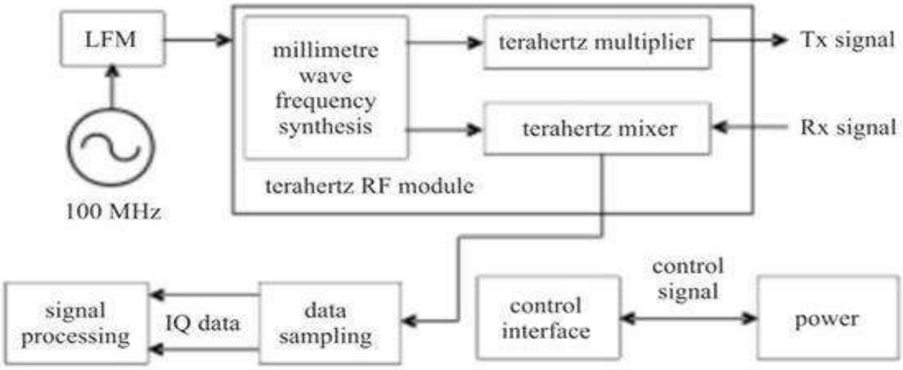


Figure19:- Block Diagram f Radar Active Imaging [Report ITU-R SM.2352-1]

It is expected that the THz imaging radar will make obvious progress and become operational in the next decade, as the performance of terahertz devices improve, and system design matures.

(ii) **Non-contacting security inspection: -**

THz radar could be used in non-contacting security inspection. Based on the abilities of penetrating clothing, cardboard and other non-polar materials while maintaining high-resolution, THz radar can achieve high-resolution perspective imaging of hidden dangerous goods. The detection distance can reach 20 to 100 metres, which can provide early warning beyond the radius of dangerous goods attack. In addition, the terahertz photon energy is low, far less than the ionization energy of human skin, which can eliminate people's anxiety about radiation damage.

(iii) **Walk-through scanning systems: -**

Walk-through scanning systems using frequency-modulated continuous-wave (FM-CW) radar are being developed for fast, high-resolution detection of both metallic and non-metallic threats in airports, helping reduce passenger queue times. These systems use dual-panel setups to scan both sides of individuals and rely on wide bandwidths for effective imaging. However, frequency bands below 275 GHz can't achieve the sub-5 mm resolution needed. THz frequencies (275–600 GHz) are more effective but require careful consideration of factors like clothing material attenuation, system output power, and antenna design. Proposed center frequencies (325–555 GHz) aim to minimize interference with passive services. Clothing transmittance varies with weave, thickness, and frequency, but materials with higher reflectivity, like metals or contraband, remain detectable within the 0.1–1 THz range.

4. Terahertz Waves Propagation Characterization

The propagation of Terahertz (THz) waves and the characterization of their channel are essential for understanding their behavior in communication and sensing applications. THz waves, which operate in the frequency range of 0.1 to 10 THz, exhibit distinct propagation behaviors compared to lower-frequency electromagnetic waves. These waves are significantly affected by factors like free-space path loss, atmospheric absorption, and scattering, particularly under varying environmental conditions such as humidity and precipitation. Notably, THz waves are highly vulnerable to water vapor absorption, which restricts their range in open air, especially at higher frequencies.

Terahertz Waves Propagation characterization involves studying THz wave behavior across different environments and assessing parameters such as channel capacity, path loss, and delay spread. In indoor settings, THz waves experience considerable path loss due to increased interaction with materials like walls and furniture. However, in line-of-sight (LOS) conditions, THz waves propagate more effectively with minimal loss. A comprehensive understanding of these propagation characteristics is vital for the design of THz communication systems, particularly for applications in high-speed data transmission and wireless networks.

A. Free Space Path Loss :-

Free-Space Path Loss refers to the loss of signal strength that occurs as an electromagnetic wave travels through free space. In ideal conditions, this loss is primarily a result of the geometrical spreading of the wave as it propagates. The signal strength decreases as the distance between the transmitter and receiver increases. This is true for all frequencies, but THz waves are particularly sensitive to free-space path loss due to their high frequency.

At THz frequencies, the electromagnetic waves exhibit shorter wavelengths, making them more susceptible to attenuation than lower-frequency waves like microwaves or millimeter waves. This higher susceptibility to loss results in a greater reduction in signal strength as the signal travels over longer distances, which is an important consideration for designing THz communication systems. The FSPL is influenced by factors such as the transmission frequency, distance, and the medium through which the waves propagate. For THz communication, the effects of FSPL can be more pronounced, which leads to the need for specialized design considerations in antenna systems and transmission power management.

The FSPL for THz communication is calculated using a formula that is based on the inverse square law of wave propagation, adjusted for the specific frequency of the electromagnetic wave. The general formula for Free-Space Path Loss is:

$$\text{FSPL (dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(4\pi/c)$$

Where:

- d = Distance between the transmitter and receiver (in meters)
- f = Frequency of the signal (in Hz)
- c = Speed of light in a vacuum (3×10^8 m/s)
- log10 = Logarithmic function to the base 10.

This formula shows the logarithmic relationship between the path loss, the frequency of the signal, and the distance over which the signal is transmitted. The first term 20log10(d) represents the increase in path loss due to the distance between the transmitter and receiver, which follows the inverse square law. The second term 20log10(f) highlights the effect of frequency on path loss, showing that higher frequencies experience greater attenuation. The third term 20log10(4π/c) is a constant that accounts for the basic characteristics of wave propagation in free space.

For THz frequencies, this formula implies that path loss will be significantly greater than at lower frequencies like 5G or Wi-Fi systems. For instance, a signal operating at 1 THz will experience more attenuation over a given distance than one operating at 100 GHz. The increased path loss is a result of the higher frequency's shorter wavelength, which causes it to spread out more quickly and result in greater energy dispersion over distance.

B. Atmospheric Absorption: -

Gas molecules can absorb energy from electromagnetic (EM) waves, but this effect is negligible in the sub-6 GHz frequency range, so traditional cellular systems often exclude it from link budget calculations. However, in the terahertz (THz) band, absorption becomes much more pronounced at specific frequencies. This stronger attenuation occurs due to interactions between EM waves and atmospheric gases. When the THz wavelength is comparable to molecular dimensions, it can trigger rotational and vibrational transitions in polar molecules. These interactions are quantum in nature and occur at distinct resonance frequencies based on molecular structure, resulting in high absorption at those points.

Oxygen is a key contributor to atmospheric absorption under clear sky conditions, while water vapor has an even greater influence on EM wave transmission in the THz range. Water vapor is typically the dominant source of attenuation, though oxygen can prevail in some frequency bands. While atmospheric absorption is extensively analyzed in disciplines like remote sensing and radio astronomy, wireless communication mainly focuses on water vapor and oxygen. Other atmospheric constituents—such as isotopic and vibrational forms of oxygen and ozone, as well as nitrogen, carbon, and sulfur oxides—have a relatively minor impact.

