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Beyond 5G: THz Spectrum Futures and Implications for Wireless Communication

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Abstract

There have been substantial technical and policy discussions about the spectrum needs of 5G and the necessity of expanding access to the higher frequency spectrum, including in the millimeter wave bands from 30 to 300 GHz. The focus, however, has been on bands below 60GHz, or at most 90GHz, which is the current limit of near-commercial technologies. As wireless markets continue to grow, demand may arise for spectrum in still higher frequency bands above 90GHz, including in the sub-millimeter Terahertz (THz) bands between 300GHz and 3THz. Although exploiting THz bands is at the frontiers of technical research today and the commercial case for it will depend on further demonstration of the value and constraints, it is worthwhile exploring how THz spectrum might impact wireless network architectures, business/usage cases, and spectrum policy. In this paper, we explore that challenge.

We first explain some of the critical features of THz spectrum that make it both attractive and challenging to use and summarize the current state of our ability to address those challenges by reference to the current engineering research and commercialization progress on exploiting millimeter wave and higher frequencies. For example, the THz spectrum would offer virtually unbounded capacity (relative to today's demand forecasts) for supporting wide-channels and extremely high data rates, but with demanding Line of Sight (LOS) requirements. THz devices operate in very narrow beams, close to optical wavelengths, and have very limited capability to penetrate materials (e.g., even a sheet of paper is sufficient to block it). Integrating such spectrum into wireless networks will impose important requirements for antenna siting (small cell architectures) and backhaul, posing greater challenges for extending core-network services to edge-networks.

We hypothesize that such spectrum may further empower equipment-based, end-user deployed strategies for deploying wireless networking, with interesting implications for industry structure and regulatory policy. Furthermore, because current spectrum policies are limited to radio frequencies below 300GHz (arguably below 90GHz), THz is the green-field frontier for spectrum policy-making. This offers an opportunity for novel thinking about how best to manage spectrum resources to enable efficient sharing. Moreover, shifting wireless services to THz might free up

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capacity in the currently scarce lower frequency bands (below 10GHz), with implications for how we should think about spectrum management across all frequency bands. This includes addressing the challenge of the appropriate licensing regime (e.g., exclusive or unlicensed) that should apply for the THz spectrum. A better understanding of the potential uses for the terahertz spectrum is essential for a better understanding of scarcity limits on the lower frequency spectrum. Although the focus of the analysis will be on the THz spectrum, informed by recent technical work being directed by the authors, the applicability of the insights will be more general and applicable to today's efforts to promote spectrum policy reform, wireless network regulation, and realization of the future beyond 5G that we are striving to implement.

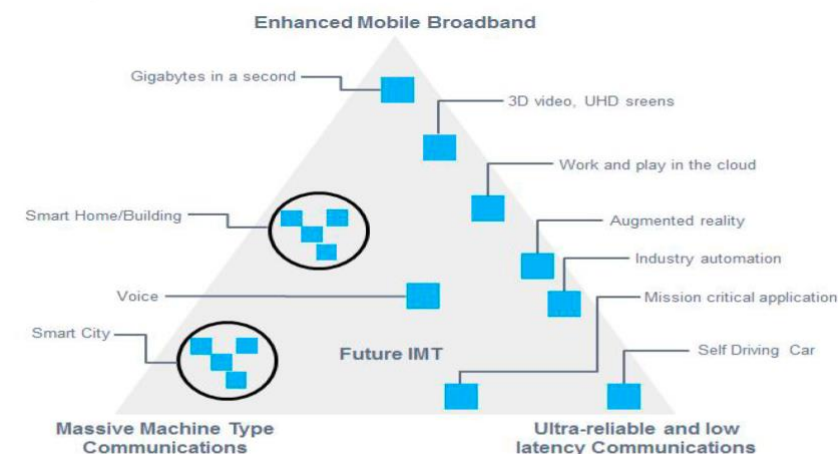
Keyword: 5G, Beyond 5G, Terahertz, Wireless, Spectrum

I. Introduction

Since the birth of wireless communication, every decade has experienced increasing demand for faster data rate and lower latency communication capabilities, a trend which is expected to continue in the future [1]. Rising consumer expectations for improved performance and ever-more-demanding applications have increased demand for ever-higher Quality of Service (QoS). Applications, such as Virtual-Reality (VR), Augmented Reality (AR), and Internet-of-Things (IoT), point toward a landscape of demanding applications. 5G is supposed to cater to a wide range of applications, starting from smart homes to smart cities, and recreational services to mission-critical applications, as shown in Figure 1 [2]. Enabling these applications and meeting the growing demand for wireless from all sectors of the economy will drive increased demand for the radio frequency spectrum. We are in the early stages of deploying 5G, and that has driven network operators to expand their demand for low, medium, and higher-band spectrum with recent auctions of millimeter band spectrum raising billions of dollars.

Exhibit 23:

5G usage case



Source: ITU

Figure 1. ITU diagram for 5G Usage Scenarios [2]

Whereas the planned 5G networks will deliver an order of magnitude improvements in performance over 4G, with respect to data rates, latency, capacity, et cetera, researchers are already beginning to look beyond 5G for how to support the next jump in performance and capacity. For example, 5G is expected to support Gbps data rates, but for Terabit per second (Tbps) data rates and less than 1ms latency, Beyond 5G (B5G) technologies will be needed [3],[4]. Research on how to support B5G is important since the development of the standards and the commercialization of the technologies needed for B5G will take years, if not a decade or more. While some may question the need for even 5G performance capabilities, looking toward the horizon is essential both to make sure we are ready if the exponential growth in traffic continues and because a better understanding our future options will help us better manage our present circumstances. A key challenge for B5G is to expand the usable capacity of the radio spectrum. With 5G, the current frontiers for near-commercial applications are in the millimeter bands at frequencies of 60GHz. In this paper, we look beyond the millimeter wave spectrum to the terahertz spectrum (THz).

Although researchers are continuing their efforts to make expand the usable capacity of spectrum under 10 GHz, we may be nearing physical capacity limits, and more importantly, the economic viability of ringing out additional capacity in low and mid-band spectrum below 10GHz. Efforts to expand the capacity focuses on improving the signal-to-interference-noise ratio (SINR) through advancements in modulation and coding schemes, moving to small cells, antenna beamforming, virtualization, and other techniques. As we approach physical limits in reducing SINR, the only way to increase capacity is to increase the available spectrum². In the last decade, we have seen the drive for reallocating or repurposing under-utilized spectrum [5] via spectrum auctions [6] and the adoption of coexistence (spectrum sharing) mechanisms [7][8]. While such efforts are important, they confront numerous economic and political challenges because the spectrum below 10GHz is already allocated, assigned, and often occupied by multiple users both in space and time. Furthermore, to enable B5G performance improvements (in capacity, data rates, and latency) and more flexible wireless network architectures, we need access to much larger channel bandwidths.

Traditionally, most spectrum users, such as broadcasting, mobile broadband, public safety, positioning, radar, and defense operations, have been allocated and assigned to bands below 10GHz in a complex matrix of paired and unpaired frequency bands of varying size (measured in MHz). That makes it costlier if not wholly infeasible to obtain large continuous channels that are needed for higher data rate services.³ Therefore, as shown in Figure 2, researchers have been exploring the ability to use spectrum above 10 GHz [9,10].

² The Shannon–Hartley theorem states that the channel data rate \mathbf{R} is directly proportional to the available bandwidth \mathbf{B} and the Signal-to-interference-noise Ratio (SNR), represented by the following equation:

$$R = B \log_2(1 + SINR)$$

Reusing frequency through shrinking cells and scaling up the number of nodes can also indirectly aid in increasing the system capacity. However, there is an optimal value after which the cost of infrastructure and interference will high enough to exceed the capacity gain.

³ Most of the wireless applications are assigned to channels of 1.4-22MHz spectrum. While some applications have the capability to do *carrier aggregation or channel bonding* (i.e., combining multiple

Significant progress has been made already in demonstrating the commercialization potential of millimeter band spectrum, with experimental tests, standards [11], and design performed at 60GHz, demonstrating the ability to support 1Gbps speeds using 2 GHz wide channels [12,13]. Although a 1-2GHz wide contiguous channel is already significantly larger than anything being used at lower frequency bands, the number of such channels available in the millimeter wave bands is limited. For example, in the 60GHz millimeter band, the maximum available spectrum is limited to only 7GHz [14]. The availability of big contiguous channels offers a number of technical and architectural advantages. Thus, moving higher, into the not heavily allocated infrared (300GHz-430THz) and visible light (430THz-790THz) bands have tremendous potential, with green-field big contiguous bandwidth available, which can help in meeting higher throughput demands, maybe close to 1Tbps [15,16].

Although it was shown in [12] that ultra-high data rate of several hundred Gbps could be achieved for short-range transmissions in 60GHz, the range is in millimeters, which is too short for mobile communication or to satisfy all of the future large-scale applications shown in Figure 1. Thus, it is necessary that we move to bands that can provide us with ultra-high data rate but for relatively higher ranges, maybe a few meters, through more contiguous channels⁴. However, the infrared and visible light bands are very sensitive to objects, reflection, noise source from the sun/ambient light, and transmit power restriction for human safety (high transmission can damage human eye). Although moving higher in the frequency results in higher channel bandwidths, it also increases path loss, decreases spatial coverage, and increases sensitive to blockages and mobile applications, as shown in Figure 2. Thus, it is useful to consider a spectrum band that lies optimally between the microwaves and infrared bands, namely the **THz Band**, thus sharing some of the benefits and limitations that the microwave and infrared bands have to offer, as shown in Figure 2.

