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Terahertz communication-Path towards beyond 5G: A Survey

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ABSTRACT
Wireless domain is constantly asking for more data rates for incorporating more high speed applications. This growing demand has invoked the need of new spectrum and higher bandwidth which will satisfy future demands. Terahertz spectrum is one such candidate ranging from 0.1-10THz. As this spectrum is not allocated much other than astronomy and pharma sector, it is beneficial for solving the spectrum scarcity problem. THz link also supports Tbps data rates making it more attractive. This paper surveys various challenges and solutions in THz communication development. The challenges include difficult generation methods, transceiver design, antenna designs, channel modelling development etc. it also addresses few solutions found in the literature. Few of them are still in the experimentation phase. Thus this area opens many new horizons for research as well.

***KEYWORDS:*Beyond 5G wireless communication,Graphene,Terahertz, Ultra massive MIMO**

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I. INTRODUCTION

Over last few years the wireless data traffic has grown immensely. According to Edholm's law of bandwidth wireless data rates have been doubled every eighteen months over last three decades. This is due to the fact that today's society creates, shares and consumes lot of information increasing multimedia traffic, voice traffic etc. 4K UHD videos, IoT application support, industrial data packets are also contributing to mobile traffic. Along with this the user density is also increasing day by day. Consumers are in need of greater data rate and lower latencies. To address these issues, 5G phase I is implemented in the year 2020 as expected. Fifth generation technologies makes use of massive MIMO, full duplexing, mmWave etc. still the problem of efficiency andflexibility in handling huge amount of quality of service (QoS) and experience (QoE) oriented data service persists [3]. 5G phase II and phase III are expected soon. On a broad level 5G technology mainly oriented on the basis on eMBB (enhanced mobile broadband), URLLC (Ultra Reliable and Low-Latency Communications) and mMTC (massive Machine Type Communications). The use cases expected from 5G are shown in the fig.1. [15]

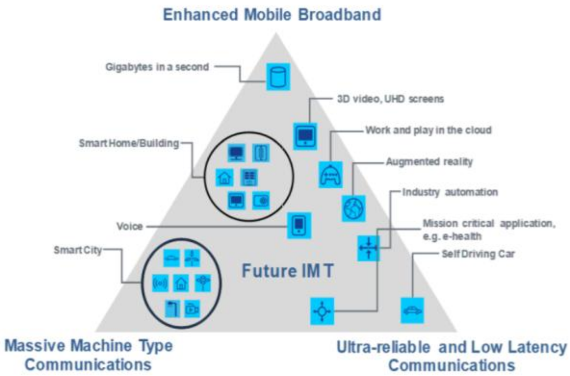

Fig. 1: 5G Usage Scenarios (Source: Recommendation of ITU-R M.2083-0 [15])

As we all know, the year 2020 is of Covid-19 pandemic all over the world. Even though lockdown has paused daily routines of many, it has burdened on telecommunication particularly wireless communication sector drastically. Thus there is a need of beyond 5G as this need of larger data rates, lower latency responses, spectrum scarcity, user density etc. issues are growing. As the trend continues, there is need of unused spectra to be considered now for B5G. B5G is expected to achieve greater system capacity of the order of greater than 100 times of 5G, Tbps data rates, greater user density, IoT support, Nano things paradigms etc. This raises the requirement of innovative technologies. There are three major ways to increase the throughput gain. They are

- Extreme densification of communication infrastructure
- Large quantities of newly available spectrum
- Massive antenna systems as per Kazi Mohammed SaidulHuq et.al.[4].

one of the key solution to address these requirements is Terahertz spectrum communication.THz band resides from 0.1THz -10 THz which is below microwave and just above infrared communication. There are few advantages of THz spectrum due to which it appears promising for wireless future technology. They are

(i) THz offers a much larger bandwidth ranging from tens of GHz to several THz depending on transmission distance.[1]
(ii) THz signals allow higher link directionality due to reduced antenna aperture and offer lower eavesdropping chances when compared to their millimetre counterparts. [13][4]
(iii) These waves allow non line of sight (NLOS) propagation.[13]
(iv) It gives better results even under inconvenient atmospheric conditions like fog, dust or turbulence.[13]
(v) This band is not affected by ambient noise arising from optical sources and it is not even associated with any health restrictions. [13]
(vi) Tbps link can be realized with less spectral efficiency (SE) as compared to mmWave frequencies.[4]
(vii) THz is lower prone to free space diffraction.[4]
(viii) As the distance between transmitter and receiver is less, power consumption is also reduced. It further reduces CO_2 emission. [4]

This paper takes a survey regarding the challenges and possible solutions for THz communication in wireless domain. It addresses various ongoing an developed researches of THz communications and shows its worthiness for beyond 5G era. It is divided into five sections. Section I gives introduction of the topic and explains the need of new technology for B5G. Section II focuses on the comparison between THz with other promising frequency bands for wireless communication. Section III addresses challenges associated in achieving THz as a practical solution for wireless communication. Section IV provides possible solutions from the available literature. Section V concludes the paper and section VI provides the bibliography.