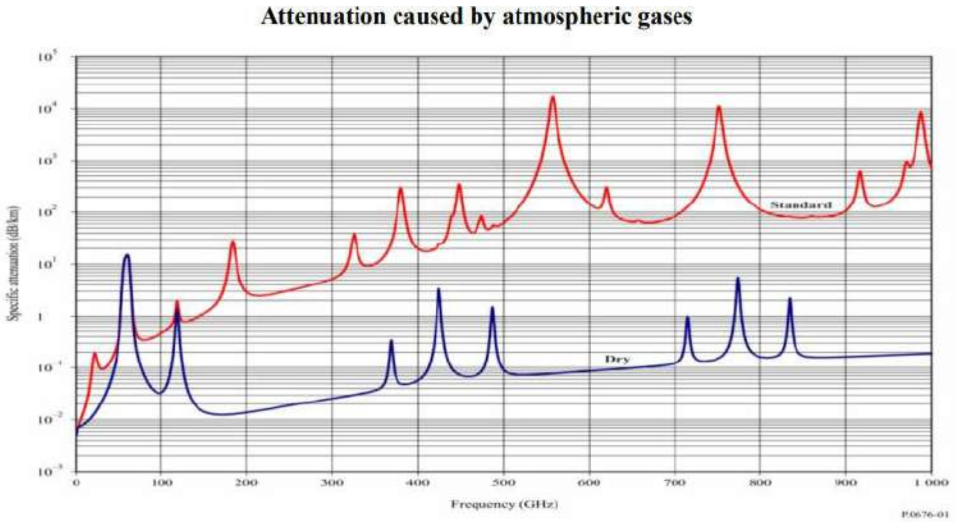


Figure 21: - Attenuation caused by atmospheric gases at 0-1 000 GHz at 1 GHz intervals [Rep. ITU-R M.2541-0]

C. Weather Effects: -

Terahertz (THz) signals, which lie in the electromagnetic spectrum between the microwave and infrared regions (approximately 0.1 to 10 THz), hold great promise for high-speed wireless communication, imaging, and sensing. However, one of the most significant challenges to the widespread deployment of THz technologies is their sensitivity to atmospheric conditions. Unlike lower-frequency signals such as those in the microwave or radio wave bands, THz waves are heavily influenced by weather phenomena due to their relatively short wavelengths and higher frequencies.

Water vapor in the atmosphere is one of the most dominant attenuating factors for THz propagation. Molecules of water exhibit strong absorption resonances in the THz range, leading to high signal attenuation, especially in humid conditions. As a result, even moderate levels of atmospheric moisture can significantly reduce the transmission range and reliability of THz systems. Rain and fog further exacerbate signal degradation by causing scattering and absorption. In rainy weather, raindrops scatter and absorb THz waves, introducing losses that are much higher than those experienced in conventional radio frequencies.

Similarly, fog, which consists of tiny water droplets suspended in air, causes Mie scattering of THz radiation, disrupting signal integrity and reducing effective communication distances. Snow and ice can also affect THz signals, though their impact is generally less severe compared to liquid precipitation, depending on the density and form of the snow particles.

Temperature and atmospheric pressure can indirectly influence THz propagation as well. Variations in temperature affect the refractive index of the air, which can lead to beam steering or dispersion effects. Furthermore, temperature-dependent changes in humidity exacerbate the absorption issue. Atmospheric pressure influences the line-broadening effect of water vapor and other gases, slightly altering the absorption profile at specific THz frequencies. Additionally, the presence of airborne particles such as dust or pollution can contribute to signal scattering and further reduce THz communication performance. These weather-related challenges have prompted researchers to explore ways to mitigate environmental attenuation in THz systems, such as using adaptive beamforming, error correction techniques, and environmental awareness protocols.

In some applications, such as short-range indoor communications or controlled environments like labs or data centers, the weather has minimal impact on THz performance. However, for outdoor or long-distance applications, especially in varying and unpredictable climatic conditions, understanding and compensating for weather effects becomes critical. Accurate weather modeling and prediction tools are essential in network planning and management to ensure the robustness and reliability of THz-based systems. Therefore, while terahertz technology offers high data rates and advanced capabilities, its vulnerability to environmental factors, especially weather, remains a primary technical hurdle.

D. Blockage Loss: -

Blockage loss is a critical factor affecting the performance and reliability of terahertz (THz) communication systems, especially in non-line-of-sight (NLOS) and dynamic environments. Terahertz signals, have extremely short wavelengths and high frequencies compared to conventional radio or microwave systems. As a result, they exhibit highly directional propagation and poor diffraction around obstacles. This makes THz waves particularly susceptible to blockage by physical objects such as buildings, vehicles, furniture, foliage, and even the human body. The penetration ability of electromagnetic waves above 92 GHz is much weaker than that of low frequency. The penetration loss varies greatly with material properties. Recommendation ITU-R P.2109 estimates building entry loss. The measured penetration loss of clear glass can reach 27.6 dB/cm at 144 GHz while 4.4 dB/cm at 28 GHz

When a THz signal encounters such obstructions, it experiences significant attenuation or complete disruption, as the signal cannot bend around the object effectively. This is in stark contrast to lower-frequency signals, which can diffract or reflect to some extent and maintain communication paths despite obstructions. The severity of blockage loss in THz systems depends on various factors including the size, material, and density of the obstructing object, as well as the distance between the transmitter and receiver. For instance, dense materials like metal, concrete, or water-rich substances cause near-total absorption or reflection of THz waves, resulting in complete signal loss. Even smaller or less dense objects, such as human limbs or clothing, can introduce substantial signal degradation due to the high absorption characteristics of water content at THz frequencies.

This becomes particularly problematic in mobile or indoor environments where dynamic blockages, such as moving people or objects, frequently interrupt the line-of-sight path. Unlike in microwave or millimeter-wave systems, the THz signal cannot easily find alternative propagation paths through reflection or scattering, making fast recovery and rerouting mechanisms essential.

To address the issue of blockage loss, researchers have explored several mitigation strategies. One approach is the deployment of dense and intelligent reconfigurable surfaces (RIS) or relay nodes that can redirect the signal around obstructions. Another is the use of beam steering and beam tracking technologies, which rapidly adjust the direction of the THz beam in real-time to maintain connectivity as blockages arise. Advanced signal processing techniques, such as multi-path exploitation and channel prediction algorithms, are also being developed to predict and compensate for potential blockage scenarios. Furthermore, hybrid network architectures that integrate THz links with more robust lower-frequency channels can offer seamless fallbacks during THz link outages.

Despite these efforts, managing blockage remains one of the most significant challenges in enabling robust, high-capacity THz communications, especially for applications like indoor wireless networks, autonomous vehicles, and wearable technologies. Effective system design must take into account the high probability of line-of-sight disruption and incorporate redundancy, spatial diversity, and environmental awareness.