It is interesting to note that there exists a disagreement among the regulators and researchers on the definition of THz spectrum range. This is mostly due to both the challenges and benefits associated with moving higher in the frequency. While the FCC [21] and ITU [22] are focused on spectrum between 95GHz-3THz (parts of millimeter and submillimeter bands) for new services and technologies, some define THz spectrum from 100GHz-10THz and 100GHz-30THz [19, 81]. As shown in Figure 2, the above-mentioned THz ranges lies partly in the millimeter bands and mostly in the infrared bands, specifically in IR-C band. Although there is a consensus on the lower bound of the THz band, the upper bound is vaguely defined. In this paper, we present a quantitative analysis in the frequency range from 95GHz-10 THz, as is common in relevant technical papers.

channels in different frequency bands to enhance the data capacity) to obtain higher bandwidth of 60-160MHz, the method results in higher complexity in the hardware and increased cost.

⁴ Moving higher in the frequency increases the absorption loss, scattering loss and penetration loss. These losses can result in shorter range communication. However, if we are able to achieve bigger contiguous bandwidth, then we can use that to compensate for these losses (bandwidth that millimeter wave is not able to provide).

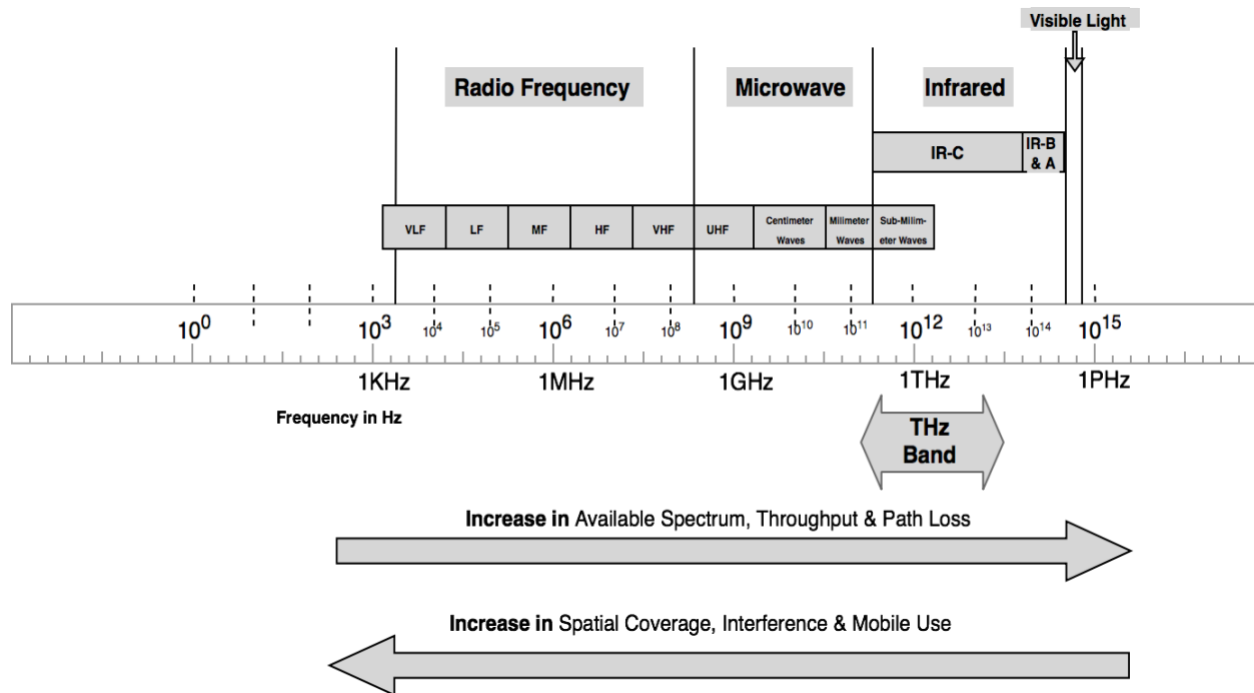


Figure 2. Spectrum Allocation Chart with potential bands for future wireless communication. A summary of the spectrum bands and sub-bands are presented in Table I.

Table I A summary of the electromagnetic spectrum and its designated frequency bands. With a summary on the benefits and challenges associated with the band

Electro-magnetic Spectrum	Designate Band Name	Frequency Range	Comment
Radio Frequency	VLF (Very Low Frequency)	3KHz-30KHz	☺ Used in long-range communication to penetrate buildings and objects, such as broadcasting, radar, satellite and mobile communication ☹ The spectrum is highly allocated, and the available bandwidth is limited to few MHz
	LF (Low Frequency)	30KHz-300KHz	
	MF (Medium Frequency)	300KHz-3MHz	
	HF (High Frequency)	3MHz-30MHz	
	VHF (Very High Frequency)	30MHz-300MHz	
Microwave	UHF (Ultra High Frequency)	300MHz-3GHz	☺ Used in medium-range communication such as WiFi and radar ☹ The upper band is sensitive to atmospheric absorption
	Centimeter Wave	3GHz-30GHz	
	Millimeter Wave	30GHz-300Ghz	
Infrared	Sub-Millimeter Wave	300GHz-3THz	☺ Can provide green-field bandwidth in GHz. Can help in secure interference friendly communication. ☹ Due to high path loss and noise, the application is limited to short-range communication, such as indoor use or static point-to-point
	IR-C	300GHz-100THz	
	IR-B	100THz-215THz	
	IR-A	215THz-430THz	
Visible Light	-	430THz-790THz	
Proposed THz Band		95GHz-10THz	A mix between Microwave and Infrared bands

The primary reason for moving into higher frequency bands is the ease of availability of green-field contiguous spectrum, which was not possible in the lower bands and millimeter wave bands⁵. However, THz (and even some millimeter wave and infrared spectrum) comes with many challenges that were not seen in the lower radio frequency bands. As we move higher in the frequency range, path loss increases and so does the need for narrow antenna beams. Narrow or pencil beam antennae demand perfect line-of-sight communication followed by frequent beam alignment in case of mobile users, which can result in frequent outages. To mitigate these challenges, THz requires technological improvements in many areas, including: channel modeling, antenna design, fast antenna beam alignment, radio resource management, protocol design, mobility management, faster handoff management, and high-speed backhaul support.

Although THz spectrum can lead to higher path loss and sensitivity to blockages, it can still be beneficial for short-range, secure, and interference friendly communication⁶. However, this does not mean that we can consider the whole of infrared band and visible light as the part of THz spectrum. As we move higher in frequency, the benefits are soon outpaced by the challenges the spectrum bands have to offer. Both infrared and visual light spectrums are very sensitive to noise, obstacles and harmful for humans under certain conditions. Therefore, most of the literature bounds THz to 10THz (30THz in some cases) and does not consider the whole infrared and visual light spectrum, as shown in Figure 2. THz falls right in the optimal range, inheriting the benefits from both microwave and infrared bands to balance the challenges.

There exist numerous applications that could make use of THz communications [17-20]. We acknowledge that due the challenges inherent in the microwave and infrared bands (namely, high path loss, low penetration power, and narrow antenna beams), THz cannot be used for highly mobile applications. However, THz can be envisioned for indoor use where user movement is constrained⁷. THz application is subjected to the environment it is deployed in. For example, the higher end of the THz band can be used for static, short-range⁸, interference free communication⁹, while the lower end of the THz band can be utilized for users with constrained

⁵ A preliminary quantitative analysis shows that the availability of contiguous spectrum is limited by multiple environmental parameters, like humidity, temperature, distance and operating frequency. With ample preventive measures, like higher antenna gain and adaptive frequency-window selection based on environmental parameters, we can observe contiguous spectrum bands of 50-250GHz, explained later in Table II. Even for distances as high as 10m we can still obtain contiguous bands of 10GHz, which is far more than what millimeter bands can offer today.

⁶ A detailed explanation is provided in Sections II

⁷ By constrained movement, we mean body, hand and head movements for VR and AR applications, which is less variable and can be tracked or predicted.

⁸ Some examples of short-range static high demanding applications are: indoor point to point (P2P) communication, for displaying 8K resolution video, high-speed uploading and downloading through Kiosks, and for mesh based backhaul communication.

⁹ Due to low transmit power and low penetration power of THz band, signals can be easily blocked by objects. The penetration power decreases as we move higher in the frequency. Thus, at higher frequency signals can be contained with small distances within a room or a cubicle. This is beneficial for mitigating interference for ultra-dense applications, a task that is very difficult to mitigate in the lower bands.

mobility and long-range communication¹⁰. THz can also support mobile wireless communication indirectly by offloading the static users from a lower band to THz and making room for mobile users in the lower bands.

Another interesting use of THz band is in antenna design. Since antenna size decreases with wavelength, THz makes it possible to produce small antennas of nanometer size and still able to communicate with optimal link loss, unlike the infrared and visible light bands. This may help scale devices exponentially, as dubbed the Internet of Nano Things (IoNT) [19]. Other than for wireless communication, THz can also be used for multiple sensing-based applications that can complement the need for ultra-high communication (we do not focus on this application in this paper).