II. COMPARISON OF THZ WITH ITS RIVAL FREQUENCY BANDS

A] THz vs mmWave: Milli-meter wave ranges from 30-300GHz and THz ranges from 300GHz-3THz as per standardelectromagnetic spectrum. THz are sometimes known as submillimetre waves.Some of the advantages and disadvantages are enlisted below. Mmwave is the major competitor for THz.

- Mmwave supports multiple Gbps data rate however THz communication supports tbps data rate over few meter distance.
- Mmwave is accepted frequency for 5G wireless spectrum by FCC (Federal communications commission) and THz is recently fixed for IEEE 802.15.3d-2017 standard for 100Gbps wireless point to point system as explained by HadeelElayan*et.al.*[7]
- Even though the range of mmwave is high but significantly serving frequency is limited to 7-9GHz reducing channel throughputthereby. Thus it makes this technology insufficient for increasing population. On the contrary THz communication provides higher link directionality and less free space diffraction. Thus inspite of using smaller antennas with good directivity reduces power and signal interference between the transmitting and receiving antennas.
- There are lesser chances of eavesdropping in THz communication compared to mmwave.
- Both mmwave and THz communication cannot be used for long distance communication due to higher attenuation. MmWave technology is quiet costly due to miniature hardware requirements which also results in lower sensitivity in a receiving system. THz technology is under development as of now.

B] THz vs infrared : Infrared links simply used intensity modulation and the radiation is detected by the photodiode. This results in poor receiver sensitivity. Similar to other optical sources, it also suffers from significant ambient light noise. outdoor infrared links are suffered by atmospheric turbulence. Compared to infrared, THz suffers less from atmospheric conditions like fog or dust. Atmospheric turbulence and ambient optical noise is supposed to have no effect on THz links.

C] Visible light vs THz: Since years VLC has attracted academicians and industrialists due to its enormous advantages. It is proved to be one of the best high speed solution for wired links. However for wireless domain, there are still many challenges persist. For higher data rates LOS links had to be set up. This also need appropriate alignment of transmitter and receiver's FOV (field of view) [8]. But as the receiver is moving, it is difficult to adjust FOV continuously which ultimately hampers the data rate. In natural surroundings, there are many occasions where this LOS gets blocked thereby degrading the link quality. However THz links supports NLoS propagation links.

D] Ultra-violet vs THz:The major drawback in the ultra violet links is the absorption due to ozone layer. When operating under NLoS conditions for long ranges, the detrimental effects of fully coupled scattering as well as turbulence deteriorate the communication link. The effect of fading further impacts the received signal resulting in a distorted wave-front and fluctuating intensity. Therefore, data rates are limited to few Gbps and distances are restricted to short ranges[7]. Also ultra violet is hazardous for health. Unlike it THz has no proven health restriction as of now.

Table 2.1[13] summarizes the comparison between mmWave, THz, visible light spectrum, infrared and ultraviolet spectrum.

Table 2.1: Comparison between wireless communication technologies

Sr. No.	Parameter	mmWave	THz band	Infrared	VLC (Visible light Communication)	Ultra-violet
1	Frequency range	30GHz - 300GHz	0.1THz-10THz	10THz-430THz	430THz-790THz	790THz-30PHz
2	Communication range	Short	Short/medium	Short/long	Short	Short
3	Power consumption	Medium	Medium	Relatively low	Relatively low	Expected to be low
4	Topology	Point to multi point	Point to multi point	Point to point	Point to point	Point to multi point
5	Noise Source	Thermal noise	Thermal noise	Solar/ambient light	Solar/ambient light	Solar/ambient light
6	Security	Medium	High	High	High	To be researched
7	Attenuation due to atmospheric effects like fog, dust etc.	Less	Less	Quiet high	--	Quiet high
8	Suitable Applications	5G wireless standard	Medical imaging, astronomy and more research undergoing	Image scanners, home security systems, play stations	Optical fiber communication	For civil and military applications (research undergoing)

III. THz LINK: CHALLENGES AND SOLUTIONS IN WIRELESS DOMAIN

There are various challenges in THz link set up for practical application. They need to be addressed and analysed appropriately. In this section, various challenges recognised till date and the suggested solutions are discussed in brief. Very limited literature is available for the solutions as this is really an open domain of research.Design of the wideband transceiver is the major challenge in THz communication. Various challenging parameters affecting transceiver design are as given below.