E. Channel sparsity:-

Channel sparsity is a key characteristic of terahertz (THz) communication systems, particularly due to the unique propagation environment at frequencies typically above 100 GHz. In these high-frequency bands, the number of significant multipath components is limited because of high free-space path loss, molecular absorption, and limited diffraction. As a result, the channel impulse response often contains only a few dominant paths, making the channel inherently sparse in both time and spatial domains. This sparsity can be advantageous, especially for designing efficient channel estimation and beamforming techniques using compressive sensing and sparse recovery algorithms.

Furthermore, in line-of-sight (LoS)-dominated scenarios, which are common at THz frequencies, the energy is mostly concentrated in a small number of directions, enabling highly directional transmission and reception using narrow beams. However, this also poses challenges such as beam alignment sensitivity and reduced robustness to blockage.

Despite these issues, channel sparsity allows for reduced training overhead and faster channel acquisition, which is crucial for ultra-high-speed and low-latency communication goals of next-generation wireless systems. It also opens opportunities for leveraging machine learning and adaptive beam selection strategies that can exploit the sparse structure to improve spectral and energy efficiency.

F. Channel Non-stationarity:-

Channel non-stationarity is a critical phenomenon in terahertz (THz) communication systems, particularly due to the unique propagation characteristics and sensitivity of the THz band, typically ranging from 100 GHz to 10 THz. Unlike traditional wireless systems operating at lower frequencies, where the channel is often assumed to be wide-sense stationary over time and space, THz channels are highly non-stationary. This non-stationarity arises due to rapid variations in the propagation environment, high susceptibility to blockages, molecular absorption, and the directional nature of antennas used in THz systems. As THz systems often rely on narrow beamforming to overcome high path loss, even small movements of the transmitter, receiver, or surrounding objects can cause significant fluctuations in the channel response, leading to time-variant and spatially variant characteristics.

Additionally, the channel impulse response may change significantly over very short distances due to the extremely short wavelength of THz waves. This results in different sets of dominant multipath components as the user moves, making spatial non-stationarity a prevalent issue. In scenarios with rich scattering or mobile users, the angular domain characteristics also change quickly, complicating beam alignment and channel tracking. Moreover, atmospheric conditions like humidity and temperature fluctuations further exacerbate temporal non-stationarity due to their impact on molecular absorption peaks. These rapid and unpredictable changes in the channel require adaptive and robust system designs.

To address channel non-stationarity, THz communication systems must employ advanced techniques such as real-time channel estimation, dynamic beam tracking, and machine learning-based predictive models. Reconfigurable intelligent surfaces (RIS) and intelligent reflecting surfaces can also help manage dynamic environments by providing alternate paths when direct line-of-sight is blocked.

G. Near-field Effect :-

Near-field effects are highly significant in terahertz (THz) communication systems, especially as frequencies exceed 100 GHz and antenna arrays become extremely large, as seen in ultra-massive MIMO (UM-MIMO) configurations. Traditionally, in lower-frequency systems, far-field assumptions—where wavefronts are considered planar and beamforming is direction-based—are valid due to the relatively large However, in THz systems, the much shorter wavelengths drastically reduce the Rayleigh distance, making the near-field region considerably larger. As a result, many practical communication scenarios fall into the near-field regime, particularly when large antenna arrays are used or when users are located relatively close to the transmitter. The Rayleigh distance R is

$$R=2D^2/\lambda$$

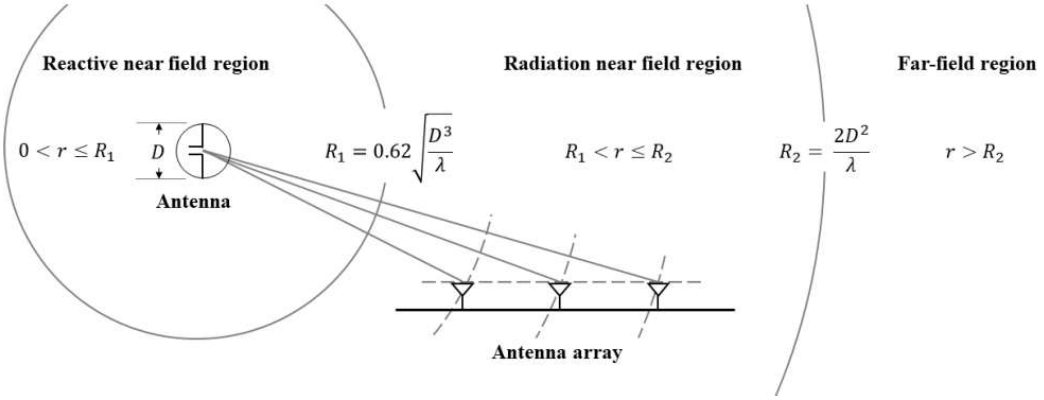


Figure 22: Near field Propogation [Rep. ITU-R M.2541-0]

In the near-field region, wavefronts are spherical rather than planar, leading to distance-dependent variations in signal phase and amplitude. This spatial variation introduces complexity in beamforming, as both direction and distance must be considered for optimal beam focus—known as beamfocusing rather than beamsteering. This effect alters the design of precoding and channel estimation techniques, requiring novel models that account for the spatial non-uniformity of the field. Furthermore, channel estimation becomes more complex due to the presence of spatially varying gains and delays across the array elements, deviating from the simpler angle-of-arrival/departure-based models in the far-field.

Near-field effects also influence system performance metrics such as spatial resolution and interference management. While they can be challenging, they offer opportunities to enhance performance through fine-grained spatial focusing and precise localization capabilities. However, user mobility poses additional challenges, as even small movements may necessitate dynamic beam recalibration to maintain optimal focusing. Addressing these issues requires advanced signal processing, 3D channel modeling, and possibly the integration of reconfigurable intelligent surfaces to manipulate near-field wavefronts.

H. Scattering Characteristics :-

Scattering characteristics in terahertz (THz) communication play a crucial role in defining the propagation behavior of signals, particularly due to the extremely short wavelengths (ranging from 30 µm to 3 mm) associated with frequencies above 100 GHz. At these high frequencies, objects with dimensions comparable to or larger than the wavelength—such as dust particles, wall textures, and human bodies—become effective scatterers. Unlike lower-frequency systems where diffuse scattering is often negligible, THz signals experience significant scattering even from minor surface irregularities. This results in a complex interplay of specular and diffuse components, contributing to both signal degradation and multipath propagation. The level and nature of scattering heavily depend on material properties, surface roughness, and the angle of incidence. For example, rough surfaces like concrete or brick tend to produce stronger diffuse scattering, whereas smooth surfaces like metal or glass yield more specular reflections.

