



**VIRTUAL EXPERIENCE
OCTOBER 11-14**



Terahertz Spectrum

Challenges, Potential And Applications

A Technical Paper prepared for SCTE by

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1. Introduction

The way we create, share and consume information has led to a tremendous increase in wireless data traffic. The demand for wireless data continues to grow exponentially and that puts extreme requirements on the future communications systems. Each generation of mobile technology, from the first to the fifth (5G), has been designed to meet the new needs of end users and network operators. While the number of mobile connected devices is increasing rapidly, from 8.8 billion in 2018 to a predicted 13.1 billion by 2023, at the same, as anticipated by Edholm’s law of bandwidth, the achievable data-rate is scaling new heights, from 20 Gigabits per second (Gbps) of peak data rate in 5G to expectedly 1 Terabit per second (Tbps) within the next few years. Figure-1 shows the roadmap for the wireless data rates up to year 2035 and is a good indicator of the past and anticipated growth in data rates.

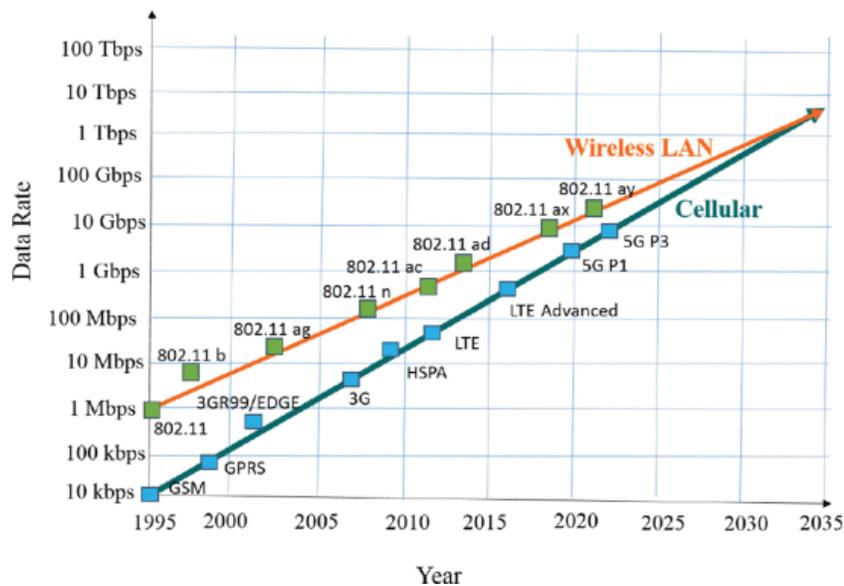


Figure 1 – Wireless Roadmap Outlook

Societies continue to become more and more intelligent, data-centric, data-dependent, and automated. Autonomous systems are hitting our roads, oceans, and air space. Millions of sensors will be embedded into cities, homes, and production environments, and new systems operated by artificial intelligence residing in local cloud and fog environments will enable a plethora of new applications. To glue this all together, communication networks will provide the nervous system for these new smart system paradigms. The demands, however, will be daunting. Networks will need to transfer much greater amounts of data at much higher speeds and lower latencies. Furthering a trend already started in 4G and 5G, sixth generation (6G) connections will move beyond personalized communication toward the full realization of the Internet of Things (IoT) paradigm, connecting not just people, but also computing resources, vehicles, devices, wearables, sensors, and even robotic agents. Beyond improving existing communication and signal processing solutions, there is a need to explore untapped frequency bands for communications. In order to enable the transmission of very high data rates (10s of Gbps), two approaches are possible. The first one is to improve spectral efficiencies beyond 10 bit/s/Hz for the systems operating at moderate bandwidths, which will be very challenging. The second

approach requires ultra-high bandwidths beyond 20 GHz while operating at moderate spectral efficiencies. But, such a large amount of spectrum is only available in the Terahertz (THz) frequency range, i.e., beyond 300 GHz.

THz band communications is being projected as a key enabling technology for next-generation wireless systems that promises to integrate a wide range of data-demanding and delay-sensitive applications. As more and more data move to the edge, the last meter solutions are getting more and more attention. The higher bandwidth and contention free data communication promised by terahertz spectrum is expected to be an important part of ITU (International Telecommunication Union) Network-2030 vision. As the wireless world moves toward 6G, radio layer Terabit per second (Tbit/s) communications and the supporting access and backhaul network infrastructures are expected to become a predominant technology trend. However, with the current approach, certain severe limitations affect the capability of future wireless communications systems to meet the combined requirements of high data rate, near-zero latency, and high spectral and energy efficiency. In this context, utilizing THz frequency bands for wireless transmissions, as an extension to optical fiber, is a promising enabler to bridge this gap and provide ubiquitous high-speed Internet access beyond 5G.

Since most of the traffic is generated indoors, the future wireless systems are also expected to rely on a significant number of indoor solutions to massively offload cellular networks. To enable this, the focus has been millimeter wave (mmWave) frequencies such as 28, 39 and 60 GHz. However, the use of mmWave solutions still leads to certain limitations as the shared throughputs will only approach a few Gbit/s. As an intermediate step between millimeter-wave and optical wireless communication systems, the THz band offers unique trade-offs between channel bandwidth and propagation properties that make it a key player in future wireless communication systems, including 6G. The THz band has sufficient resources not only to satisfy the 5G requirements of 10 Gbit/s peak data rate but to enable a number of new tempting high data rate applications.

However, the THz band brings a few novel challenges in terms of propagation (THz wall) and device availability (THz gap). To achieve wireless throughput of 100 Gbps and beyond, THz spectrum seems like a logical solution due to the availability of large bandwidths. The global community have been putting a lot of effort in developing THz band-based solutions and has shown some promising early development, but still have a long way to go before we see commercial solutions available.

As the THz band continue to gain noticeable attention within the global community. Seamless data transfer, unlimited bandwidth, microsecond latency, and ultra-fast download are all features of the THz technology that is anticipated to revolutionize the telecommunications landscape and change the way people communicate and access information. Motivated by the potential of THz technologies to shape the future of wireless communications, this paper seeks to identify the unique characteristics of THz waves, the critical technology gaps in system design, recent developments and some potential use cases/applications.

2. Terahertz (THz) Spectrum Overview

The Terahertz spectrum region of electromagnetic radiation lies between the microwave and infrared portions of the spectrum. Basically, THz range extends from the highest frequency radio waves to the lowest frequency infrared light. Theoretically, THz band should start at 1000 GHz, but for all practical purposes spectrum beyond 100 GHz is considered a part of THz band as shown in figure-2.

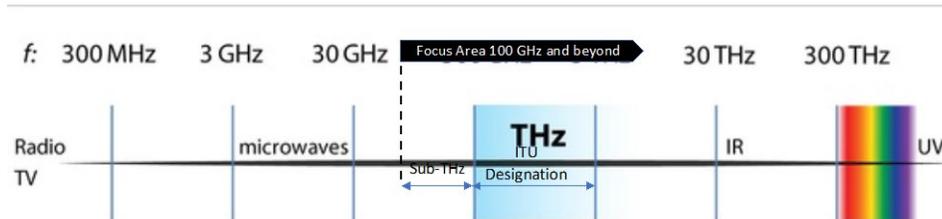


Figure 2 – Terahertz Spectrum

THz waves, also known as T-waves, T-rays, sub-millimeter waves or micrometer waves, are the electromagnetic waves in the frequency band of about 0.1 to 10 THz. ITU (International Telecommunications Union) has designated 300 GHz to 3 THz as the THz band. The spectrum between 100 GHz to 300 GHz is known as sub-THz band.