In this paper, we explore in detail the benefits and challenges associated with the THz spectrum. Through technical and cost analyses, we consider use cases and show where THz may be beneficial and where its use is not justified. We also provide recommendations on where the THz spectrum might be deployed and managed, with consideration of benefit to regulators, manufacturers, operators, and users. The rest of the paper is organized as follows. In section II, we discuss the characteristics of the THz spectrum that makes it both challenging and beneficial for use in mobile communication. In section III, we perform quantitative analysis for the THz spectrum and analyze properties, like path loss, the achievable data rate for static and mobile use, and user coverage. In section IV, we qualitatively discuss the need for THz band and summarize the applications and implications associated with implementing THz.

II. Characteristics of THz Spectrum

In this section of the paper, we take a deeper dive into the characteristics of the THz spectrum and overview the current technical challenges, benefits, and open research. Together, these items can be used to inform the business and policy case for moving into the THz bands.

A. Current Challenges:

THz has many characteristics that make it stand apart from the microwave and the infrared bands. However, some of these characteristics end up being technical challenges that can limit the application/distribution of THz. In this section, we explore those characteristics.

High Path Loss: THz Spectrum is attractive because it promises ultra-high data rate due to the high availability of bandwidth, yet it comes with a cost of high path loss¹¹. The total path loss in this band is highly sensitive to: (a) humidity, and (b) TX-RX distance. Even for a 1-meter

¹⁰ Compared to the upper frequency bands of the THz spectrum, the lower frequency can be easily used for mobile use. However, the lower bands will still require smart antennas, faster beam alignment algorithms and seamless handoff methods, to cater to mobile applications.

¹¹ Path Loss is the difference between the received and transmitted power, measure in dB (decibels). Path loss occurs due to free-space loss, absorption loss, reflection, refraction, scattering, and penetration loss.

distance, the total path loss in THz spectrum can range from 100-200 dB, which is more than the path loss experienced in the lower LTE bands (900 MHz, 1800MHz, 2100 MHz, and 2600 MHz) at a distance of 1Km [23]. Moreover, as we move higher in the spectrum, the path loss is not constant. Instead, it has occasional attenuation peaks of more than 200 dB, which makes it challenging to use a continuous frequency band [24]. These peaks are specific to an operating frequency and need to be avoided for higher throughput. However, avoiding these peaks results in the reduction of the size of channels. Availability of continuous bandwidths and operating frequency becomes conditioned on the environment. A detailed analysis is shown in Section III A & B.

Low Penetration Power: THz has a low penetration power and cannot go through walls and other surfaces. This property might be suitable for non-communication purposes, like detecting weapons and explosives [25], high-resolution imaging [26], and spectroscopy¹² [27], but is a challenge for mobile communication. Lower penetration power results in reduced coverage in space and sensitive to blockages that can come between a TX and RX link. Thus, for a better communication link, we require almost a perfect line-of-sight (LOS) communication¹³. Another alternative is to use non-line-of-sight (NLOS) communication [28], but it is dependent on the surface type, restricted to second order reflections and might require additional mirrors/lenses [29-31].

Low Transmit Power: To compensate for the high path loss, transmit power can be increased. However, technically, it is difficult to obtain high transmit power for antenna operating higher than 300 GHz. The transmit power decreases as we go higher in frequency¹⁴. Currently, there exists TXs with transmit power of ~5dBm¹⁵ for 650GHz and 0dBm for 800GHz [24].

Improve Antenna Gains: The received power is directly proportional to the transmit power and antenna gains, and inversely proportional to path loss¹⁶. As we move higher in frequency, the

¹² THz can be used to replace X-rays for detecting weapons, since it is fairly harmless to humans in a controlled environment and does not contain ionized radiation.

¹³ LOS communication is easy for static applications. In case of mobile users, the frequent change in device orientation can result in constant link outages. Therefore, we need more research advancements in methods, like NLOS communication, fast beam alignment, smart antennas and seamless handoff algorithms.

¹⁴ Technically, it is harder to produce devices that can transmit at higher power at higher operating frequency. To compensate for the low, transmit power, the receivers need to have high sensitivity and low noise figures. Different materials, like silicon germanium (SiGe), CMOS, gallium nitride (GaN), and graphene, are promising technology for THz transceivers. However, most of them 1) do not produce high peak output power, 2) have a very low breakdown power, low sensitivity, and high noise, and 3) are costly to produce. The technologies are still immature and need innovative design and support.

¹⁵ **Decibel (or dB)** is dimensionless unit that is a ratio of power fields in watts (W) on a logarithmic scale.

$$P(dB) = 10 \log_{10}(P(W) / 1W)$$

While dBm is a dimensionless unit for power ratio on a logarithmic scale with reference to 1mW.

¹⁶ **Received power P_R** at the receiver is calculated based on the following equation in dB:

$$P_R (dB) = P_T (dB) + G_T (dB) + G_R (dB) - L (dB)$$

path loss increases, and due to technical challenges, the transmit power decreases. Therefore, the next best solution to improve received signal strength is to improve the antenna gain, which is inversely proportional to the antenna beamwidth¹⁷. Using a directional antenna with narrow antenna beams can increase the antenna gain by 27-45dBi, which is quite high compared to the traditional omnidirectional antenna with a gain of 1dBi. There has been work going on to improve antenna design for THz bands that can provide gains with perfect main lobes [33], using of graphene-based [34,35] antennas, or through the use of an array of antennas [36]. THz has pushed the evolution of antenna design from omnidirectional to directional and now to pencil beams. The downside of using directional antennas is that we need to know the position of the transmitters and receivers beforehand, which is possible in static/fixed wireless communication. However, in a mobile scenario, the TX and RX antennas have to be continuously aligned and trained to coordinate perfect beam alignment [37]. The beam alignment and training process takes up much time, which can range from 5ms to 100ms based on the antenna structure and algorithm [38-40]. The time spent in beam alignment can quickly increase exponentially in a dense deployment scenario¹⁸, eventually reducing the overall system throughput¹⁹.

Outages: Very low penetration power and narrow beamwidths can result in frequent link failure or outage in the THz spectrum. An outage can occur either due to blockages, i.e., blockage induced outages (permanent objects or moving object between the TX-RX path) or due to change in device orientations (mobility induced outages). To avoid blockage induced outages non-line-of-sight (NLOS) communication is preferred; yet, the method is restricted due to the type of material of surface and to second order reflections [29]. On the other hand, mobility induced outages can occur due to orientation change of the device or the object on which the device is mounted (like, hand, head or body). To attain higher antenna, gain the antennae use narrower beamwidth, which requires perfect alignment between the TX-RX pair. Small-scale mobility,

Where P_T is the transmit power, G_T and G_R are the antenna gains at the transmitter and receiver respectively and L is the link loss. To obtain higher throughput, in an idle scenario, we need to improve the received power.

¹⁷ To compensate for the low P_T and high L , one of the best solutions is to improve the antenna gains, G_T and G_R . **Antenna gain** is a measure of the antenna's directivity and efficiency. Therefore, gain can be defined as follows:

$$G = \frac{X}{\delta_h \delta_v}$$

Where X is an aperture dependent factor, which is 52,525 and 41,253 for a uniformly illuminated circular and rectangular apertures respectively, and δ_h, δ_v are horizontal and vertical beamwidths in degrees.

¹⁸ Each beam alignment between an TX and RX requires beam training and beam steering. In a mobile setting the orientation of the device needs to be tracked for perfect beam alignment. Moreover, other than physical objects, moving users can also act as blockages for a TX-RX link. Thus, in a dense deployment, random movement of the users and the orientation of the device can lead to random training time.

¹⁹ The training time is mostly dependent on the antenna beamwidth, which is important for higher antenna gain. As antenna beamwidth decreases, the antenna gain increases and so does the training time and system complexity. To compensate for higher path loss in THz, we require higher antenna gain, i.e., lower antenna beamwidth. Due to the tradeoff between antenna gain and training time, there exists optimal antenna beamwidth values, which are perfect for particular scenarios, as explained in Section III E & F.

such as the human body movement can result in frequent misalignments, thus resulting in outages [41]. Therefore, small-scale mobility management is required to avoid these outage scenarios. A detailed analysis is shown in Section III E & F.

B. Benefits Unique to THz:

At a first pass, it may seem that THz has more challenges than benefits. There are a lot more benefits of THz than meets the eye. There are many characteristics in the THz band that makes it unique and promising for a future in mobile wireless communication. In this section, we explore those characteristics.

Limitation of other Bands: One of the primary reasons for adopting the THz band is the easy availability of large chunks of spectrum, which can result in higher throughput. The traditional lower bands (<6GHz) are nearly fully allocated and occupied, and it is complicated to open large chunks of spectrum. Moreover, higher frequencies, like the mmWave, do not have enough free bandwidth compared to THz [15], while the Infrared bands are susceptible to objects, reflection, noise source from sun/ambient light, and power restriction for safety (high transmission can damage human eye).

Green-field Spectrum: THz is a green-field spectrum since it avoids the need to deal with legacy users and provides an opportunity to implement novel models for sharing or access spectrum [42]. The ease of enforcement and innovation makes THz the next frontier for ultra-high mobile communications. FCC is already invested [43] in using THz for mobile applications. However, there does exist some restrictions on spectrum use. The spectrum is already occupied for purposes such as satellite services [44], Earth-Exploration Satellite Services (EESS), meteorological, and spectroscopy [28], out of which the critical Primary User (PU) are the EESS services [42]. If we avoid co-existence with EESS users in the THz band, we can only use less than 10GHz bandwidth. Thus, there is a need for spectrum sharing methods with EESS and future THz mobile services. Nevertheless, it may be an easier task compared to spectrum sharing methods proposed in lower bands [7,8]. The THz Interest Group established by IEEE 802.15 is already invested into standardization and finding applications for the THz band between 275 GHz-3THz [45].