In indoor environments, this scattering can sometimes aid in maintaining connectivity through non-line-of-sight (NLoS) paths, although these paths typically exhibit higher attenuation. However, the high frequency also means that the energy of scattered signals drops rapidly, leading to channel sparsity. Scattering at THz frequencies is also sensitive to environmental changes such as humidity, temperature, and object mobility, making the channel highly dynamic. Understanding and modeling these scattering effects accurately is vital for the design of reliable THz communication systems, influencing decisions on antenna placement, beamforming strategies, and channel estimation algorithms. As such, scattering is not just a challenge but also a fundamental characteristic that shapes the overall performance and reliability of THz wireless networks.

5. Enabling Technologies for Terahertz Communication

Enabling technologies for terahertz (THz) communication are pivotal to unlocking the vast potential of ultra-high-speed wireless networks, particularly for future 6G systems. Due to the unique challenges posed by the THz band, such as high free-space path loss, atmospheric absorption, and hardware limitations, several breakthrough technologies are being developed. Key among these are advanced semiconductor devices like resonant tunneling diodes (RTDs), high-electron-mobility transistors (HEMTs), and quantum cascade lasers (QCLs) for efficient THz signal generation and detection. Photonic-based approaches, such as photomixing and optical rectification, are also crucial for achieving tunable and high-purity THz sources.

Additionally, metamaterials and plasmonic structures are enabling the development of miniaturized, tunable THz antennas and modulators. Advanced channel modeling, incorporating effects like scattering, absorption, and non-stationarity, is critical for designing robust transceivers. Integration with silicon photonics and III-V compound semiconductors is further enhancing the feasibility of compact, low-power THz transceivers. Some of the technologies are given below :

5.1 Antenna Technologies: -

Antenna technology plays a pivotal role in enabling terahertz (THz) communication, which promises ultra-high data rates for next-generation wireless networks such as 6G. Due to the extremely short wavelengths at THz frequencies (ranging from 3 mm to 30 μm), antennas must be designed with high precision and often on a microscale. Traditional antenna designs face significant challenges at THz bands, including high free-space path loss, limited gain, fabrication complexity, and integration issues.

As a result, advanced antenna technologies are being explored, such as **plasmonic antennas**, which exploit surface plasmon polaritons to confine and guide electromagnetic energy at the nanoscale, improving efficiency and enabling ultra-compact designs. **Leaky-wave antennas, on-chip antennas, and phased array systems** are also gaining attention due to their high directivity and beam steering capabilities, which are critical for overcoming the directional nature of THz signals.

Materials like graphene and metamaterials are further revolutionizing antenna performance by enabling tunability, flexibility, and miniaturization. Integration with CMOS and silicon photonics platforms is allowing the development of highly compact, cost-effective THz antenna systems suitable for chip-scale integration.

Moreover, reconfigurable antennas using MEMS or tunable substrates are being developed to dynamically adapt radiation patterns, frequency bands, and polarization states in real time. These innovations not only address propagation challenges but also support functionalities like beamforming and spatial multiplexing.

The antenna technologies which will be suitable for terahertz communication are:-

A. **Photo-conductive lens antenna**: -

A photoconductive lens antenna is a critical component in terahertz systems, designed to efficiently generate and direct THz radiation. It typically consists of a photoconductive antenna fabricated on a semiconductor substrate, such as low-temperature-grown GaAs, coupled with a hyper-hemispherical silicon or quartz lens. When excited by ultrafast optical pulses, the photoconductive material emits THz radiation, which is then collimated and focused by the lens to achieve high directivity and low beam divergence.

B. **Reflect-array and transmit-array**:-

Reflect-arrays and transmit-arrays are advanced planar antenna technologies used to control and shape electromagnetic wavefronts, including in terahertz communication. A reflect-array consists of a planar surface with an array of passive or active elements that reflect incident waves with adjustable phase shifts, enabling beam steering and focusing.

Transmit-arrays, in contrast, allow electromagnetic waves to pass through the surface while manipulating their phase, effectively acting like a flat lens. Both arrays offer low-profile, lightweight alternatives to bulky conventional antennas, and are particularly valuable at terahertz frequencies for enabling high-gain, steerable beams in compact, cost-effective designs suited for 6G and imaging applications.

C. Metasurfaces :-

Metasurfaces are engineered, ultrathin structures composed of subwavelength elements that can manipulate electromagnetic waves with high precision. In terahertz communication, metasurfaces are used to control the phase, amplitude, and polarization of THz waves, enabling dynamic beam steering, wavefront shaping, and polarization conversion. Their low-profile, compact nature makes them ideal for integration into THz systems, overcoming limitations of traditional bulky optical components. Tunable metasurfaces, using materials like graphene or liquid crystals, offer real-time reconfigurability, crucial for adaptive communication environments. As a result, metasurfaces are pivotal in developing efficient, high-performance antennas and transceivers for next-generation THz wireless and sensing applications.

D. Nano-photodetectors: -

Nanophotodetectors are ultra-sensitive, nanoscale devices designed to detect light, including terahertz (THz) and infrared radiation, with high speed and resolution. These detectors use advanced nanomaterials such as graphene, quantum dots, or nanowires, which exhibit strong light-matter interaction and ultrafast carrier dynamics. In terahertz communication, nanophotodetectors play a critical role in enabling compact, low-power, and high-frequency detection systems. Their small size allows easy integration into on-chip systems, supporting miniaturized, high-speed THz receivers. Additionally, they offer enhanced sensitivity, low noise, and broad spectral response, making them ideal for applications in THz imaging, spectroscopy, wireless data reception, and quantum sensing technologies.

E. Antenna-on-chip and antenna-in-package: -

Antenna-on-chip (AoC) and antenna-in-package (AiP) are two integration approaches critical for terahertz (THz) communication systems, aiming to miniaturize and enhance high-frequency performance. **Antenna-on-chip** integrates the antenna directly onto the same semiconductor substrate as the transceiver circuitry, offering compact size, reduced parasitics, and cost-effective mass production. However, AoC often suffers from substrate losses and limited radiation efficiency due to high dielectric losses in silicon.

In contrast, **antenna-in-package** places the antenna within the device packaging, often on an interposer or the package substrate, allowing more flexibility in material choice and better radiation efficiency. AiP provides design freedom for optimizing antenna performance while maintaining close proximity to active circuits, ensuring reduced signal loss and improved system integration. Both technologies are essential for developing compact, high-frequency systems, especially at THz bands, where traditional antenna designs are impractical.

5.2 Semiconductor Technologies: -

Semiconductor technology is at the heart of advancing terahertz (THz) communication, providing the foundational platform for developing efficient sources, detectors. Due to the challenges in generating and detecting THz signals using traditional electronics or optics, specialized semiconductor materials and devices have become critical enablers. Compound semiconductors such as gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), and silicon-germanium (SiGe) are widely used in the fabrication of high-electron-mobility transistors (HEMTs), heterojunction bipolar transistors (HBTs), and resonant tunneling diodes (RTDs), all of which are capable of operating at THz frequencies. These materials offer superior carrier mobility and higher breakdown voltages compared to silicon, allowing faster signal transitions and reduced power losses.