3. Terahertz Wall - THz Waves Propagation and Other Characteristics

The THz link suffers from several path loss mechanisms, the free space path-loss (FSPL) due to signal spreading, the effective antenna aperture, and the molecular absorption. The latter is a distinguishing feature of the millimeter and sub-millimeter bands. The main difference between the mmWave and the THz band is the progressively increasing molecular absorption loss.

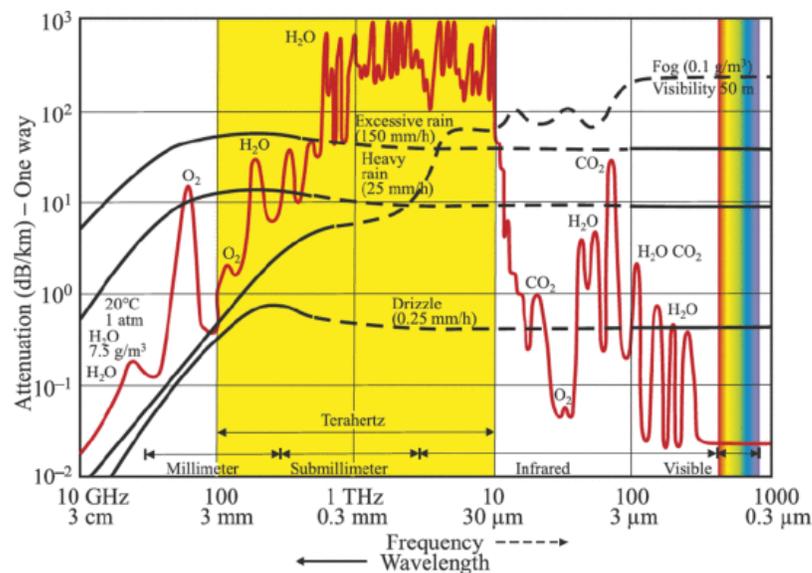


Figure 3 – Terahertz Propagation

At terahertz frequencies the propagation losses are very high, meaning the signal die down very fast. The impact of atmospheric attenuation for THz links is shown in figure-3. Although propagation losses are very high, a closer look indicates that not all frequencies suffer the same amount of propagation loss and the losses are not linear as we move towards high frequency region. Despite the existence of absorption peaks centered at specific frequencies, the availability of transmission windows allows for viable communication in the THz frequency band. These windows of opportunity (low absorption windows) for transmission at 94, 140 and 220 GHz are shown in figure 4 below.

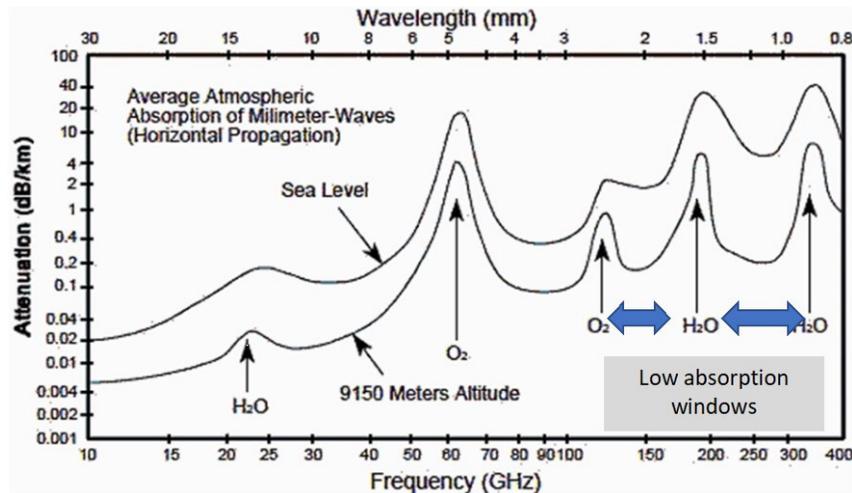


Figure 4 – Terahertz Propagation: Low Absorption Windows

The propagation distance of THz waves is significantly impacted by very high atmospheric loss. Based on the propagation studies, table-1 below shows the anticipated loss at a certain frequency using a specific bandwidth. Since water and oxygen are seen as the strongest absorber of the THz waves. For designing a THz link, it is very important to estimate the weather impact on high-capacity data links. As the THz band channel is considered highly frequency selective, the transmission distance is limited by attenuation and the appropriate carrier frequency should be determined according to the application.

Table 1 – Terahertz Ranges For Fixed Links

Frequency Range (GHz)	Contiguous Bandwidth (GHz)	Loss (dB/km)
275-320	45	<10
335-360	25	<10
275-370	95	<100
380-445	65	<100
455-525	70	<100
625-725	100	<100
780-910	130	<100

At terahertz frequencies the propagation takes the form of narrow a beam (similar to laser) and not a broadcast, which makes them more suitable for the point-to-point links. As shown in the

figure-5, THz waves quickly achieves a point where further power increase does not make any improvement in the link distance. This phenomenon is also known as terahertz wall. Figure-5 shows a comparison of different scenarios for horizontal transmission at sea level during good weather, bad weather, a range of distances (from 1 meter up to 6 kilometers), and specific frequencies between 35 gigahertz and 3 terahertz, to determine how much the signal strength degrades as conditions vary. The higher losses with rain and fog can be clearly seen as represented by dotted lines.

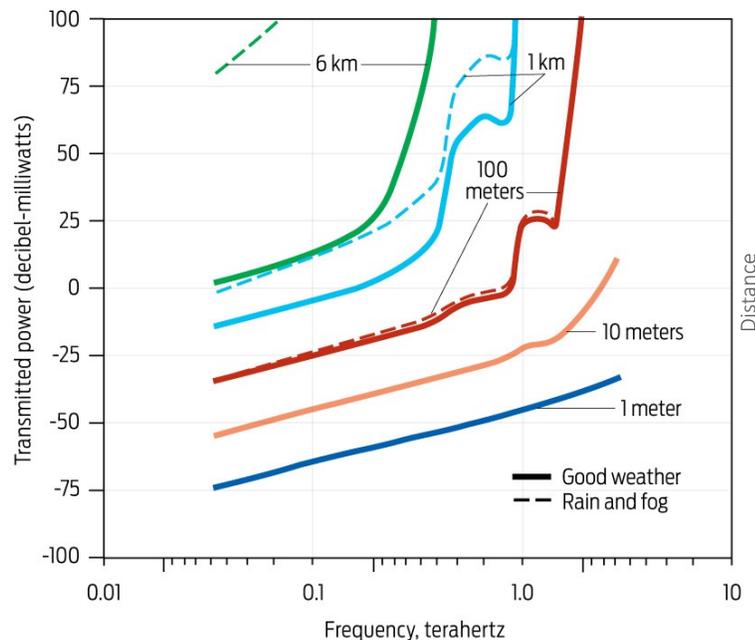


Figure 5 – Terahertz Wall: Frequency, Power versus Distance

For short-range operation, for example, signals traveling 10 meters or less—the effects of the atmosphere and bad weather don't really come into play. Any effort to send anything farther than that will quickly hit the terahertz wall. No matter how much the signal is boosted, essentially nothing gets through. A 1 watt signal with a frequency of 1 THz, for instance, will dwindle to nothing after traveling just 1 km, it only retains about 10-30 percent of its original strength. Even if transmit signal power is increased to the ridiculously high levels say a petawatt, it would get attenuated to a mere femtowatts by the time it reached its destination. Currently there are no terahertz sources capable of producing anything approaching a petawatt; the closest is a free-electron laser, which has an output in the low tens of megawatts and isn't exactly a field-deployable device. Basically, the extreme attenuation or propagation loss rules out using the terahertz region for long range terrestrial communications.