High Bandwidth: One of the lucrative characteristics of THz spectrum is that it can offer a large chunk of the contiguous spectrum, as high as 250GHz (refer Table II)²⁰, which was not possible in the lower bands²¹. As pointed out earlier, due to occasional path loss peaks, these bandwidth values are sensitive to humidity, distance, and operating frequency. Thus, the available

²⁰ Even for distances as high as 10m, we can still obtain bands of 10GHz, which is still more than what mmWave bands can offer.

²¹ Most of the lower bands (900MHz, 1900 MHz bands) have available bandwidth of 20-60MHz. If we move higher to the 2400MHz and 3600MHz bands we can obtain 100-200MHz bandwidth by carrier aggregation methods. (A list of LTE bands available: https://www.xgpforum.com/new_XGP/en/001/TDD_band.html)

bandwidth can range from 50-250 GHz based on the values of the parameters mentioned above. It is necessary that we have a system that can adaptively select the best spectrum ranges based on the environmental factors. A detailed analysis is shown in Section III C.

Fronthaul Boost: THz can be easily integrated with the existing lower band deployment and instead work as auxiliary support. By offloading high demanding users to THz and proper allocation of resources, we can improve the throughput and at the same time maintain concurrent operations. The integrating of THz with lower and mid-band spectrum can: (a) satisfy high user demands that end up overwhelming the network, (b) freeing up spectrum in the lower band for mobile users by offloading the nomadic users in the lower bands to THz spectrum, (c) satisfy small user demands that cannot be satisfied due to lack of resources in the existing infrastructure, (d) increasing the user coverage at the edges of the cell, (e) increase user coverage by easy deployment of APs [46] or by Information Shower²² [47], (f) high speed upload and download through ultra-high Kiosk²³ [48].

Interference Friendly: In lower/mid bands (such as 2100 MHz, 2600 MHz, 2.4GHz and 5GHz), concrete walls can act as wireless friendly buildings [49]. Likewise, due to terahertz's low penetration power and highly directional antennas, interference can be contained to rooms/cubicles or even few meters depending on the transmit power and antenna gains. This can result in opportunistic spectral re-use (a solution for coexistence with EESS services). However, due to the dense deployment of APs and UEs and random directionality of antennae, interference can be extremely varying, until blocked by walls or blockages. Although blockages can result in significant outage scenarios, interference analysis for THz bands shows that the presence of blockages significantly reduces interference [50,51]. Currently methods used to mitigate harmful interference results in reducing throughput. For example, in the lower bands, harmful interference can be controlled by regulating the transmit power of a device, which results in reduced throughput and user coverage. On the other hand, even with low transmit power and low penetration power, THz spectrum is still able to be maintain ultra-high throughput due to large channels.

Security: The directional beams and limited propagation distance makes THz spectrum perfect for secure wireless communication. With pencil-beams and highly directional antennae, communications can be made jamming [52] and eavesdropping [53] resistant. Ultra-high speed and limited communication distance can be beneficial to create secure links, for example, in the case of a UAV. Moreover, spreading the information across a broad bandwidth makes it difficult for an attacker to jam the system [21].

Scalability: We noted that the antenna size is directly proportional to wavelength and THz (high frequency, low wavelength) allows the manufacturers to produce antennas of a nanometer in size. In the future, with proper research and investment, dense deployment of THz antenna will

²² Ultra-short-range technology providing users with massive content download through a wireless link [47]. The ability to download massive content seamlessly is sometimes called an "information shower."

²³ A small booth or stand with the capability to provide high speed internet connection through THz spectrum. Since, the user's device needs to in proximity to the Kiosk, the effect of path loss and mobility induced outages can be ignored.

become cheaper. Furthermore, with limited propagation distance and being interference friendly, THz is an ideal candidate for an ultra-dense network (UDN) [77]. This will not only help in the easy and dense deployment of devices, but also can be useful in special applications scenarios, like body area network (BAN) [54], nanobots, and Internet of Things (IoT).

Backhaul Support: One of the most significant assumptions for using THz in fronthaul is that the backhaul has a higher data rate compared to the fronthaul. Fiber optic cables support today's high-speed backhaul connection. However, it might not be able to support THz with the ultra-high throughput it promises to deliver for B5G applications. Upgrading fiber is a costly affair and might result in a critical bottleneck for THz deployment. Advancements in the content delivery network (CDN) can somewhat ease the situation, but we will still require advancements in the backhaul technology. One solution is to carry THz as a baseband signal over fiber, which requires much less signal modulation, while another solution is to use THz for wireless backhaul [69]. THz can replace fiber and obtain a faster backhaul though high-speed point to point communication. Despite the challenges associated with wireless backhaul (weather conditions and interference), it is one of the cheapest option available. To overcome the high attenuations offered by the environment, we can have a mesh of point-to-point THz antennas communicating within small distances to support a high-speed backhaul. As the distance between the server and end user increases, the THz backhaul mesh size will increase. Feasibility of such huge mesh network depends on availability of infrastructure²⁴ and advancements in routing algorithms. We acknowledge that wireless THz backhaul cannot be used in every scenario nor be used to replace fiber cables. However, THz can still be integrated with fiber, such as a fiber-THz-fiber [70], or THz-fiber-THz links, as a buffer to reduce latency and/or cost [70].

Other Benefits: There exists other non-communication application of THz spectrum, like high-speed on-chip communication [55], onsite video streaming for Public Safety [57], scanning the human body for metals and/or concealed weapons [26,27], spectroscopy [28], and replacing fiber cables in data centers [56]. THz can be used to replace X-rays for detecting weapons, since it is fairly harmless to humans in a controlled environment and does not contain ionized radiation. Moreover, with a range of these new sensing-based THz applications might eventually economically boost the need for more wireless/wired communication-based applications. For example, in case of a public safety event where human help is delayed, a swarm of drones can be sent to the incident site to allow authorities to monitor the situation through sensing application mounted on the drone — leading to live video streaming²⁵ for authorities to take life-critical decisions remotely. Another example will be the use of these sensing applications in smart homes that monitor temperature, air quality, and object movement, in real-time. Both THz and non-THz based sensors can send back notification to the central hub about changes, which could trigger an alert to the user. The user now might through communication channels either send back a command to the hub or want to access a video stream²⁶.

²⁴ Since THz spectrum will not be able to penetrate buildings or mountains, it will need to be relayed over existing infrastructure like roads, highways, tunnels and bridges.

²⁵ A high-speed, low-latency, and secure THz fronthaul and backhaul is required for this application.

²⁶ By using THz for a high speed backhaul it will be easier to remotely access live video stream.

C. Scope of Current Research Issues

The characteristics as mentioned earlier, can be both challenging and beneficial depending on the application and the use case scenarios, meaning that more research is needed.

Testbeds: Need to perform more experimental evaluations and channel modeling for different environmental scenarios and operating frequencies [58-60]. Testbeds [61] for THz application are already in place, which is looking into channel modeling, channel coding, and field tests. However, most of these are constrained to below 300GHz. We need to invest more into experimentations involving frequencies above 300GHz.

Antenna Design: We need advancement in antenna design that can provide wider bandwidth gains [32], with perfect main lobes. Most of the current research assumes a perfect conical shape antenna beam [41]; however, it is difficult to obtain such a perfect antenna pattern for higher frequency. Dynamic massive MIMO can also be used to overcome the high path losses, which might demand cooperative communication among devices [19].

Adaptive Systems: We need smarter systems that can adaptively change parameters based on environmental settings. In section III C & D, we show that the operating frequencies, the available bandwidths, and achievable data rates are highly dependent on environmental settings. By using Machine learning/Artificial Intelligence tools, scenario-wise optimal values for the antenna parameters can be inferred to get the best of the THz band [62-64].

AP Specification: To avoid high path loss, the Access Points (APs) need to be strategically placed in an indoor setting. One solution is to use a THz-Plug, where the AP can be plugged into a data jack (e.g., an ethernet port) on a wall or part of another data device [65], but this could constrain the user mobility or coverage. For a more mobile distribution, the APs might be broader distributed throughout the room to provide complete coverage [46, 66]. Due to low penetration power, THz cannot penetrate walls or objects, which leads to low spatial coverage. However, spatial coverage might also be increased by bouncing the signal off of mirrors or guiding it with the use of lenses [18, 28].

Mobility Management: In the case of blockages, to continue communication, the solutions are: non-line-of-sight (NLOS) communication, changing operating frequency band, or wait till the blockage is moved. On the contrary, mobility induced outages can be maintained and avoided by proper analysis. One such solution is beam alignment, but this event is time-consuming and may complicate in case of MIMO antennas, if not properly coordinated. Time for beam alignment can go as high as 100ms depending on the system and beam learning process [38,39]. As we move higher in the THz spectrum, the mobility management methods will become more complex. Instead, we can use THz spectrum to indirectly support mobile users by offloading users into THz and freeing up spectrum in the lower bands.

New Access Protocol: THz is sensitive to path loss and frequent outage scenarios based on the presence of blockages and/or device mobility patterns. Although a single THz AP will have the capability to cover multiple users with limited throughput (shown in Section III F), due to the

random presence of blockages, THz will have to use multiple APs with seamless handoff and multi-hop communication. This requires changes in the algorithms of the network and link layers [18]. THz spectrum might also require support from lower/mid bands and offload traffic when THz is not able to provide coverage²⁷. There is a need to build a seamless offloading method between THz and lower band infrastructure.