Quantum cascade lasers (QCLs), based on semiconductor heterostructures, are among the most promising THz sources, providing coherent radiation in the mid to far-infrared range. On the detection side, Schottky diodes, photoconductive antennas, and

bolometers built on semiconductor substrates enable efficient THz signal capture with high sensitivity and bandwidth.

As high integration capability is an important requirement for above 100 GHz adaptive antenna systems (AAS), neither GaAs nor InP semiconductor technology, are seen as appropriate for IMT2030 systems. In this context, the silicon-based technology, complementary metal oxide semiconductor (CMOS) and silicon germanium (SiGe), are considered to be the feasible technologies, owing to their cost and integration advantages over the III-V compounds technologies. CMOS-compatible THz circuits are under active research, aimed at integrating THz components on silicon for cost-effective, large-scale production. Advances in nanofabrication and material engineering, such as the use of 2D materials like graphene and black phosphorus, are further expanding the capabilities of semiconductor devices for THz communication. These materials exhibit ultrafast electron mobility and tunable electrical properties, ideal for ultrathin, flexible, and tunable THz components.

5.3 Material Technologies: -

One of the key difficulties in operating above the 92 GHz frequency band is the highly obstructed propagation environment, primarily caused by significant signal attenuation and blockages. To address this, following technology is useful: -

Reconfigurable Intelligent Surfaces (RISs):-

Reconfigurable Intelligent Surfaces (RISs) are an emerging technology poised to revolutionize wireless communication, especially in challenging environments such as high-frequency millimeter-wave (mmWave) and terahertz (THz) bands. RISs are engineered surfaces made up of a large number of small, programmable unit cells that can dynamically manipulate electromagnetic waves in real time. Each unit cell can independently adjust parameters such as the phase, amplitude, and polarization of incident signals, thereby enabling the control of the wave’s direction and behavior without requiring active transmission. This ability allows RISs to reflect, refract, or focus wireless signals towards specific directions, overcoming obstacles and enhancing coverage in non-line-of-sight (NLOS) scenarios.

The working principle of RISs is based on the concept of metasurfaces, which can steer and shape wavefronts by modifying the electromagnetic response at the sub-wavelength level. By integrating electronic components like varactor diodes, PIN diodes, or tunable materials such as liquid crystals or graphene, each unit cell becomes tunable and reconfigurable through software control. This reconfigurability allows RISs to adapt dynamically to changing communication environments, user locations, and channel conditions.

RISs can operate in passive or active modes. In the passive mode, RISs simply reflect incoming signals without amplifying them, requiring minimal energy and no RF chains, thus making them energy-efficient and cost-effective. In contrast, active RISs are equipped with signal amplification and even digital processing capabilities, allowing them to function similarly to relay nodes or distributed MIMO systems. The deployment of RISs enhances spectral efficiency, extends coverage, improves signal strength, and reduces power consumption, making them ideal for 6G and future wireless networks. Their effectiveness depends on parameters such as surface size, number of elements, incident angle of incoming waves, and placement relative to the transmitter and receiver. With increasing research and prototype development, RISs are expected to become a key enabler in next-generation wireless ecosystems.

6. Identification of frequency bands of interest for THz communication systems

Based on the regulatory status and application scenarios, the frequency band 100 GHz - 10 THz is discussed in three ranges, as shown in Figure below: -

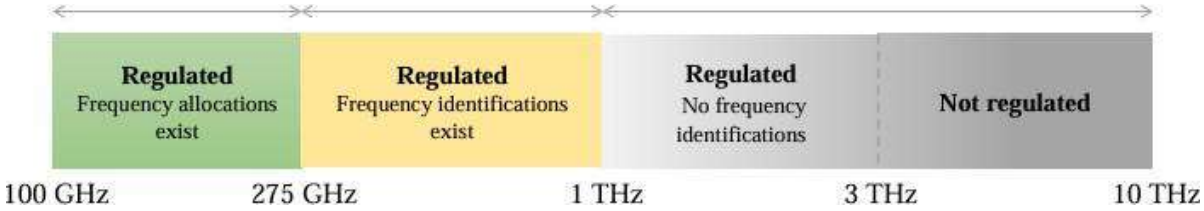


Figure23: Frequency Ranges within the THz band with different regulatory status [ETSI GR THz 002 V1.1.1]

Frequency bands between 100 and 275 GHz are already allocated for terrestrial services on an international level through the ITU-R Radio Regulations. Sharing and compatibility scenarios have been investigated up to 450 GHz. As technology evolves, the THz frequency band is becoming more feasible for exploitation, and the need to identify the most interesting parts increase.

6.1 Frequency range 100 - 275 GHz: -

The frequency range 100 - 275 GHz is included in the Table of Frequency Allocations of the Radio Regulations. Following decisions at WRC in total 20 bands are allocated MOBILE and FIXED services, some adjacent to each other, on a co-primary basis with other services, summing up to a total of 98,4 GHz of available bandwidth for terrestrial radio communications applications.

Based on this and limiting to available contiguous bandwidth of 6 GHz, the frequency range 100 - 275 GHz is subdivided into the following eight frequency bands of interest:

- Frequency Band 1: 102 - 109,5 GHz.
- Frequency Band 2: 141 - 148,5 GHz.
- Frequency Band 3: 151,5 - 164 GHz.
- Frequency Band 4: 167 - 174,8 GHz.
- Frequency Band 5: 191,8 - 200 GHz.
- Frequency Band 6: 209 - 226 GHz.
- Frequency Band 7: 231,5 - 239,2 GHz.
- Frequency Band 8: 252 - 275 GHz.

Table 2 :- Services allocations in Frequency Range 100–275 GHz [ETSI GR THz 002 V1.1.1]

Frequency Range (GHz)	**Bandwidth (GHz)**	**Band No.**	**Services Allocated To**
102 – 109.5	7.5	Band 1	FIXED, MOBILE, RAS, SRS
141 – 148.5	7.5	Band 2	FIXED, MOBILE, RLS, RAS
151.5 – 164	12.5	Band 3	FIXED, MOBILE, RAS, RLS, FSS, MSS
167 – 174.8	7.8	Band 4	FIXED, MOBILE, FSS, ISS
191.8 – 200	8.2	Band 5	FIXED, MOBILE, ISS, MSS, RNS, RNSS
209 – 226	17	Band 6	FIXED, MOBILE, SRS, FSS, RAS
231.5 – 239.2	7.7	Band 7	FIXED, MOBILE, FSS, EESS, SRS, RLS, RNS, RNSS
252 – 275	23	Band 8	FIXED, MOBILE, RAS, FSS, MSS, RNS, RNSS

6.2 Other frequency bands between 100 - 275 GHz

There are more frequency bands in the range between 100 - 275 GHz which are allocated on a co-primary basis to FIXED and MOBILE services. Table below lists the frequency bands with less than 6 GHz contiguous bandwidth.