Some of the other unique properties of the terahertz waves are being harmless to the tissue and ability to pass through opaque materials. These properties make them promising candidate for use in noninvasive imaging in industry, medicine, and security. Unlike X-rays, terahertz waves are too low in energy (0.004 electron volt) to knock electrons off atoms, which could damage living tissue. Also, because of their shorter wavelength, they can produce pictures that are far sharper than those made with microwaves, the current safe imaging alternative. Terahertz waves also occupy a unique window of the electromagnetic spectrum where a large

number of molecules emit and absorb radiation. The signals produced when a molecule jumps among rotational modes form a unique and highly distinctive chemical fingerprint. Terahertz waves also pass through most dielectrics, opaque materials for example textile, paper, plastics, cardboard etc. Since water absorption is high, terahertz waves can be used to monitor water content in food and chemicals. How these properties can be used for imaging and spectroscopy applications are briefly covered in the section 5.2 and 5.3 of this document.

4. Terahertz Gap – THz Technology Development Challenges

Terahertz region sits between the microwave (electronics) and far infrared optical (photonics) regimes. To make something as simple as a terahertz transceiver, a device that's capable of both emitting and detecting terahertz radiation, a few adjustments to a conventional electronic or photonic transceiver should have been possible. But neither technology is really suitable for the task. For example, trying to adjust a radio transceiver so that it operates at terahertz frequencies, fundamental physical limitations are quickly encountered. The rapidly flipping voltage of a high-frequency alternating current can have strong electromagnetic effects on the transistors in a transceiver, giving rise to parasitic resistances and capacitances that take power away from the devices. More fundamentally, there is a speed limit on how fast electrons can move. Beyond a few tenths of a terahertz, the frequency of oscillations becomes so high that an electron can't cross a transistor channel from the source to the drain before the voltage flips its polarity, forcing the electron to reverse direction and causing transistor power to drop precipitously. As shown in figure-6 below, the current devices exhibit very poor power-frequency scaling in THz range.

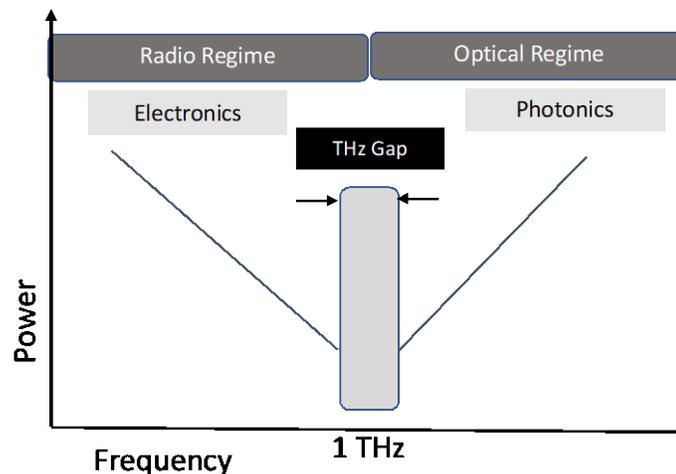


Figure 6 – Terahertz Gap: Power versus Frequency

This poor power versus frequency response exhibited by the current technologies have resulted in the device unavailability. This lack of devices in the terahertz spectrum as shown in figure-7 below is known as THz gap - a region in electromagnetic spectrum that does not have devices available for generation and detection. THz gap results from the lack of compact, energy-efficient device technologies. Most of the currently available devices are bulky, expensive and energy inefficient with power efficiencies in a single digit. At higher frequencies due to small antenna, device sizes create a lot of fabrication challenges, for example difficulty in ensuring

noise and inter-component interference suppression. In fact, integrated electronics are becoming large in comparison to the size of the corresponding antennas. Also, the high power and current density requires adequate cooling to prevent the device from disintegration.

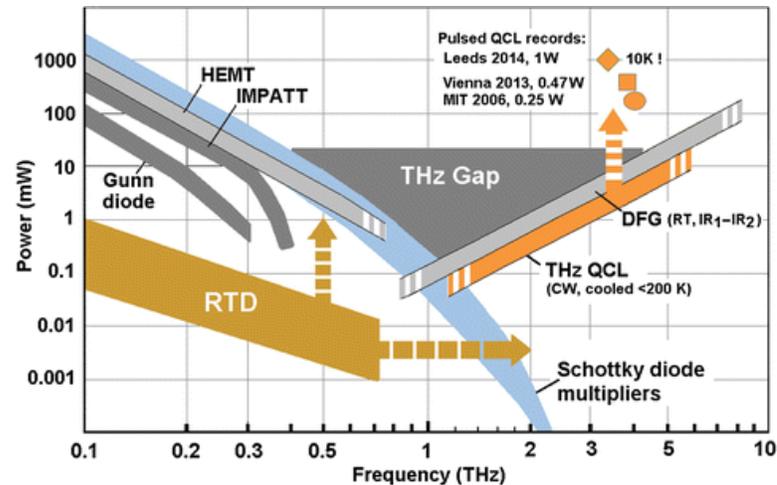


Figure 7 – Terahertz Gap: Current Device Technologies

These limitations are driving the invention of new materials. Progresses in electronic, photonic, and innovative plasmonic device technologies is continuously bridging the THz gap. Some of the promising technologies to achieve good output power and efficiency are Gallium Arsenide (GaAs), Gallium Nitride (GaN), Indium Phosphide (InP), complementary metal oxide semiconductor (CMOS), Silicon Germanium (SiGe), and fully depleted silicon on insulator (FD-SOI) CMOS. Figure-8 provides a high-level view of capabilities being offered by current technologies in terms of supported frequency and power output with still a long road ahead.