Spectrum Access: There needs to be a discussion among regulators, operators, and manufacturers on the frequency blocks that can be assigned for licensed or unlicensed use. THz can promote unlicensed use of this spectrum consequentially resulting in tremendous profits and innovation, like we have observed in the ISM bands [21]. However, there is also a need for some amount of licensed spectrum in THz. As we move higher in the THz spectrum, the characteristics change, and so does the use case. It is necessary to decide how the licensed and unlicensed users will be divided into the spectrum. One solution is to propose a dynamic frequency selection method coupled with a dynamic auction strategy to promote a fair share of spectrum among the users.

Changes in Hardware: With THz spectrum able to provide Tbps data rates, there is a need to upgrade the associated hardware²⁸. Since THz lies both in the microwave and infrared, it shares the properties of both wireless and optics²⁹. This requires the hardware to be able to process and convert signals between wireless and optics. THz devices also need to be equipped with beam steering techniques, which can increase the complexity of the hardware. The manufacturers might also have to rethink a device design that is short-distance and beam steering friendly. THz devices are currently costly; however, technological advancement and economies of scale could result in cheaper production. Silicon germanium (SiGe), CMOS, gallium nitride (GaN), and graphene are some of the promising technologies that might bring low-cost fabrication technology to market for THz devices [19, 75, 81]. Advancement in nanofabrication technology and microelectromechanical systems (MEMS) could also expedite this process [18].

Safety Standards: Most countries have restrictions on electromagnetic radiation (EMR) based on the device transmit powers and its applications. For example, in the USA, the FCC follows the standards set by IEEE, which range from 3KHz to 300GHz [76]. In the infrared band, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) sets limits on device operation [77]³⁰. Since THz resides in the infrared band, it inherits the property of being thermal,

²⁷ Handoffs can be of two types horizontal and vertical. In horizontal handoff, the user seamlessly switches between APs that are operating on the same technology and frequency band (this may or may not be in the same channel). In vertical handoff, the user switches between APs that are operating in different frequency bands and/or different technology.

²⁸ We need to upgrade the hardware to improve digital signal processing techniques, sophisticated coding schemes to reduce the bit error rate (BER), parameter aware modulation schemes, accurate local oscillators for generating carrier frequency, and antenna design [19, 74].

²⁹ THz systems might demand additional hardware to support both wireless and optical properties, like phase arrays, lenses, or mirrors to steer the beams [19, 28].

³⁰ There are multiple THz spectrum range definitions in literature. The FCC has just recently recognized the 95GHz to 3THz band for new services and technologies, while many technical researchers consider a

meaning it heats a surface that absorbs it, like the human skin. To compensate for the high path loss narrow pencil beams are required for THz communication. These THz laser beams can have a thermal effect on human skin and tissues. Experimental results show that for 0.4THz to 0.6THz, the maximum human skin penetration depth is approximately 0.3mm [78], which might result in thermal effects on the epidermal layer of the skin and in some cases even the eye. As an example, a possible use case of THz is for VR goggles and AR contact lenses [17], which might require power restrictions to avoid injury to the eye. There may also be unsubstantiated claims of harmful effects from the use of THz spectrum. The impact mostly depends on the transmit power and the duration of exposure of the beam, which is likely to be low enough not to affect humans. Nonetheless, additional testing to assess such harm is justified.

III. Quantitative Analysis

In this section, we perform a quantitative analysis on various THz characteristics as mentioned in Section II³¹. At the end of each section, we provide a non-technical overview of the meaning and findings of that section.

a) **Expected Absorption Loss**³²

THz is sensitive to multiple environmental parameters, out of which humidity and distance results in the maximum loss. Hence it is necessary that we quantify the amount of absorption loss for better deployment of APs. The signal absorption loss happens due to molecular absorption and is mostly due to the presence of water vapor. For a constant water vapor concentration, the attenuation scales up rapidly as we move from a 1m Euclidian distance to 30m at a fixed relative humidity of 20%, as shown in in Figure 3 [69]. It can be observed that different frequencies show different absorption rates with occasional spikes in loss. To observe the nature of these peaks, let us consider a small spectrum band of 0.3-1THz, i.e., the sub-millimeter band. In Figure 4, we observe the effect of humidity on the sub-millimeter band at a fixed distance of 10m. As the water vapor concentration ρ increases from 0 g/m³ (dry air) to 23 g/m³ (100% absolute humidity) the attenuation peaks scale up.

range from 300GHz to 10THz. The said frequency range also falls in the infrared band, particularly in the IR-C band (300GHz to 100THz), and within the subcategory of the far infrared (FIR), i.e., 300GHz to 20THz [77]. Currently, we do not have safety standards for THz spectrum, but one might draw insights from the FIR region in infrared band.

³¹ While the FCC and ITU define the THz band as radio spectrum between 300GHz and 3THz [22,23], here we present our analysis for frequency ranging from 95GHz to 10THz, as is common in technical papers.

³² Path loss is the combination of all forms of losses a signal experiences, like free-space loss, absorption loss, reflection, refraction, scattering, and penetration loss. We consider absorption and spreading losses, which constitutes the major of the path loss. Since, absorption loss is quite abrupt in THz, we perform a separate analysis for absorption loss in Section A.

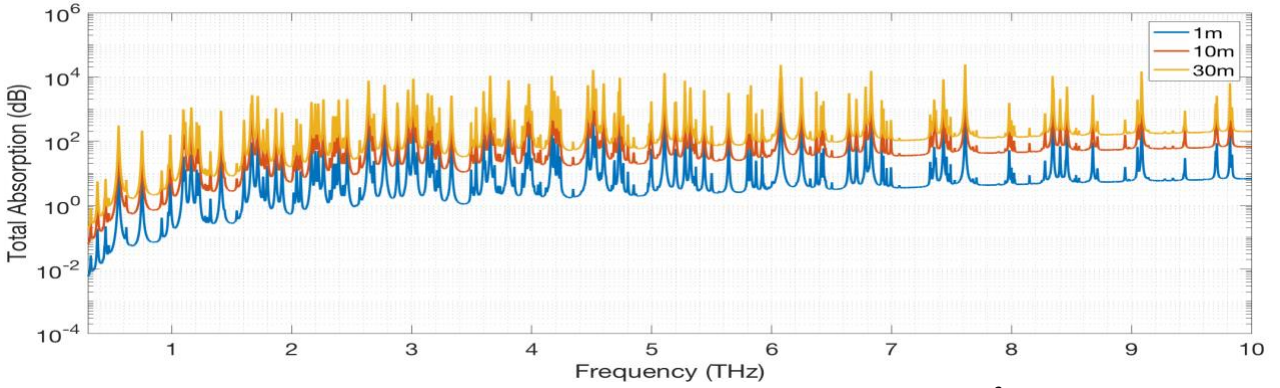


Figure 3 Total absorption loss from 0.1 to 10 THz frequency with 20% (5 g/m^3) concentration of water vapor at 25°C

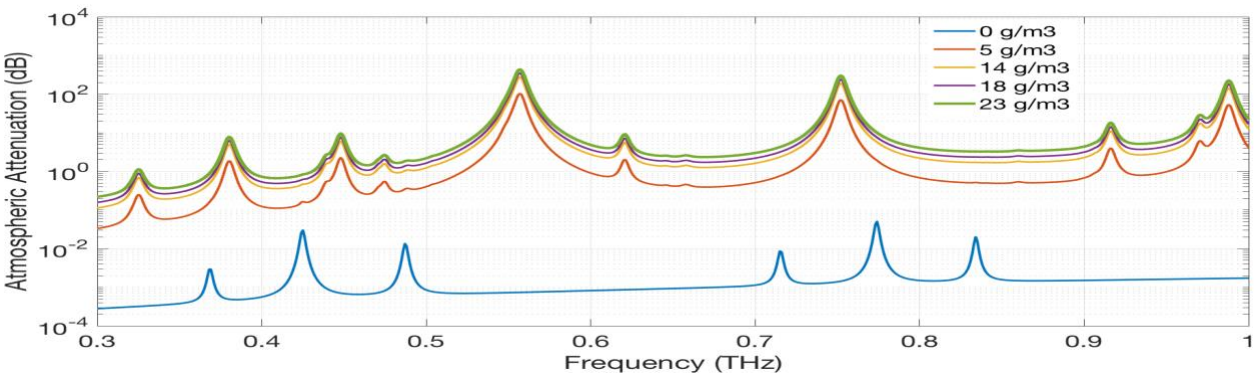


Figure 4. Atmospheric attenuation from 300 GHz to 1 THz frequency for different concentration of water vapor at 25°C and 10m distance. For clear understanding and brevity, we analyze a subset of the THz band from 300GHz-1THz.

Overview: THz spectrum is highly sensitive to distance and humidity, which can result in high absorption loss. Deploying THz devices for short distance communication is beneficial and will require minimal signal improvement methods. On the other hand, humidity cannot be controlled and would need systems that can adaptively monitor humidity and take measure to improve the signal³³.

b) Expected Path Loss

Path loss is the combination of all forms of losses a signal experiences, like free-space loss, absorption loss, reflection, refraction, scattering, and penetration loss. We consider the absorption and spreading losses in our calculation since other loss types are subjected to environmental conditions. Other than absorption loss, THz also suffers from high spreading loss, which is directly proportional to the square of the distance and frequency, which is inherent in all

³³ As the humidity increases the system should be able adapt and seek among methods to improve the signal strength, like improving antenna gain, using non-line-of-sight communication, improve modulation or coding schemes.

frequency bands. Therefore, as we move higher in the THz frequency, the total path loss, sum of absorption and spreading loss, also increase along with occasional path loss peaks, as shown in Figure 5.