a. Challenge 1- Generation of THz waves:
THz frequency band is too high for conventional oscillators and too low for optical photon emitters[12].

i. Solutions suggested
The signal generation at the THz link can be carried out by two methods namely top down and bottom up methods. The bottom up method is performed by multiplexer and the top down method makes use of photonics system as per [10]. As per [11] there are various methods of THz wave generation. They are enlisted in the Table 3.1. [11]

Table 3.1: THz wave generation methods

Sr.No.	Technology	Power	Tunability	Coherence/stability	Availability	Misc.
1	Blackbody radiation	Poor	Good	Poor	Good	F > 5THz
2	Free electron Laser	Excellent	Excellent	Good	Bad	Very wideband
3	Photomixer	Fair	Good	Very good	Fair	F <3.8THz tunable, CW
4	Laser pulse excited THz generation	Fair	Fair	Fair	Poor	Good at higher frequency f
5	Monolithic nonlinear transmission lines	Fair	Fair	Good	Good	F <1THz

Apart from these techniques, as per [1] photodiodes and QCL (quantum cascade Lasers) can also be used for generation of THz band frequencies. They can be used in local oscillators in the heterodyne transceiver architectures. But their use is challenged by the factors like requirement of external Laser for pumping, temperature dependence and its size. Also optical rectification and linear opto-electric effect can also be used but they have issues with size and power consumption. Thus this area has to be investigated for flawless THz signal generation methods.

b. Challenge 2- Antenna design

There are various challenges in the antenna designing for THz links like high gain (>20dBi) , wide bandwidth, >90^0 half power beam-width, small size etc. broadband antennas are needed for THz link. The major factor under consideration will be high path loss in case of antenna design.

- *Beam Steering:* Beam steering is also important parameter to be considered at THz antenna designs. Beam steering is about changing the direction of the main lobe of the radiation pattern of the antenna. Because beam steering helps to meet strong LOS/NLOS link budget needs in case of THz communication.
- *High Path loss :*Path loss is the difference between transmitted and received power. It is measured in decibels. In THz link case path loss is highly affected by the factors like humidity, the distance between transmitter and receiver and medium used. Hence for outdoor communication, continuous monitoring of humidity levels is important so that system adapts itself accordingly. Detailed analysis is presented by *Rohit Singh et. al.*[6]. As per experimentation carried out by *Josep*

Miquel Jornet et. al.[9] the total path loss depends on operating frequency, the transmission distance and the composition of the medium at molecular level under consideration. Actually the absorbent molecules in the medium used, drastically changes the channel behaviour. Hence it needs to be studied in detail. Thus molecular absorption defines various operating windows whose position and width depends on the transmission distance. For distances much below 1 m, molecular absorption loss is almost negligible and, thus, the THz Band behaves almost as a 10 THz wide transmission window. However, for transmission distances over 1 m, many resonances become significant and the transmission windows become narrower[1].

- *Low transmit power:*High transmission power is needed to mitigate high path loss. But it is technically difficult to achieve with antennae above 300 GHz. Increasing transmission power also faces issues of safety[6].
- *High antenna gain:* According to the well known *Friss*formula, the received power is directly proportional to the transmit power and inversely proportional to the path loss. Hence as the path loss increases, the received power decreases thereby decreasing gain. As per the antenna literature gain is inversely proportional to beam-width. Hence if the antenna with narrow beam width are used, then path loss issue can be solved up to some extent. Hence pencil beam forming techniques are suggested in the literature at this band of frequencies.
- *Frequent link failures*: THz waves have very less penetration power and it cannot pass through walls etc. This limits the communication range. It majorly needs LOS propagation. Blockages in between Tx and Rx can cause link failures. NLOS communication can be used in this case. But high path loss factor reduces the throughput in case of NLOS communication.

i. Solutions suggested

1. *Phased array antenna [11]:*In this system model, the baseband and RF signal are similar for all the antennas employed at the transmitter side. Its amplitude and phase can be changed. At the receiver side all the RF signals from all the patch antennas are combined. As For THz link s feed loss could be higher, each patch antenna can have its own embedded power amplifier. It faces the issue of size and long feed networks. Also implementation of complex multipliers is challenging task for THz band of frequencies.
2. *Graphene based antennas[10]:*Graphene based antennas can be operated with much low powers as compared to metal antennas. Graphene supports SPP (surface plasmon polariton) wave propagation. Plasmonic graphene antennas can be designed in nanoscale. Response of graphene based nano antennas can be improved by material doping. A reconfigurable graphene based Yagi Uda MIMO antenna is made with graphene patch array. Even though it satisfies the requirements of the THz link, it need to be further studied for more aspects.
3. *Horn antenna or paraboloid antenna [10]:*They can provide the radiation bandwidth of 10% of their center frequency approximately about 30GHz Even though it is good candidate with gain of almost 18dBi, its size limits its use in THZ communication.
4. *Planar antennas [10]:*They are easy to fabricate but deprived of high gain and directivity.