Table 3:- Overview of other frequency bands between 100 - 275 GHz with FIXED and MOBILE allocations [ETSI GR THz 002 V1.1.1]

Band #	**Frequency range**	**Absolute bandwidth**	**Fractional bandwidth**	**Services Allocated To**
1	111.8-114.25 GHz	2.45 GHz	2.2%	FIXED, MOBILE, RAS, SRS
2	122.25-123 GHz	0.75 GHz	0.6%	TBD
3	130-134 GHz	4 GHz	3%	FIXED, MOBILE, ISS, RAS, EESS(active)

A lack of sufficiently wide, contiguous bandwidth poses a significant constraint—not just for enabling ultra-high bitrates, but also from a practical implementation standpoint. Using narrower frequency bands demands sharper filters in transceivers, which must have a higher quality factor (Q). These high-Q filters tend to be costlier, though technological advances are continually expanding what's achievable.

In addition to the bands described in the previous clauses a couple of smaller fragmented spectrum parts exist between 100 GHz and 275 GHz. Due to the small channel bandwidth available in these spectrum parts, these bands are of less interest for THz communications and might be used for specific applications only.

6.3 Frequency range 275 - 1 000 GHz

The frequency range between 275 and 1000 GHz is not allocated to specific services, but identified for use by administrations for passive and active service applications. The frequency band 275 - 1000 GHz is subdivided into the following 12 frequency bands:

- Frequency Band 1: 275 - 296 GHz.
- Frequency Band 2: 296 - 306 GHz.
- Frequency Band 3: 306 - 313 GHz.
- Frequency Band 4: 313 - 318 GHz.
- Frequency Band 5: 318 - 321 GHz.
- Frequency Band 6: 327 - 333 GHz.
- Frequency Band 7: 333 - 356 GHz.
- Frequency Band 8: 356 - 368 GHz.
- Frequency Band 9: 391 - 433 GHz.
- Frequency Band 10: 452 - 520 GHz.
- Frequency Band 11: 598 - 722 GHz.
- Frequency Band 12: 786 - 953 GHz.

Table 4:- Frequency Range 275-1000 GHz [ETSI GR THz 002 V1.1.1]

Frequency Band No.	**Frequency Range (GHz)**	**Transmission Window (TW)**	**Identified Services**	**Notes**
Band 1	275 – 296	TW2	Fixed, Mobile	Identified at WRC-19; Exclusion zones for radio astronomy.
Band 2	296 – 306	TW2	Fixed, Mobile (Conditional)	Protection of passive services required under Resolution 731.
Band 3	306 – 313	TW2	Fixed, Mobile	Studies ongoing under WRC-27 & WRC-31.
Band 4	313 – 318	TW2	Fixed, Mobile (Conditional)	Conditional use based on Resolution 731 for passive service protection.
Band 5	318 – 321	TW2	Fixed, Mobile	Same as Band 1 and 3.
Band 6	327 – 333	TW3	Fixed, Mobile	Protection required for radio astronomy.
Band 7	333 – 356	TW3	Fixed, Mobile (Conditional)	Conditional use; co-existence with passive services addressed under Resolution 731.
Band 8	356 – 368	TW3	Fixed, Mobile	Co-sharing scenarios considered.
Band 9	391 – 433	TW4	Fixed, Mobile	Includes passive allocations. Shared with Earth exploration and space research services.
Band 10	452 – 520	TW5	Fixed, Mobile	Passive service sharing identified (e.g., RAS, EESS, SRS).
Band 11	598 – 722	TW6	Fixed, Mobile	Co-shared with passive services like RAS.

Frequency Band No.	Frequency Range (GHz)	Transmission Window (TW)	Identified Services	Notes
Band 12	786 – 953	TW7	Fixed, Mobile	Co-existence with passive services like RAS, EESS; part of ITU-R studies.

6.4 Frequency band 1000 GHz - 3000 GHz

The high path loss in this frequency band and the very short transmission ranges makes interference unlikely and enables sharing without further mitigation measures. All frequencies in this band may be used by both active and passive services. No specific protections are required. This frequency band can be used without any regulatory restrictions.

7. Terahertz (THz) Devices: Global Landscape

Terahertz (THz) radiation occupies the electromagnetic spectrum between microwaves and infrared light, typically ranging from 0.1 to 10 THz. This frequency band has garnered significant attention due to its unique properties, such as the ability to penetrate various materials and its non-ionizing nature, making it suitable for applications in imaging, spectroscopy, and high-speed wireless communications. The development of THz devices is crucial for harnessing these properties in practical applications.

7.1 Global Developments in Terahertz Devices

A. Canon's Semiconductor Terahertz Source [2024]

Canon has developed a groundbreaking semiconductor terahertz source that is significantly smaller and more powerful than conventional systems. Using resonant-tunneling diodes (RTDs) integrated with a 36-element antenna array, it achieves 10 milliwatts of output at 450 GHz—ten times higher than typical semiconductor sources. The device is 1,000 times more compact and offers 20 times the directivity of traditional setups. This innovation enables efficient, long-range terahertz transmission without bulky optics. Potential applications include 6G communications, security screening, non-destructive testing, and medical imaging.

B. ROHM's Resonant Tunneling Diode-Based THz Devices [2025]

ROHM Semiconductor has introduced the industry's smallest terahertz (THz) wave oscillation and detection devices, leveraging Resonant Tunneling Diodes (RTDs) to advance terahertz wave applications and pave the way for ultra-fast communication technologies. These devices offer a promising alternative to conventional wireless transmission and enable high-resolution radar sensing. The RTD chip, measuring just 0.5mm × 0.5mm, operates at a typical frequency of 320GHz and delivers an output power of 10–20μW. Mounted in a compact PLCC package (4.0mm × 4.3mm) commonly used for LEDs, this innovation is over a thousand times smaller than conventional oscillators. Its ultra-compact design supports terahertz wave applications, even in space-constrained environments. Terahertz waves hold significant potential for applications such as nondestructive testing, imaging, and sensing in the medical and healthcare sectors. When the antenna surfaces of the oscillation and detection devices are positioned 10mm apart, they achieve a typical dynamic range of 40 dB. These devices operate at room temperature, consuming just 10mW of power, eliminating the need for cooling equipment required by some conventional methods..

C. TeraView's Terahertz Imaging Systems

Terahertz Imaging Systems offers advanced imaging systems that utilize terahertz pulsed imaging for non-destructive analysis across various industries. In pharmaceuticals, this systems provide 3D maps of tablet coatings, aiding in quality control and manufacturing efficiency.