Overview: Although we haven't considered other loss types, like reflection, scattering, and penetration loss, in our calculation, Figure 5 gives us intuition about the free-space path loss experienced in the THz band. Figure 5 also shows that there exist occasional spikes in path loss, which makes specific frequencies impractical for use. Thus, it is necessary that we identify these frequency bands with relatively consistent path-loss.

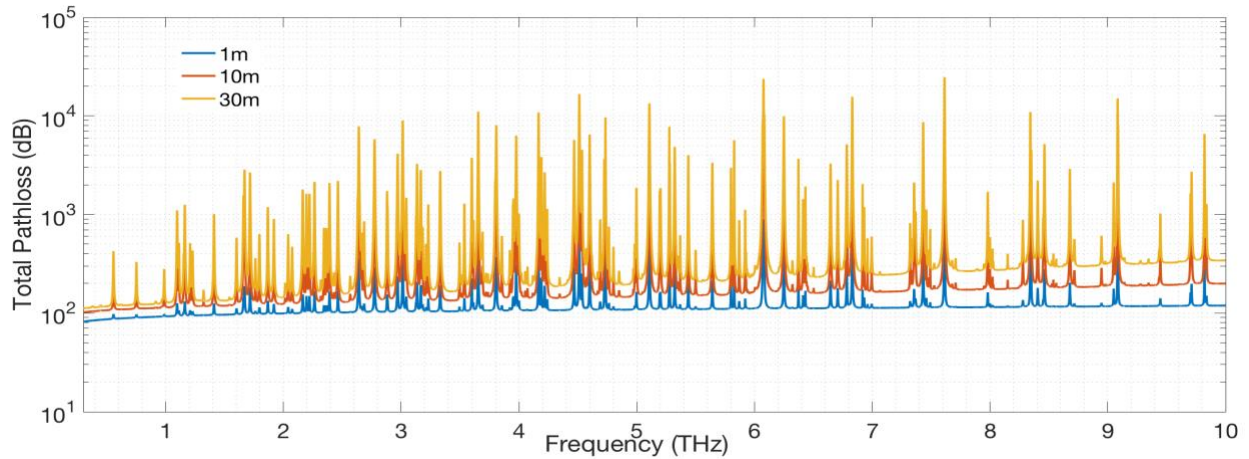


Figure 5 Total Path loss from 0.1 to 10 THz frequency with 20% (5 g/m³) concentration of water vapor at 25°C

c) Expected F-Windows

Here we try to identify the frequency bands/channels and corresponding bandwidths that can be utilized opportunistically based on the distance for higher throughput. As shown in Figure 5, there exists a variable number of attenuation peaks in the THz band, which can result in a reduced number of continuous channels. Thus, it is crucial that we figure out these continuous frequency windows (F-Windows), i.e., frequency bands without abrupt attenuation peaks, which are critical to gain larger bandwidths. For simplicity, let us consider the spectrum 0.3-1THz, i.e., the sub-millimeter band, and analyze the average center frequencies, average bandwidth, and 50GHz channel count, as shown in Table II.

Overview: Detailed analysis of F-windows in the THz spectrum shows that the usable bands are sensitive to distance and humidity. It is interesting to observe that at 0.3m we can get a maximum of 250GHz of continuous spectrum, while at 10m it drops to about 100GHz. Even for distances as high as 10m, we can still obtain bands of 10GHz, which is still more than what mmWave bands can offer today. Detailed F-window analysis for the whole THz band will help regulators and operators to divide the spectrum bands either into fixed or dynamic channels.

Table II A frequency-window lookup table for 300GHz to 1THz spectrum with varying distances and ρ of 5 g/m³, i.e., 20% humidity at room temperature of 25°C³⁴

Distance	Average Center Frequencies (in GHz)	Average Bandwidths (in GHz)	Continuous Windows of 50 GHz
0.3 m	424.5, 659.5, 842, 946	249, 173, 150, 50	4 (>50GHz), 0(<50GHz)
1 m	374.5, 498.5, 599, 684, 843, 946.5	149, 95, 44, 120, 146, 49	5 (>50GHz), 1(<50GHz)
1-2 m	340, 416.25, 497.25, 603.25, 683.25, 847, 946.5	80, 62.5, 88.5, 35.5, 114.5, 136, 43	5 (>50GHz), 2(<50GHz)
3-10 m	313, 351.7, 416.8, 466.7, 504.5, 611, 681.2, 854.7, 946.2	76.75, 56.75, 18.75, 56.5, 20, 104.5, 120.75, 36	5 (>50GHz), 3(<50GHz)
10-11 m	313, 351.5, 414.75, 467, 503.5, 611.5, 646.25, 694.25, 856.75, 945.75	26, 45, 46.5, 16, 48, 10, 25.5, 66.5, 106.5, 29.5	2 (>50GHz), 8(<50GHz)

d) Expected Antenna Gains

Although THz has challenges in the form of absorption and spreading losses, we can still obtain ultra-high throughput by increasing the antenna gains. Here we quantify the amount of antenna gain required to compensate for the high path loss. As stated previously, with narrower beamwidth δ the gain increases, so it is necessary that we aim for narrow beamwidths. This is evident when we compare Figures 6 (a) and (b). Antenna with narrow beamwidth dissipates less energy, which results in a higher antenna gain³⁵. With a relatively wider beamwidth of 20°, the user can move more freely without incurring a drastic change in gain. This observation is critical for users with frequent change in position and requires a steady throughput. For a constant data rate, it will be interesting to find beamwidths which are specific to user service type.

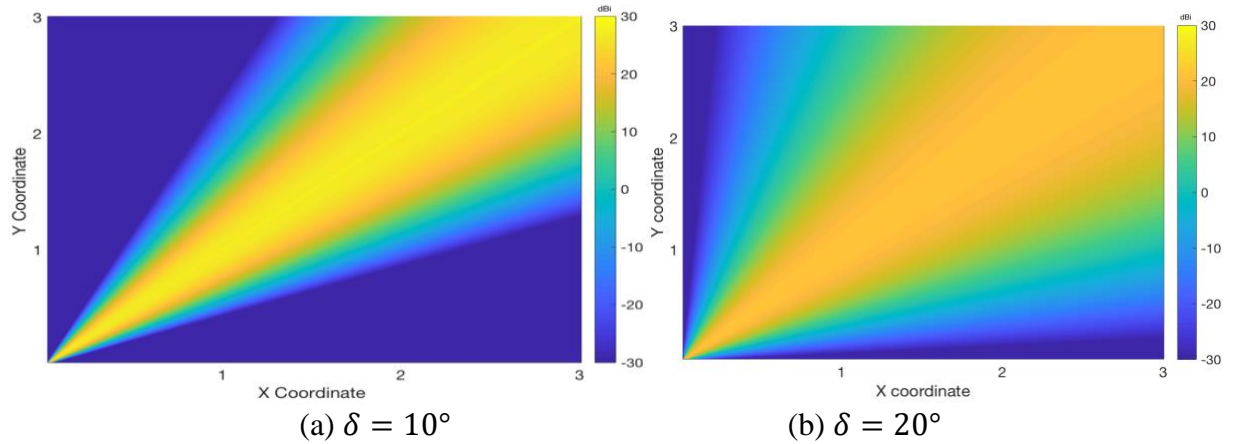


Figure 6. Antenna gains for different antenna beamwidths δ

Overview: To compensate for the high path losses, it is necessary that we have higher antenna gains. Reducing the antenna beamwidth results in a more directive beam, and the energy is less

³⁴ Similar frequency-window analysis can be drawn for the whole THz band defined in Figure 2. For the sake of clarity and brevity, in this table we analyze the 300GHz to 1THz band.

³⁵ Moreover, the relative positions of AP and user antenna are also responsible for the amount of gain at each transmitter and receiver.

dispersed. Although reducing the antenna beamwidth can improve gain, it demands constant beam alignment and training for mobile users, which can result in frequent outages and reduction in average throughput.

e) Expected Data Rates

Now that we have quantified the path loss and the antenna gains available let us observe the achievable data rate for different operating frequencies and Euclidian distances. Since the average data rate is also dependent on the mobility of the users, we further our analysis of static and mobile users.

a. For Static Use

From Figure 7, we can observe that at higher frequencies, it is hard to achieve ultra-high data rate with high distances and limited bandwidth. It is hard to predict the distance values for mobile users, but for relatively static application, the TXs can be strategically placed such that the distance is always within a tolerable margin. Therefore, for a relatively mobile application, to maintain a higher data rate, it is necessary that we have higher bandwidth. As we increase the bandwidth from 1 GHz (shown in Figure 7.a) to 10 GHz (shown in Figure 7.b), the data rate also scales up proportionally (doesn't scale linearly since the noise per GHz also increases). Figure 7 also can highlight that to achieve higher throughput it is necessary to identify these continuous frequency windows, i.e., without attenuation peaks, as shown in Table II.