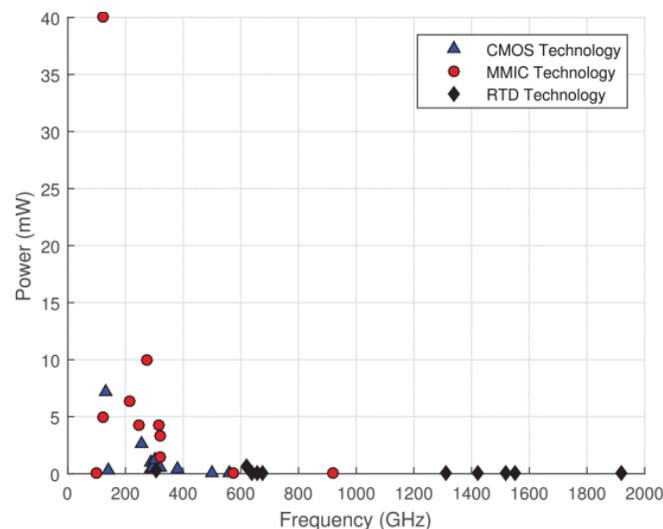


Figure 8 – Solid State Electronics: Frequency of versus power

Although today's technology has scarce high-power THz transmitters, it is expected that signal generators with high power can be created in the near future considering ongoing studies on graphene and InGaAs (Indium Gallium Arsenide) mHEMT (Metamorphic High Electron Mobility Transistor) monolithic microwave integrated circuits (MMICs). In the electronics approach, frequency multiplying and mixing chains enabled by transistor and diode technologies, resonant tunneling diodes, and traveling wave tubes are some of the major players. In a photonics approach, the beating of two lasers or frequency-difference generation, photoconductive antennas and quantum cascade lasers are examples of THz technologies aimed at closing the gap coming from the other end of the spectrum.

In addition to the device availability some of the other major areas that require a lot of work include radio frequency frontend and antenna design, propagation and channel modeling, waveforms, signals, and coding, beamforming and (ultra-massive) MIMO as well as resource management and medium access control schemes. All of these challenges demand for higher processing powers thus driving the need for new advanced processing devices.

THz spectrum offer the potential for breakthrough high data throughput applications. However, there are four key considerations for optimizing the performance of sub-terahertz systems operating over wide or extreme bandwidths: optimizing signal to noise ratio (SNR), minimizing phase noise, addressing linear and nonlinear impairments and making a waveform selection. In order to optimize SNR to achieve the best Error Vector Magnitude (EVM) performance, maximizing signal power (S) can achieve the highest SNR, but reducing the signal power becomes necessary to avoid harming any components along the signal chain. The noise contributions for SNR can be problematic for wideband applications since the noise power is integrated over wide signal bandwidths. For example, 10 GHz bandwidth signal will have 1,000 times more integrated noise than a 10 MHz signal. Basically, due to power level and high bandwidth contributing to poor SNR, basically SNR is effectively "squeezed" both on the high end and the low end. This is a key consideration in moving to extreme bandwidth test systems, and the SNR can often translate into what residual EVM is achievable. Also, up conversion from an intermediate frequency (IF) to sub-terahertz frequencies involves frequency translation with a local oscillator (LO) signal source(s) and frequency converter(s). A frequency multiplier will increase the phase noise by $20 * \text{Log}(N)$, where N is the multiplication factor. Furthermore, the multiplier can introduce additive phase noise that will further degrade the multiplied LO phase noise, dependent on the quality of the multiplier used. Low residual EVM test system performance at sub-terahertz frequencies requires high-quality, low-phase-noise LO signal sources.

To make the most out of the very large bandwidth provided by the THz band channel, new communication and signal processing techniques are needed. These include, among others, time, frequency and phase synchronization techniques, when transmitting at Tbps and in the presence of phase noise, real time channel estimation and equalization of tens to hundreds of GHz-wide bandwidths; and modulation strategies that can make the most out of the distance-dependent bandwidth of the THz channel. All these techniques need to be realized while keeping in mind that the sampling frequency of the fastest digital to analog and analog to digital converters is far below the required Nyquist frequency, which motivates the exploration of heavily parallelized systems as well as analog signal processing solutions. As opposed to traditional wireless networking paradigms, where the channel bandwidth is the scarcest resource that needs to be efficiently shared, the vast spectral resources in the THz band flip the script and change the focus to effectively everything else. Innovation is required in the higher layers of the

protocol stack, including dynamic power and bandwidth multi-hop relaying strategies that efficiently leverage the THz channel and real-time buffer-less routing protocols able to overcome the traditional delays associated with store-and-forward policies at the network layer; or innovative end-to-end transport layer solutions, which can accommodate frequent lack of connectivity between highly directional nodes.

Though the list of challenges in designing ultra-high frequency large bandwidth systems is very large, but the research community is continuously working on bridging this gap with new materials, processes and techniques.

5. Terahertz (THz) - Use Cases/Applications

Based on their properties discussed in the section 3, the applications of the THz waves can be broadly divided into three areas:

- Wireless Data Communications - THz can support high bandwidth (GHz), high data rates (Tbps) in the short range
- Imaging – THz waves are non-ionizing and harmless to tissues, can pass through opaque surfaces
- Spectroscopy - THz wave rotational and vibrational frequency matches those of molecules resulting in the creation of unique spectral fingerprint

Since the focus of this paper is wireless data communication, therefore communication related use cases will be discussed in more details, while imaging and spectroscopy will be covered at a very high level.

5.1. THz based Wireless communication applications

This section outlines some of the applications/use cases that will require ultra-broadband connectivity to work effectively. Due to high atmospheric losses the long-range communications (a few kilometers) with THz is not possible, but still there is a huge potential in using THz waves in the short range. At a high level the communication uses cases can be divided into three categories: Nanoscale (nano to centimeter), Microscale (centimeter to meter) and Macroscale (a few meters).

5.1.1. Terahertz Nanoscale Applications

Very small size of THz transceivers and antenna is driving a lot of application at a nanoscale. Over a very short distance referred to as nanoscale, the THz waves can be used to support intra-chip, inter-chip or intra-device communications. Chip-to-chip communications means wireless links inside computers or any other electronic devices. It is of high relevance because wired connectors and micro strip lines on printed circuit boards potentially become a bottleneck of upcoming bus systems and inter chip connections.

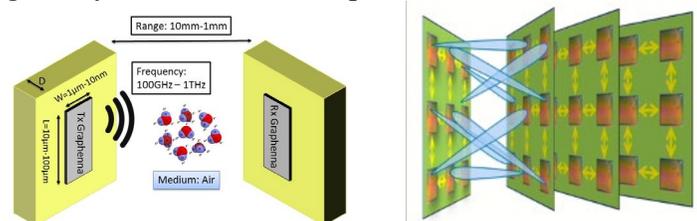


Figure 9 – Terahertz: On chip or chip to chip communications

Since transmission ranges are a few cm and the fully static environment allows for a fixed alignment during design process with automatic beam steering as an option for sequential multipoint operation between more than just two chips. Energy and chip real estate are two scarce resources in devices (e.g., smartphones, tablets, laptops). With the new advances in the coding and modulation used in the physical layer (PHY), chip to chip communications can be used to reduce the area and energy overheads of a given interconnect. Thus, terahertz waves can be used to implement simple and energy efficient on chip or inter-chip communications. The THz wireless communication is quickly evolving into a key enabler of applications involving operations inside computers and devices for a typical range of a few centimeters which includes chip-to-chip, board-to-board and device-to-device communications.

Additionally, nano-antennas enable wireless interconnection amongst nano-sensors deployed inside and over the human body resulting in many bio-nano-sensing applications.