In the semiconductor sector, their Electro-Optical Terahertz Pulse Reflectometry (EOTPR) enables high-resolution fault isolation in advanced packaging. Their technology also supports art restoration by revealing hidden layers in artworks. Additionally, these systems are employed in medical imaging, offering potential in cancer detection due to terahertz radiation's sensitivity to water content in tissues. These versatile applications underscore TeraView's role in advancing terahertz imaging solutions

D. Sustainable Materials in THz Devices

Sustainable materials are increasingly being integrated into terahertz (THz) devices to reduce environmental impact while maintaining high performance. Researchers are exploring eco-friendly substrates like cellulose nanofibers, biodegradable polymers, and recyclable metals for antennas and packaging. These materials offer mechanical flexibility, low cost, and minimal ecological footprint. Additionally, advances in additive manufacturing and green fabrication processes further support low-energy, waste-reducing production of THz components. Sustainable THz devices are particularly promising for wearable sensors, medical diagnostics, and portable imaging systems. The shift toward environmentally responsible materials aligns with global efforts to create greener electronics without compromising the functionality or efficiency of THz technologies.

7.2 Terahertz Research in India

A. Defence Research and Development Organisation (DRDO)

The Defence Research and Development Organisation (DRDO) has been actively advancing terahertz (THz) technologies to bolster India's defense capabilities. Key DRDO laboratories, including the Solid State Physics Laboratory (SSPL), Instruments Research and Development Establishment (IRDE), and Microwave Tube Research and Development Centre (MTRDC), are spearheading research in THz sources, detectors, and applications.

SSPL focuses on developing advanced semiconductor devices, such as Gallium Nitride (GaN) and Gallium Arsenide (GaAs) based components, which are crucial for high-frequency THz applications. These efforts aim to achieve self-reliance in critical technologies like high-power amplifiers and laser diodes, essential for directed energy weapons and communication systems.

IRDE is engaged in designing and developing optical and electro-optical instruments, including THz imaging systems. Their work encompasses the creation of terahertz sources and imaging technologies for surveillance and reconnaissance, enhancing capabilities in target identification and acquisition under various environmental conditions.

MTRDC has organized specialized courses on sub-THz technologies, emphasizing the design and realization of devices operating in the sub-terahertz frequency range. These initiatives are critical for developing solid-state sources and components for advanced communication and sensing applications.

B. IIT Guwahati:

The Terahertz Optics and Meta-Photonics Laboratory at the Indian Institute of Technology Guwahati, is a leading research facility dedicated to advancing terahertz (THz) photonics and metamaterials. Established in 2013, the lab focuses on both theoretical and experimental studies in areas such as terahertz plasmonics, metamaterials, guided wave devices, and nanoporous silicon applications. A significant aspect of the research involves developing terahertz plasmonic devices using corrugated structures and exploring near-field coupling in terahertz metamaterials and sensors.

The research has led to notable publications, such as studies on tunable terahertz absorption modulation in graphene-assisted dielectric metamaterials and thin-film sensing characteristics in terahertz meta-waveguide structures.

C. IIT Roorkee:

IIT Roorkee is at the forefront of terahertz (THz) technology research, focusing on innovative designs for communication, sensing, and biomedical applications. The Department of Electronics and Communication Engineering houses the Terahertz Communication and Sensing (TCS) group, which is actively developing advanced THz devices and systems. One notable project is the collaboration with the Centre for Development of Telematics (C-DOT) to develop a 140 GHz fully integrated transmitter and receiver module for 6G and beyond. This initiative aims to create compact, energy-efficient THz chips suitable for portable devices, enabling ultra-high-speed data transfer with reduced latency.

D. IIT Delhi:

Researchers at the Indian Institute of Technology (IIT) Delhi have developed a groundbreaking device capable of emitting high-intensity terahertz (THz) radiation, marking a significant advancement in the pursuit of next-generation 6G communication technologies.

The newly developed device, termed a spintronic terahertz emitter, operates on a bilayer system composed of ferromagnetic and non-magnetic materials. Specifically, the team utilized a combination of cobalt and platinum to create a semimetal material that generates high-intensity pulses in the terahertz frequency range. Unlike existing THz sources that often require low-temperature environments, this device functions efficiently at room temperature, enhancing its practicality for real-world applications. The high-frequency radiation emitted by the device holds promise for revolutionizing various sectors like Medical Imaging, Wireless communications for faster and more secure wireless network. This research was a collaborative effort between IIT Delhi's Center for Applied Research in Electronics (CARE) and the National University of Singapore

E. Tata Institute of Fundamental Research (TIFR)

The Tata Institute of Fundamental Research (TIFR) in Mumbai established India's first terahertz (THz) laboratory in 1998, marking a significant milestone in the country's scientific research landscape. The lab initially specialized in ultrafast spectroscopy of semiconductors, focusing on carrier dynamics in semiconductor nanostructures and bulk crystals using techniques like time-resolved photoluminescence, nonlinear photoluminescence, degenerate four-wave mixing, and differential reflectance.

Building upon this foundation, the laboratory expanded its research scope to include terahertz spectroscopy. Under the leadership of Professor Shriganesh Prabhu, the lab developed new THz sources, detectors, and home-built spectroscopy setups. The research encompassed various areas, including THz spectroscopy of materials, THz optical properties of crystals, THz plasmonics, and photonic crystals. Notably, the lab achieved a significant milestone by capturing India's first THz image of Mahatma Gandhi from the watermark of a ₹500 currency note.

F. Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR)

The Ultrafast Terahertz Spectroscopy and Photonics (UTSP) Lab at the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Bengaluru focuses on exploring the fundamental properties of emerging quantum materials using ultrafast terahertz (THz) spectroscopy. Under the leadership of Dr. Abhishek Kumar, the lab investigates light–matter interactions in quantum materials, aiming to understand phenomena such as light–electron and light–spin interactions, as well as hidden orders in equilibrium or excited states. The UTSP Lab's research encompasses two primary areas:

a. **Spectroscopic Investigation of Emerging Quantum Materials:** Utilizing ultrafast THz spectroscopy, the lab probes the interactions between light and various degrees of freedom in quantum materials, including spin, charge, orbital, and phonon. This approach enables the disentanglement of these interrelated properties, providing insights into many-body phenomena and unconventional light–matter interactions.

b. **Micro-Nano Photonics for Disruptive Applications**: The lab also focuses on developing micro- and nanoscale photonic devices that leverage the unique properties of quantum materials. These devices have potential applications in areas such as high-speed communication, sensing, and quantum information processing.

G. Indian Institute of Science (IISc)

The Tera-QuaNTA Research Laboratory at the Indian Institute of Science (IISc), Bengaluru, is a leading center for terahertz (THz) science and technology, focusing on ultrafast spectroscopy and the development of THz photonic and spintronic devices. Under the leadership of Dr. Manukumara Manjappa, the lab investigates the fundamental properties of low-dimensional quantum and topological materials using advanced THz spectroscopic techniques. These techniques enable the probing and control of spin, charge, and lattice dynamics, facilitating studies in strong-field and ultrafast physics within the realms of cavity quantum electrodynamics (c-QED) and pump-probe experiments.

8. Regulatory Landscape for Terahertz Communication in India

India is actively shaping a forward-looking regulatory framework for terahertz (THz) communication, especially as it eyes leadership in 6G technology. The Telecom Regulatory Authority of India (TRAI) has proposed a comprehensive set of recommendations on Tera Hertz Spectrum dated 21.08.2024, to unlock the potential of the 95 GHz to 3 THz frequency range.