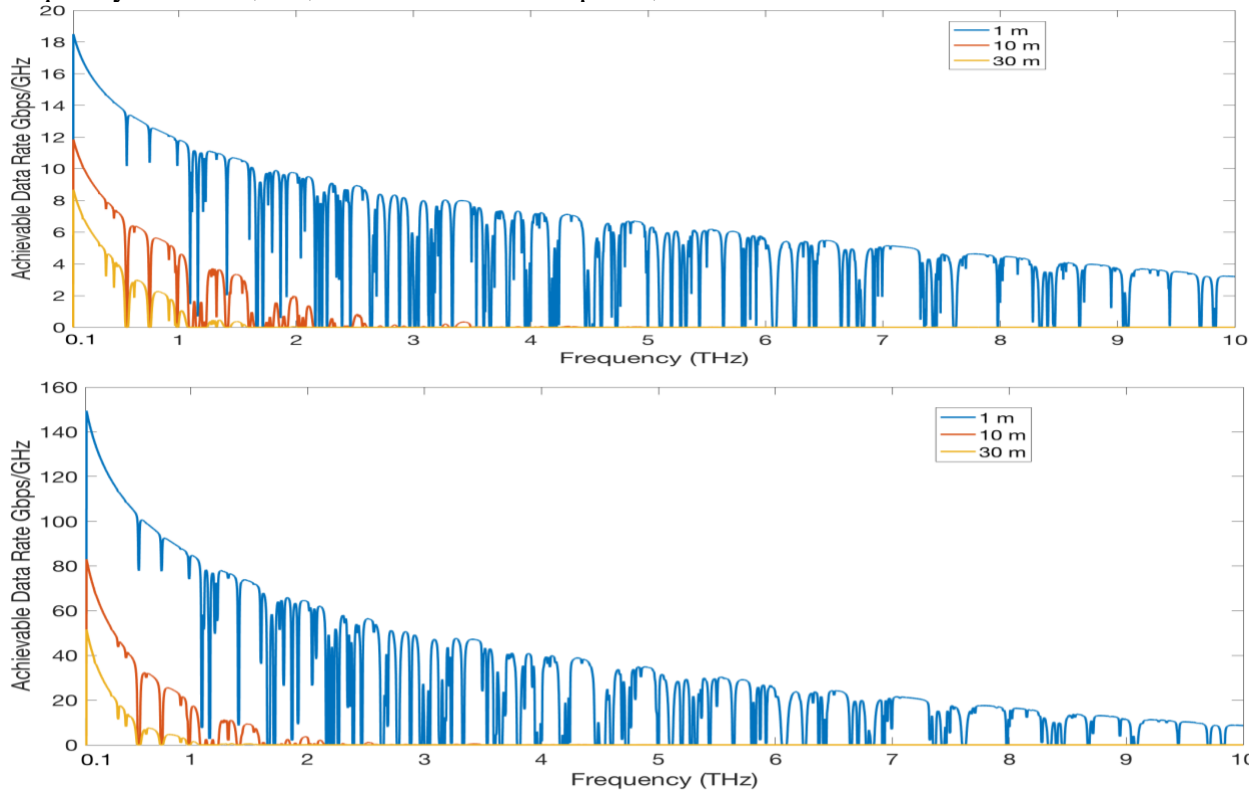


Figure 7 Achievable data rate for beamwidth (a) 1GHz and (b) 10 GHz. We assume transmit power of 0dBm, an antenna beamwidth of $\delta = 10^\circ$, and 20% (5 g/m^3) humidity at 25°C

b. For Mobile Use

In a relatively mobile scenario, we observe that the throughput doesn't scale, as shown in Figure 8. We observe the change in throughput with respect to time for three different user mobility scenarios, (a) S1: High Mobility (e.g., high intense games), (b) S2: Constrained Mobility (e.g., fast and slow walking), and (c) S3: Low Mobility (e.g., sitting or standing). Antenna beamwidth scales the throughput values; however, user mobility type significantly affects the average throughput.

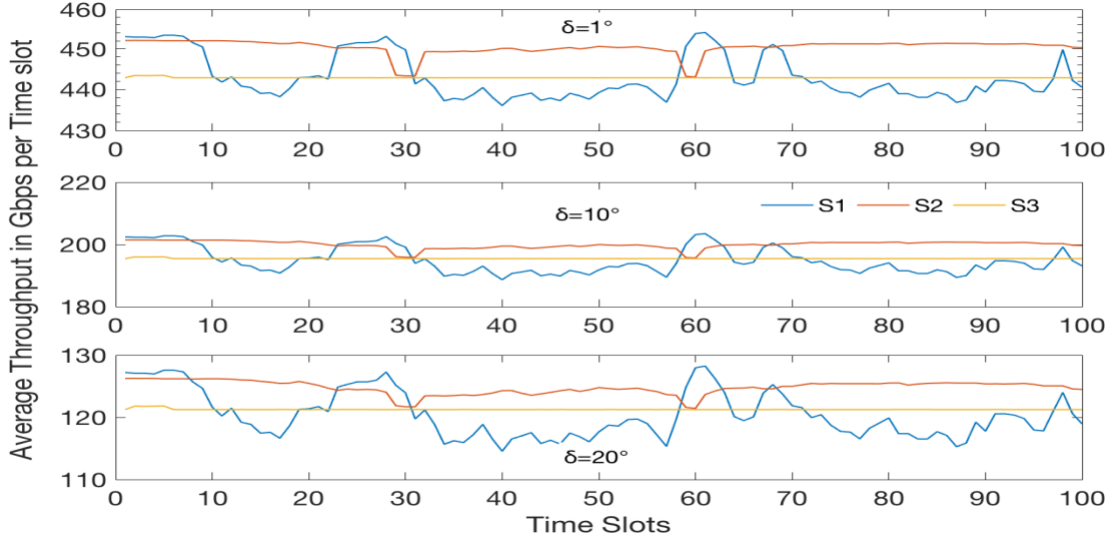


Figure 8. Time average throughput for different beamwidths δ with adaptive Frequency-window selection and 20% (5 g/m³) concentration of water vapor at 25°C

Overview: For static users, the throughput is only dependent on distance, humidity, and operating frequency. To improve throughput in static users, we can reduce the TX-RX separation or move to lower THz bands or reduce the antenna beamwidth. On the contrary, mobile users are highly sensitive to antenna beamwidth. Human action consists of occasional yaw, roll, and pitch movements. The rate of change of these movements can result in frequent outages if the antenna beamwidth is quite narrow. For mobile users, we require smart systems that can sense/predict human/device movements to adaptively change antenna beamwidth and provide better average throughput.

f) Expected User Coverage

As explained in Table II, THz is sensitive to blockages and mobility, which can result in outages, reduced average throughput, and reduced user coverage. Here we try to quantify the effect of the outage on the amount of user coverage for a single AP. For the analysis done in Figures 7 and 8, we assumed a single user with direct LOS to the AP, which is not the case in real life. There are generally multiple users that need to get satisfied by a single TX (for spectrum efficiency). Therefore, for a system other than obtaining higher throughput, it also needs to obtain higher user coverage. In such a scenario, other than parameters, such as humidity, distance, frequency,

and bandwidth, the user coverage is also dependent on antenna beamwidth values. Although with narrower beamwidth we can gain higher throughput, it can also result in link failure – leading to a “beamwidth dilemma” scenario. Thus, for a given scenario, there exists an optimal beamwidth value for which we can maximize the throughput/user coverage. Outage times can result in significantly reducing the average throughput and in a multi-user scenario leads to decreasing user coverage. In Figure 9, we observe that these outages times are related to the beamwidth values and mobility types. In a highly mobile scenario S1, the average human yaw, pitch and roll movements vary from 12-15° and in low mobility scenario S3 it varies from 3-6°, which is also based on human velocity. Although for a low beamwidth value between AP and UE, the antenna gain increases significantly, due to varying mobility types can result in frequent outages.

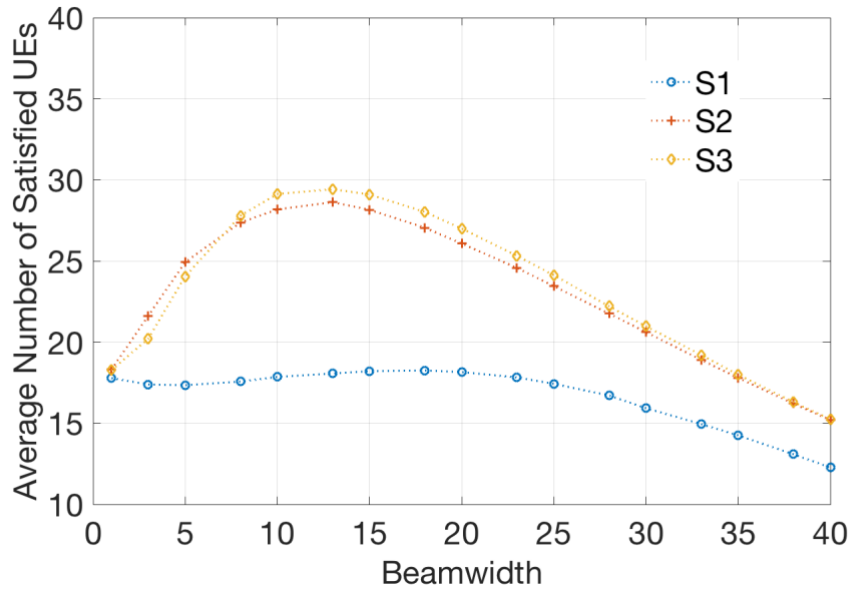


Figure 9. Average users satisfied for varying beamwidth and mobility types for a single AP with 0 dBm transmit power and adaptive frequency window selection. We assume all users are requesting 10Gbps data rate with a Time Division Duplexing (TDD) spectrum usage model.