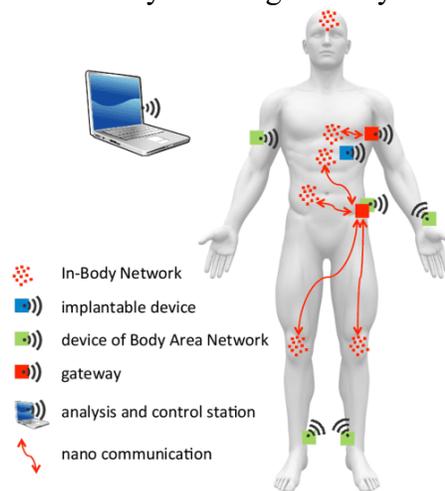


Figure 10 – Terahertz: Body area network (BAN)

As shown in figure-10 above, THz sensors can be planted inside and outside body to gather and transmit data to the wireless gateway connected to the diagnostic application.

5.1.2. Terahertz Microscale Applications

Wireless local area network (WLAN) and wireless personal area network (WPAN) form the basis of microscale applications which include high-definition television (HDTV) in home distribution, wireless displays, seamless transfer of files, and THz access points in the areas with device congestion. The THz band provides small cell communication for mobile cellular networks, where ultra-high data rate can be provided to mobile users within transmission range up to 20 m. As shown in figure-11 below, wireless personal area networks can be used for ultra-high-speed ad-hoc connections between devices over short distances, for example between a printer and a laptop. The typical THz deployment will be indoors and the alignment of high gain antennas should be ideally done by automatic beam steering, but rough manual alignment may be thinkable in case of less directive antennas.

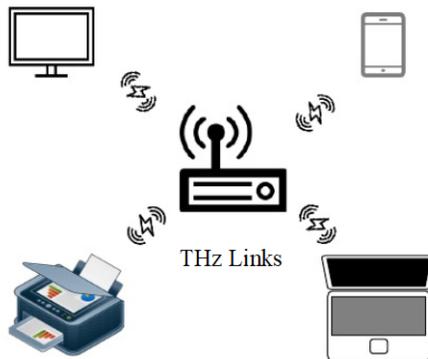


Figure 11 – Terahertz: Wireless Personal area network (WPAN)

THz frequencies can be used to provide transmission solutions in ad-hoc networks and for nomadic users by facilitating connection to access points for example at railway, stations, public buildings, shopping malls, etc. Microscale wireless communication at the THz band can also be used to transmit uncompressed high definition (HD) videos for education, entertainment, telemedicine, as well as security purposes. Kiosk downloading is another example of microscale application at THz frequencies, which offers ultra-high downloads of digital information to users' handheld devices. For instance, advertisement posters in metros, trains or streets can be the front interface for downloading pre-fixed contents such as newly released movie trailers, CDs, books, and magazines.

Wireless data centers are considered another promising application at the microscale. THz links in data centers can be deployed as a parallel technology to cabling, whereas the THz links can be used for the rack to rack or inter-cluster connectivity as shown in figure-12 below.

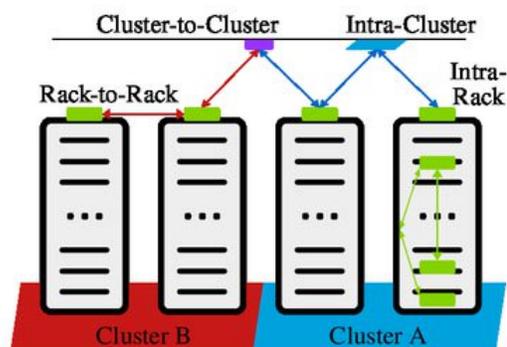


Figure 12 – Terahertz: Data Center Networks (DCN)

Such deployment in data centers results in an enhanced performance experience along with immense savings in cabling and time to deploy. For the optimization of capacity within data centers, a frequent and dynamic reconfiguration of the architecture is required, which is extremely difficult to achieve with fully wired systems. This introduction of ultra-high data rate wireless hops shown in figure-12 above, are considered as an attractive alternative. For wireless hops in a data center, racks are equipped with highly directive steerable antennas on top of the

racks. Connections between different racks are realized by aligning the beams of the corresponding antennas.

5.1.3. Terahertz Macroscale Applications

On a macroscale, THz wireless communication facilitates potential outdoor applications which range from few meters up to kilometers. For example, wireless backhauling/fronthauling is one of the envisioned applications for the standard 100 Gbps transmission solutions. THz links can be used for backhaul for base stations of macro cells especially in the areas where optical fiber is not available. For fronthaul THz point-to-point links can be used to connect the radio controller of a base station and the remote radio head (radio unit). An example of fronthaul application is shown in figure-13 below. The increasing number of mobile and fixed users in both the private, industrial and service sectors will eventually require hundreds of Gbps to be carried either to or between cell towers (backhaul) or between cell towers and remote radio heads (fronthaul).

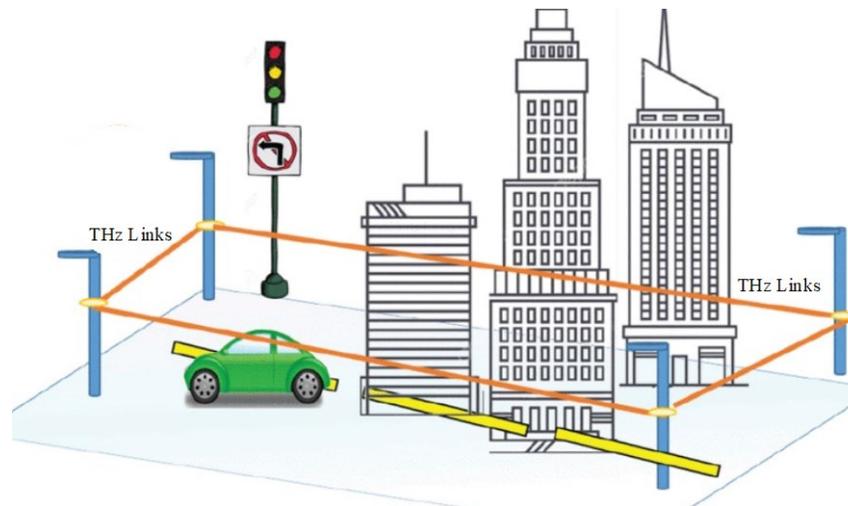


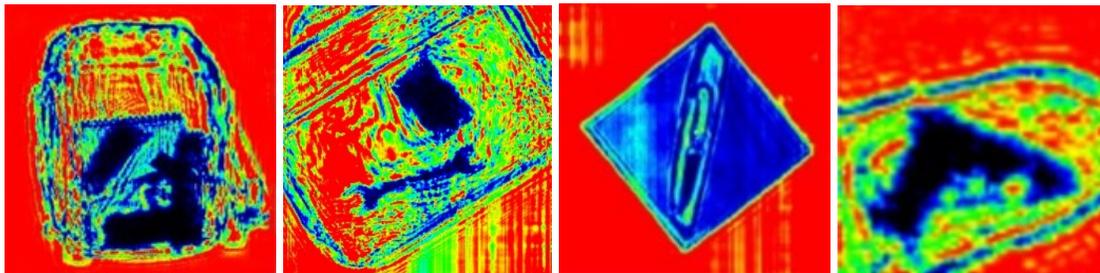
Figure 13 – Terahertz based fronthaul

Future advancements which include massive deployment of small cells, implementation of cooperative multipoint transmission and Cloud Radio Access Networks (C-RAN) may increase the required data rates for either fronthauling or backhauling or both. Therefore, fixed links with ultra-high data rates can be utilized for the wireless extension of backbone networks, for the aggregation of multiple backhaul links with lower data rates as well as for the wireless backhaul of future cellular base stations with very high overall throughputs.