Here are the key highlights:

1. TeraHertz Experimental Authorization (THEA): A new licensing framework designed to promote R&D, testing, and trials in the THz band. It allows Indian entities—including academic institutions, R&D labs, and telecom providers—to conduct experiments and even market experimental devices.

2. Low-Cost Access: THEA comes with a nominal fee of ₹1,000 for a five-year period, making it accessible to a wide range of innovators.

3. Open Bands: Specific frequency bands—like 116–123 GHz, 174.8–182 GHz, 185–190 GHz, and 244–246 GHz—are recommended for license-exempt operations, encouraging broader experimentation.

4. Automotive Radar: The 77–81 GHz band is being opened up for radar systems, a move aimed at enhancing road safety through advanced driver-assistance technologies.

These steps are part of India's broader ambition to become a global hub for 6G R&D, with the THz spectrum expected to play a pivotal role in ultra-high-speed, low-latency communication systems.

9. Conclusion

Terahertz (THz) communication and sensing represent a transformative field at the intersection of photonics, quantum physics, and next-generation wireless engineering. The terahertz band, typically defined as spanning 0.1 to 10 THz, lies between the microwave and infrared regions of the electromagnetic spectrum and has long been underutilized due to technological limitations in generation, detection, and modulation. However, recent advancements in materials science, ultrafast spectroscopy, and nanotechnology have reignited global interest in exploiting the unique properties of the THz range. THz waves offer extremely high bandwidths—orders of magnitude greater than current sub-6 GHz and mmWave bands—making them critical enablers of 6G and beyond wireless communication systems. Simultaneously, their ability to penetrate non-metallic materials without ionizing biological tissues positions them as invaluable tools in imaging, spectroscopy, and sensing applications across domains such as biomedicine, security, and industrial quality control.

From a communications perspective, the THz band holds the promise of delivering ultrafast wireless data rates—up to hundreds of Gbps or even Tbps—over short distances. This capability is vital for supporting emerging data-intensive applications like holographic video conferencing, immersive virtual reality, and real-time massive machine-type communications in smart cities. Unlike optical fibers, THz links can support high-speed connectivity in dynamic and mobile environments, such as satellite-to-satellite or drone-based backhaul networks. To overcome this, researchers are exploring beamforming, reconfigurable intelligent surfaces, adaptive modulation schemes, and channel coding tailored for the highly dynamic and lossy THz propagation environment. Additionally, device miniaturization and integration challenges are being addressed through advanced fabrication techniques and novel THz materials, such as graphene, 2D semiconductors, and topological insulators, which exhibit favorable optoelectronic properties at THz frequencies.

In sensing and imaging, THz radiation offers several distinct advantages. First, it is non-ionizing, making it safer than X-rays for biological applications. Second, many organic molecules and explosives exhibit unique absorption signatures in the THz band, enabling chemical identification through THz time-domain spectroscopy (THz-TDS). This capability is being harnessed for security screening at airports, non-invasive cancer diagnostics, and the detection of hazardous substances. THz imaging can reveal structural details hidden beneath surface layers, allowing for the inspection of semiconductor wafers, pharmaceutical tablets, and composite materials. In biomedical research, THz spectroscopy is being used to study hydration dynamics, protein folding, and DNA conformational changes—phenomena that are otherwise difficult to probe at molecular time and length scales. One of the most exciting developments is the integration of THz systems with artificial intelligence and machine learning, enabling intelligent interpretation of spectroscopic data and enhancing the sensitivity and specificity of THz-based sensors.

To realize the full potential of THz technologies, multidisciplinary collaboration is essential. Physicists are developing novel THz sources and detectors, such as quantum cascade lasers, spintronic emitters, and photoconductive antennas, that operate at room temperature and with high efficiency. Electrical engineers are designing THz transceivers, circuits, and antennas capable of high-speed modulation and integration with existing semiconductor platforms. Materials scientists are creating metamaterials and photonic crystals with engineered dispersion properties for manipulating THz waves. On the systems side, network architects are exploring how THz links can be embedded within hybrid 6G networks, dynamically switching between optical fiber, mmWave, and THz depending on bandwidth, latency, and coverage requirements. Furthermore, regulatory bodies are beginning to allocate spectrum above 100 GHz, paving the way for commercial deployment of THz communication systems in the near future.

The global research landscape in this domain is vibrant and rapidly evolving. Institutions like the Tata Institute of Fundamental Research (TIFR) established India's first THz laboratory as early as 1998, laying the foundation for ultrafast spectroscopy studies in semiconductors and nanostructures. More recently, IIT Delhi developed a spintronic THz emitter using a cobalt-platinum bilayer system, capable of operating at room temperature and generating intense THz radiation for communication and sensing applications. The Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Bengaluru established the Ultrafast Terahertz Spectroscopy and Photonics Lab to explore light–matter interactions in quantum materials, particularly focusing on excitonic and spintronic phenomena. Similarly, the Tera-QuaNTA Lab at the Indian Institute of Science (IISc) is conducting advanced research on THz photonics and spintronic devices, including pump-probe and cavity QED experiments on quantum materials. These initiatives align with national visions such as ―Bharat 6G‖ and ―Atmanirbhar Bharat,‖ with institutions like C-DOT collaborating to develop indigenous THz hardware.

While the technological potential of THz communication and sensing is vast, challenges remain. The high propagation loss of THz waves necessitates the development of directional antennas and repeaters. High-speed electronic-to-optical converters and modulators for THz systems are still in their infancy. Fabrication of low-cost, scalable THz components requires breakthroughs in nanomanufacturing and hybrid integration techniques. Moreover, standardization, interoperability, and cybersecurity in THz networks are active areas of research. Environmental concerns, such as the biological impact of prolonged THz exposure and the influence of atmospheric conditions on performance, also need further study.

In summary, terahertz communication and sensing constitute a transformative research frontier with the potential to redefine wireless communication, security, healthcare, and industrial monitoring. With its unprecedented bandwidth, unique interaction with matter, and capacity for non-invasive diagnostics, the THz spectrum holds the key to unlocking applications that span from 6G mobile systems to real-time chemical imaging and quantum photonic computing. As researchers continue to push the limits of materials, devices, and systems at THz frequencies, the vision of a connected, intelligent, and sensor-rich world powered by terahertz technologies is rapidly becoming a reality.

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Acronyms

IMT - International Mobile Telecommunications
6G – Sixth Generation
RAS - Radio Astronomy Service
SRS - Space Research Service
RLS - Radiolocation Service
FSS - Fixed-Satellite Service
MSS - Mobile-Satellite Service
ISS - Inter-Satellite Service
RNS - Radiodetermination Satellite Service *(sometimes also used for Radiocommunication Navigation Service)*
RNSS - Radio Navigation Satellite Service
EESS - Earth Exploration Satellite Service