Overview: Other than providing ultra-high data rate, THz can also be used to improve user coverage. It is relatively easier to satisfy multiple static users, but as the users become mobile, the outage probability increases. We observe that for a single AP, the user coverage is dependent on the antenna beamwidth and user service types. For higher user coverage, we require a smart system that can use machine learning and artificial intelligence algorithms to sense/predict the user service types and/or movements.

IV. The Need for THz Spectrum and More

Currently, we have applications that only require a maximum of 1-5Gbps speed, and that can be enabled by technologies such as mmWave, massive MIMO, and smart radio resource management. So, it is **logical to ask, is there a need to move to the THz band to obtain such ultra-high data rates?** The answer to this question is not a direct yes or no, but specific to scenarios. There are scenarios where the use of THz is not justified, while there also exist many use cases where the benefits may outweigh the costs.

Firstly, THz lies in the sweet spot between microwave and infrared bands, shown in Figure 2, which makes it a promising investment. THz can provide higher bandwidth compared to what mmWave or any lower LTE bands combined can provide. However, it doesn't mean that going higher to infrared bands, will provide higher bandwidth or provide additional benefits. The losses in the infrared bands are so sensitive to blockages, weather, and noise that it is not able to provide such bandwidth gains. Secondly, in section II, we discussed the different characteristics of the THz band, that at first glance come up as drawbacks compared to the lower and mmWave bands. However, these characteristics are "blessing in disguise" and can be beneficial in certain scenarios. We summarize each of these characteristics along with their pros, cons, and pending issues in Table III.

As discussed above, there are enormous challenges that constrain the application of THz to wireless applications. Given THz's sensitivity to device orientation and blockages, constant antenna beam alignment is required, which can quickly become involved with the densification of users. Therefore, THz is mostly envisioned to be deployed for static applications or could be used to offload static users from lower bands and free up a lower spectrum for mobile application. Furthermore, THz can be useful where harmful interference occurs because of the dense use of lower bands. With THz's limited penetration power, harmful interference can be constrained by small rooms or cubicles.

Although THz has some challenges, such as high path-loss, low penetration, sensitive to mobility, and hardware challenges that limit its application, THz can still be used in multiple indoor and outdoor related applications. For an indoor setting, THz can be used for ultra-high indoor point to point (P2P) communication, for displaying 8K resolution video, and high-speed uploading and downloading. THz has the potential for implementation of indoor on-demand ad-hoc networks with ultra-high data rates and very low latency. For example, an ad-hoc wireless personal area network (WPAN) can be established among multiple devices to improve the Quality of Service for a VR/AR application or establish ultra-high data/video transfer among wearable devices [19]. For an outdoor setting, THz can be used for fixed wireless access (FWA) or aid in building a reliable backhaul, which is still a bottleneck for many current technologies. THz is a promising candidate for unmanned autonomous vehicles (UAV) application. With THz, UAV can establish low-power, directive, and secure connections [80,81], which can help in public safety, commercial, and defense purposes. However, outdoor use of THz is also sensitive to weather conditions, such as rain and snow, which can cause scattering [79].

THz can also be envisioned to provide ultra-high throughput to both indoor and outdoor wireless nomadic application. However, it is challenging to cater to wireless mobile users. THz demands

mechanisms that can continuously monitor these mobile users and physical blockages to avoid outages. The mechanisms are quite complex and can quickly scale up with densification of devices. Although it is challenging for THz to cater to these mobile users directly, THz can indirectly aid by offloading the nomadic users from the lower spectrum and free up spectrum that can be used for mobile users. These mobile users might not be able to experience ultra-high throughput but is a better tradeoff.

It is interesting to ask -- is there a profit in such “offloading”? Firstly, the UE devices need to be equipped with antennae that can oscillate quickly from a lower frequency to a terahertz frequency. Secondly, there are questions such as -- which users should be offloaded; when should it be offloaded; and how often should these transfers occur? We also need to discuss where this kind of offloading model is justified and not justified. For example, THz offloading may be justified where there is enormous user demand with static or constrained mobility, but not justified for users with high mobility or in environments that are full of obstacles that can result in frequent outages.

Other than providing multiple benefits for wireless communication, THz can also help in sensing-based applications, like detecting weapons and explosives [25], high-resolution imaging [26], and spectroscopy [27]. THz can be used to replace X-rays for detecting weapons, since it is harmless to humans in a controlled environment and does not contain ionized radiation³⁶. Sensing based applications are very sensitive to noise, and THz is able to provide lower noise compared to higher frequency, like infrared and visual light. Given the supplementary and critical application of THz spectrum, in the future it might be necessary that these applications coexist with other THz communication applications. Moreover, a range of new sensing-based THz applications might economically boost the need for more wireless/wired communication-based applications.

Therefore, while there are many attractive benefits, the detractions make the viability of this band in the near-term questionable. However, with the proper assignment of applications/users to particular frequency bands, we can exploit the best of what the THz spectrum has to offer. For example, the lower THz bands should be relatively more useful for mobile users, outdoor applications, and in the presence of blockages, while the higher THz bands should be more useful for nomadic users, constraining interference, indoor applications, and ultra-dense networks. As we move higher in the THz spectrum, we gain bandwidth at the cost of higher path loss, and we can constrain interference at the cost of small spatial coverage. These tradeoffs make THz a promising candidate for multiple applications ranging from civilian to commercial domains.

³⁶ <http://terasense.com/products/body-scanner/>

V. Conclusion

In this paper, we review the current challenges and benefits associated with the THz spectrum. Although there exist many challenges limits the deployment of THz for mobile applications, other characteristics make it particularly desirable for ultra-high speed communications. A summary of the THz characteristics, challenges, benefits, and pending issues is shown in Table III. THz is a unique spectrum band that can provide higher bandwidth compared to the traditional radio spectrum and mmWave but at the cost of higher path loss. Furthermore, compared to the high-frequency spectrum, such as in FSO and IR communication, THz is not as sensitive to opaque objects and doesn't pose a risk for human eyes.

In the future, compared to the traditional lower bands, THz can provide high demanding applications with easy access to nearly 50-250 GHz of bandwidth. With proper methods to compensate for the high path loss, applications can eventually experience ultra-high throughput, which was not possible in the lower bands. Although the THz spectrum's low penetration power makes it sensitive to blockages and mobility, we can use this property for avoiding harmful interference in ultra-dense deployment. In this paper, we quantify some of the characteristics of the THz spectrum, like path loss, the achievable data rate for static and mobile use, and user coverage. It is not possible for THz to independently cater to future demand. However, it will require constant support from lower bands and existing infrastructure to compensate for the challenges. We envision this paper as a starting point for the discussion of THz's application in 5G and Beyond 5G services. To further the deployment of THz in future high-demanding services, regulators, manufacturers, operators, and researchers need to solve the pending research and policy related challenges associated with THz.

Table III. A Summary of THz Spectrum Characteristics, Benefits, Challenges and Pending issues

#	Characteristics	Benefits	Challenges	Recent Work	Pending Issues
a	Green Field Technology	Less enforcement	Uncertainty in price and infrastructure	[21,42,44]	Efficient allocating of spectrum Spectrum sharing methods with existing primary users, like EESS
b	High Bandwidth	Available bandwidth 50-250 GHz Reach ultra-high throughput	Need a high speed backhaul Environment sensitive	[18,61,63]	Identify scenarios and environment settings
c	Fronthaul Boost	Load balance Traffic offloading	Need to balance resource	[9,46]	Identify efficient allocation of THz spectrum
d	Scalability	Antenna nm in size	Low transmit power	[14]	Resource coordination among TXs
e	Humidity Sensitive	Interference Friendly	High atmospheric attenuation	[67,68]	Identify locations and scenarios when THz use is not justified
f	High Spreading Loss	Interference Friendly	Scales quadratically with frequency and distance	[68]	Identify optimal distance values based on environment & scenarios
g	Low Penetration Power	Interference Friendly Medical Imaging & Spectroscopy	Sensitive to blockage Increase outages Need almost LOS communication	[29-31]	Identify operating frequencies suitable for particular material
h	Interference Friendly	Contains harmful interference to small areas/rooms	Reduced user coverage	[49-51]	Identify Interference map for different environmental properties Need better antennae design
i	Narrow Antenna Beams	Higher Antenna Gains	Sensitive to device orientation, can result in frequent link outages	[37-40]	Need faster beam alignment mechanisms for dense mobile UEs
j	Mobility Management	Innovation	Need to monitor the orientation of devices	[41]	Smart system that can predict human actions to avoid outages
k	Cell Placement	Smaller than femto cells (maybe Auto Cells)	Sensitive to antenna degree of freedom and blockages nearby	[28,46,65, 66]	New methods for resource allocation and frequency reuse
l	Security	Antijamming Encryption of beam possible	Thermal noise can cause interference	[21,52,53]	Can THz be used for Secure MANETs or FANETs?
m	Spectrum License	Ease of spectrum allocation	Which spectrum bands should be licensed or unlicensed?	[21,43]	Identify frequency blocks Frequency allocation method
n	New Access Protocol	Innovation Seamless offloading	May require new network design Uncertainty of Cost	[19,71-73]	Cost of upgrade Consensus among the stakeholders
o	Hardware Upgrade	Innovation Nanoscale deployment	Cheaper nanofabrication technology	[18, 28, 74,75, 81]	Cost and ease of scalability Design THz friendly devices

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