Even though the path loss increases with frequency, the antenna gain is related to the square of the operating frequency. Therefore, high gain antennas can cope with the extreme path loss in the THz band. As known, antennas with high operating frequency have relatively narrow beams compared to lower frequencies; hence, THz antennas can be utilized in point-to-point links to backhaul small cells. Moreover, since the antenna size decreases with frequency, it is possible to place a massive number of antennas on small surfaces. For example, it is possible to cover a 1 mm² area with four antennas at 300 GHz. Beyond massive multiple-input multiple-output (mMIMO), namely ultra-massive (UM-MIMO), can be employed to increase the communication distance as well as the data rate enhancement.

5.2. Terahertz Imaging

Terahertz waves are nonionizing, meaning its photons are not energetic enough to knock electrons off atoms and molecules in human tissue, which could trigger harmful chemical reactions. THz waves can also penetrate a variety of non-conducting, amorphous, and dielectric materials, such as glass, plastic, and wood. These see through and non-ionizing properties makes them a good candidate for imaging application. Due to shorter wavelength compared to microwave radiation, THz waves create higher resolution images as well. Absorption and reflection of terahertz waves are highly material-dependent, and helps in providing the contrast in the images. Some examples of terahertz imaging with see-through capability are shown in figure-14 below. The images demonstrate THz imaging ability to reveal hidden objects.



Hidden Objects (Notebook/gun in a bag, wrench in a bag, knife in a book, gun in a box)

Figure 14 – Terahertz see-through imaging

The applications of THz imaging are endless and have been the key focus of research community. A lot of commercial products are available for industrial inspection, quality control, security scanning, medical imaging etc., for example, to screen for skin cancer and tooth decay. In the future, imaging capability in a reflection mode could be incorporated in smartphones for seeing through packages to detect what is inside without opening them, walls to locate wires and pipes, or decorative pieces to detect air voids and cracks another application for 3D THz imaging is to use it for providing accurate position determination and object detection capability. Terahertz radiation also offers a safe, non-ionizing solution to the problem of screening travelers passing through airports and crossing national borders.

5.3. Terahertz Spectroscopy

Terahertz waves also occupy a unique window of the electromagnetic spectrum where a large number of molecules emit and absorb radiation. The signals produced when a molecule jumps among rotational modes form a unique and highly distinctive chemical fingerprint. These unique fingerprints at terahertz radiation can be used for chemical detectors. As an example, in figure-15 below, unique fingerprints for a drug and explosive are shown.

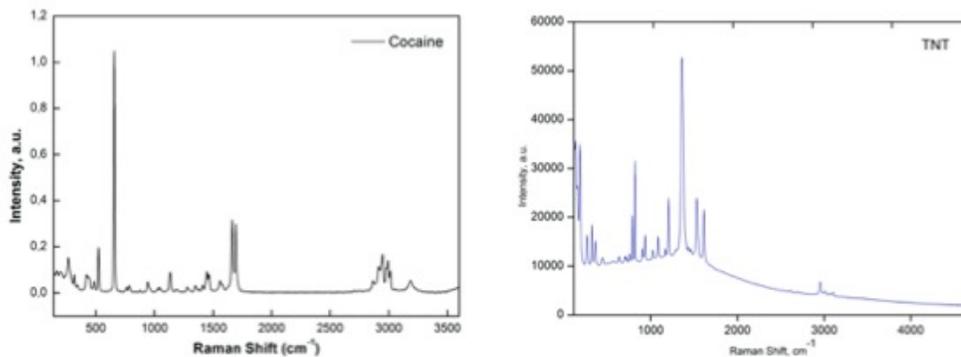


Figure 15 – Terahertz unique chemical fingerprints

Unique chemical fingerprints at THz waves makes them a good candidate for material and gas sensing, for example, environmental monitoring includes detection of pollutants and contaminants to meet the requirements of health and safety, monitoring of atmospheric components for weather and climate observation. Analyzing gases exhaled in human breath is a highly promising application, with the potential for early detection of disease biomarkers. Such detection would be fast and non-invasive, facilitating early diagnosis and state-of-health monitoring. Potential detectable diseases include lung cancer, diabetes, some neurological disorders, and smoking and alcohol consumption. In biochemistry, THz applications have been developed to explore the bioactivity of chemical compounds and identify protein structures.

For security and public safety applications, many explosives (for example, C-4, HMX, RDX and TNT) and illegal drugs (for example, methamphetamine and heroin) have characteristic features in the THz range. In an example (source RIKEN, Japan) below use of THz spectroscopy to inspect a package containing different chemicals has been demonstrated.

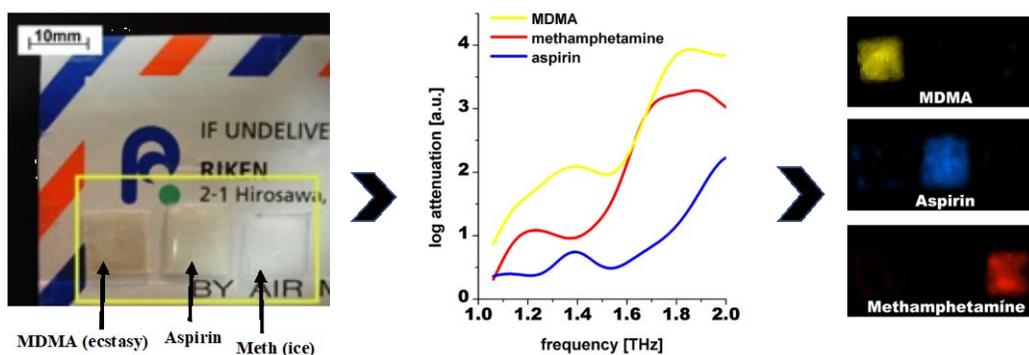


Figure 16 – THz spectroscopy for substance detection

As shown in figure-16, three different substances produce a unique fingerprint which can be used to detect the substance without opening the package. The combination of terahertz imaging and spectroscopy has resulted in a lot of commercially available products for non-destructive testing and new applications are growing every day.

6. Terahertz (THz) Development status

Seamless data transfer, unlimited bandwidth, microsecond latency, and ultra-fast download are all features of the THz technology that is anticipated to revolutionize the telecommunications landscape. These features have resulted in the terahertz band gaining noticeable attention in the global research community. The enthusiasm of the research community is reflected in the increased number of publications issued in the recent years on IEEE, SPIE etc. The potential associated with THz technology has attracted the broader research community. The combined efforts of active research groups are resulting in new designs, materials and fabrication methods that demonstrate endless opportunities for THz development. In table-2 below are some examples of various groups conducting THz research. The list below is a testimony of the focused research in this area being conducted in the laboratories across the globe.

Table 2 – Research Groups Working on Terahertz

Research Group/Lab	Location	R&D Activities
Mittleman Lab at Brown University	USA	THz PHY layer, spectroscopy, THz probes
Broadband Wireless Networking Lab at Georgia Tech	USA	THz PHY and MAC layer, THz Nano-communications, THz devices
NaNoNetworking Center in Catalunya	Spain	THz Nano-communications
Ultra-broadband Nano-Communications Lab at Univ. of Buffalo	USA	THz PHY and MAC layer, THz Nano-communications, THz devices
THz Electronics Lab at UCLA	USA	THz devices, reconfigurable meta-films, spectroscopy
MIT Terahertz Integrated Electronics Group	USA	Sensing, Metrology, security and communication.
Fraunhofer Institute for Applied Solid State Physics	Germany	THz PHY and MAC layer, THz electronics
Terahertz Communication Lab	Germany	Channel investigation and THz reflectors
Core Technology Lab Group NTT Corp	Japan	Terahertz IC and modularization technology
Texas Instrument Kilby Lab	USA	Ultra-Low Power sub-THz CMOS systems
Tonouchi Lab at Osaka Univ.	Japan	THz Nanoscience, THz bio-science, THz bio-sensing and industrial applications
THz Electronics Systems Lab at Korea Univ.	Korea	THz PHY and MAC layer, THz electronics
Nano-communications Center at Tampere Univ. of Technology	Finland	THz PHY layer, THz Nano-communications

Various regulatory and funding agencies have been supporting THz projects and opening up new horizons in communications and devices for deployment beyond 5G technology. The regulatory framework for spectrum above 100 GHz is beginning to take shape, as discussed in the subsequent sections.

6.1. International Telecommunications Union (ITU)

In November World Radiocommunication Conference 2019 (WRC-19) which meets every four years to discuss international radio rules (RRs) and other topics, made 190 GHz (252 to 356 GHz) of spectrum available for THz communication with no specific EESS (Earth Exploration Satellite Services) protection requirements. Before WRC 2019, there were no allocations above 275 GHz. Allocations were made for fixed and mobile communications for in 275-296 GHz, 306-313 GHz, 318-333 GHz and 356-450 GHz bands. Resolution was also made for a study plan for ITU-R for increased sharing above 71 GHz. Bands of interest include 100 - 102 GHz, 116 - 122.25 GHz, 148.5 - 151.5 GHz, 174.8 - 191.8 GHz, 226 - 231.5 GHz and 235 - 238 GHz. This came as a very encouraging news for the worldwide research community focused on THz research.

6.2. Federal Communications Commission (FCC)

The United States, through the Federal Communications Commission's (FCC) Spectrum Horizons First Report and Order, is taking a leadership role in the future of 5G and beyond. As a result of this initiative, the FCC is making more spectrum available. On March 21, 2019, the FCC adopted new rules to encourage development of new communication technologies and expedite the deployment of new services above 95 GHz. As a part FCC 19-19, the FCC opened 95 GHz- 3 THz band for unlicensed and experimental communications under "Spectrum Horizons" program. The FCC made the entire band available for experimental authorizations. In addition, the FCC made a total of 21.2 GHz spectrum available for unlicensed use. As shown in figure-17 below the unlicensed spectrum would span several band segments (116-123 GHz, 174.8-182 GHz, 185- 190 GHz, and 244-246 GHz).

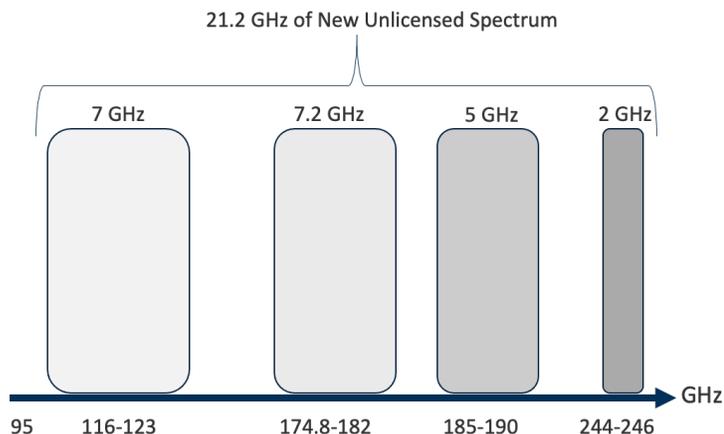


Figure 17 – FCC Spectrum Horizons Initiative: Unlicensed Spectrum

21.2 GHz of new unlicensed spectrum between 95 GHz and 3 THz can be used by devices that do not interfere with existing governmental and scientific operations and that operate within a maximum threshold of average EIRP (Effective Isotropic Radiated Power) of 40 dBm, as stated in the FCC order. This initiative gives researchers, innovators, and entrepreneurs the flexibility to conduct experiments blocks between 95 GHz and 3 THz through experimental licenses lasting up to 10 years. Researchers may also more easily market and demo equipment during the trial period. This will encourage the development of communication technologies and services above

95 GHz, such as data-intensive high-bandwidth applications; wireless cognition; and imaging, positioning, and sensing operations.

6.3. IEEE (Institute of Electrical and Electronics Engineering)

In 2008, the IEEE 802.15 established the 802.15.3d Task Group (Terahertz Interest Group) as a milestone towards investigating the operation in the so called “no man’s land” and specifically for frequency bands up to 3 THz. The new group was tasked to identify THz band communications as a feasible wireless technology for extremely high access rates of up to 100 Gbit/s. The group has worked closely with the International Telecommunication Union (ITU) and the International Radio Amateur Union (IARU) regarding the description of the frequency bands higher than 275 GHz.

The ratification of the IEEE 802.15.3d amendment to 802.15.3, was a significant step towards standardization consumer wireless communications in the sub-THz frequency band. IEEE 802.15.3d offers switched point-to-point connectivity with data rates of 100 Gb/s and higher at distances ranging from tens of centimeters up to a few hundred meters. IEEE approval of channelization standard is considered a major milestone towards THz wireless communication.

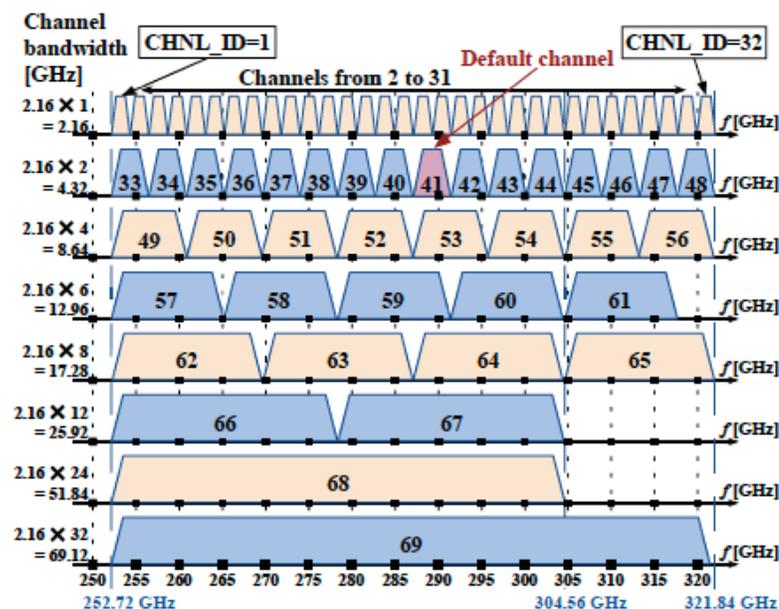


Figure 18 – Bandwidth and channels for IEEE 802.15.3d standard

The major highlights of IEEE 802.15.3d standard are:

- 8 different channel bandwidths (as multiples of 2.16 GHz)
- 2 PHY-modes (THz-SC PHY, THz-OOK-PHY) with 7 modulation schemes: BPSK, QPSK, 8-PSK, 8-APSK, 16-QAM, 64 QAM, OOK
- 3 channel coding schemes: 14/15-rate LDPC (1440,1344), 11/15-rate LDPC (1440,1056), 11/15-rate RS(240,224)-code.

As shown in figure-18 above, IEEE 802.15.3d may operate over the sub-THz frequencies between 252.72 GHz and 321.84 GHz. In total, there are 69 overlapping channels. There are 8 supported channel bandwidths ranging from 2.16 GHz (same as in mmWave IEEE 802.11ad 2012) up to massive 69 GHz channel bandwidth. Depending on the use case and the hardware capabilities, either the entire frequency range can be allocated for a single 69.12-GHz-wide channel (CHNL_ID = 69) or can be shared between several smaller channels. The bandwidths of the channels are integer multiples of 2.16 GHz. The channel number 41 with the bandwidth of 4.32 GHz (2x2.16 GHz) is the default channel.

Following the decision at World Radio Conference 2019 (WRC-2019), all the bands depicted in Figure-18 are available for THz communications globally if specific conditions to protect radio astronomy and earth exploration satellite service (EESS) are met. These conditions do not explicitly specify any transmit power limits and are applicable, in practice, primarily to the narrow areas surrounding the ground radio astronomy stations.

6.4. European Union ICT (Information and Communication Technologies)

There is a sharp increase in recent years in the research funding by European Union, body like Horizon 2020 (H2020). This funding ranges from enhancing research on the device technology to communication aspects including channel, physical, MAC and network layer characterization. The THz band related projects currently funded by H2020 are summarized in the table-3 below. Some of the projects are based on establishing the feasibility of communication windows within Terahertz Gap, for example Ultrawave, Dream, EPIC, and WORTECS.

Table 3 – EU Horizon 2020 Terahertz Related Projects

Project Name	Band	Target Speed	Focus
iBrow	60 GHz-1 THz	10 Gbps	Innovative ultra-broadband ubiquitous wireless communications through THz. Low cost and simple wireless transceiver architecture. Integrated semiconductors emitters and detectors with seamless fiber-wireless links
TERRANOVA	300 GHz	100 Gbps	Tbps wireless connectivity by THz innovative technologies to deliver optical network quality of experience in systems beyond 5G
TERAPOD	300 GHz	100 Gbps	Terahertz based ultra-high bandwidth wireless access networks for data centers
ULTRAWAVE	300 GHz	100 Gbps	High capacity backhaul links to enable 5G cell densification by exploiting bands beyond 100 GHz.
EPIC	-	1 Tbps	Enabling practical wireless Tbps communication with next generation of coding. Develop new FEC (forward error correction) codes for Tbps rates.
DREAM	D-band	100 Gbps	D-band reconfigurable meshed radio solution at 100 Gbps by exploiting radio spectrum bands like 130-174.8 GHz with beam steering functionality to reach optical systems speed.
WORTECS	90 GHz	10 Gbps	Wireless optical radio terabit communication system. Use 90 GHz for proof of concept with Gbps rates.

Project Name	Band	Target Speed	Focus
ThoR	300 GHz	100 Gbps	Front and backhaul solutions at 300 GHz for data rates beyond 5G.
TERAPAN	300 GHz	100 Gbps	Adaptive wireless point-to-point terahertz communication systems for indoor environments for distances of up to 10 m at data rates of up to 100 Gbps
ROOTHz	THz	-	Development of solid state nanodevices at room temperature of THz communications

The project which involves the research on advancing the communication methodologies while considering the MAC layer issues and challenges are TERAPOD, TERANOVA, and ThoR. Their aims and objectives include the device, channel and antenna characterization. They are also focusing on designing a simple and efficient MAC protocol for point to point and multipoint scenarios. However, each project is looking at a specific scenario. For example, the TERAPOD project is aiming to design a communication methodology for a data center environment, which involves potentially the channel, antenna and Physical layer considerations for an indoor environment only. The TERRANOVA on the other hand focuses on the backhaul point to point scenario for outdoor long range environment including small cells. Each scenario requires a different modelling approach for antenna, channel and propagation model and therefore requires different strategies to access the channel to establish communications. Similarly, ThoR is also looking at high speed link upto 100 Gbps over 300 GHz band for backhaul with partial involvement of point to point scenario for MAC layer channel access. These projects have helped creation of new THz devices, communication techniques which will lay new foundations for the rapid development of practical systems.

7. Conclusion

The paper has presented the current status in research, spectrum regulations and standardization activities in the field of THz communications. Though there are challenges developing terahertz products i.e., closing the THz gap by discovering new devices and the THz wall, the inherent high propagation loss caused by atmospheric absorption. Still, the field of THz communications has drastically changed in the last ten years and, what used to be a relatively niche discipline, is now identified as one of the key enablers of the future ultra-broadband networks, 6G and beyond. Major progress has occurred worldwide in the last decade both in terms of materials and devices as well as communication techniques. With these advances, wireless Tbit/s communications and the supporting backhaul network infrastructure are expected to become the main technology trend within the next ten years and beyond. To facilitate this, an unprecedented amount of 160 GHz of the spectrum was recently opened for THz communications after WRC 2019. Moving forward, besides addressing the technical open challenges, the adoption of the THz spectrum for communications needs to be accompanied by supporting spectrum policies that ensure an efficient, fair and secure use of the spectrum by both active (communications) and passive (sensing) users. Based on the recent progress, the commercial introduction of THz communications can be expected in the not-too-distant future and will help coping with the ongoing tremendously increasing demand for wireless data rates.

Abbreviations

5G	5 th Generation
BAN	body area network
bps	bits per second
BPSK	binary phase shift keying
C-4	composition-4
CD	compact disc
CMOS	complementary metal oxide semiconductor
C-RAN	Cloud Radio Access Networks
DCN	Data Center Network
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FD-SOI	fully depleted silicon on insulator
FEC	forward error correction
FSPL	free space path loss
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gbps	giga bits per second
GHz	gigahertz
HDTV	high-definition television
H ₂ O	chemical formula for water
HMX	high melting explosive
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunications Union
InP	Indium Phosphide
LO	local oscillator
MAC	medium access control
mHEMT	metamorphic high electron mobility transistor
MMIC	monolithic microwave integrated circuit
mMIMO	massive multiple-input multiple-output
O ₂	chemical formula for oxygen
OOK	on off keying
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RDX	royal demolition explosive
RTD	resonant tunneling diode
SCTE	Society of Cable Telecommunications Engineers
SiGe	Silicon Germanium
SNR	signal to noise ratio
SPIE	Society of Photographic Instrumentation Engineers
THz	terahertz
TNT	trinitrotoluene
UM-MIMO	ultra-massive multiple-input multiple-output
WLAN	wireless local area network
WPAN	wireless personal area network
Tbps	terabit per second

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