Apart from these antennas unique Massive MIMO schemes of large antenna arrays can also be employed for THz links to achieve increased gain. Dynamic Massive MIMO is open area of research in this domain.

Apart from these, large antenna arrays to satisfy Massive MIMO technology is also one of the solution provided and is under research asof now.

c. Challenge III-Transceiver material

The main requirement of the transceiver is high power, high sensitivity and low noise figure to deal with high path loss issue. Currently available transceiver designs are not suitable for THz communication. Another major challenging factor in this is achieving sufficient output power which is the requirement for mobile communication domain.

3.3.1. Solution suggested:

1. Silicon germanium (SiGe) BiCMOS and CMOS technology [1] [10]:

It provides cost effective solution with high gain, low noise, good linearity, and good power handling capability. SiGe also provides on-die silicon CMOS multi-level metallization with low-loss transmission lines. But it shows limited improvement up to 1THz. It has limited power gain and insufficient breakdown voltage. Actual demonstration of SiGe for low THz band of frequencies has been already carried out but practical implementation of this technology for THz communication is still open area of research.

2. Gallium Nitride (GaN) [1][10]:

It is good candidate for high power gain. It provide better results as compared to SiGe based and CMOS technology. It has the advantage of high breakdown voltage in limited applications.

3. *Indium Phosphide (InP)[1][10]:*

It can be used for the cut off frequency f >600GHz and maximum oscillation frequency of about 1.2 THz. It has high breakdown voltage and low noise figure.

4. *Graphene [10]:*
A it is carbon material, it has high electrical conductivity and it supports SPP waves. Even though it is very competitive candidate amongst all the available material currently, still a lot of research is needed. Graphene is still very immature technology.

5. *QCL (Quantum cascade Lasers) [1][10]:*
QCL has very high operating frequencies with high power output. But it is affected by the temperature changes. Also size can be concern in this case.

Apart from these, hybrid architectures like SiGe and GaN based devices are also under consideration as per the literature. These hybrid devices can also be enhanced with Graphene advantages.

d. Challenge IV- Channel and noise modelling

Currently available low frequency channel models are not suitable for THz links as they do not consider high molecular absorption and high reflection loss in case of LOS communication. Also NLOS communication should also be considered.

- *LOS propagation [1][11]:* in LOS propagation the main factor affecting the link parameters is the path loss. In this case, the path loss is the combination of the molecular absorption loss and the attenuation due to spreading loss (dispersion as the wave travels along longer distance). Thus THz channel is highly frequency selective. As per the data available from the experimentation by various researchers, there are many transmission windows available in which molecular absorption is minimum. But total path loss is still an issue which leads to high gain high directive antenna. Overall nine transmission windows are suggested in [11]. They are ω_1=0.1-0.55THz, ω_2=0.56-0.75THz, ω_3=0.76-0.98THz, ω_4=0.99-1.09THz, ω_5=1.21-1.41THz, ω_6=1.42-1.59THz, ω_7=1.92-2.04THz, ω_8=2.05-2.15THz, ω_9=2.47-2.62THz. These frequency ranges can be used for wireless communication.
- NLOS propagation: NLOS transmissions can be categorized into: specular reflected propagation, diffusely scattered propagation and diffracted propagation. For NLOS communication ,coefficient of reflection, scattering and diffraction need to be determined. Material, geometry of the surface, frequency and angle of incidence etc. affects these parameters.

i. Solutions suggested:

There are two main methods for propagation analysis namely deterministic approach based Ray tracing or Ray launching and statistical model.

1. *Ray tracing model [1][10]:*
For studying multipath propagationindividual rays are studied at the receiver. For LOS only incident and reflected rays need to be studied so it becomes easier. On the contrary for NLOS communication, scattering effects also need to studied.This channel model also needs prior knowledge of environmental geometry. The complexity increases exponentially with the size of the environment. It is already used for few kiosk applications.

2. *Statistical model [1][10]:*
The stochastic models get the average of the environmental effects. Different frequency selective parameters that affects the received multipath signals which may include LOS and NLOS parameters, propagation delays and path gain etc. Hence characterization of unique channel for THz becomes an open area of research. It still remains as unresolved challenge in THz link.

e. Challenge V: challenges in signal processing

The practical implementation of the THz spectrum complete design and development of the physical layer parameters.

1. *Modulation schemes:* Currently available modulation schemes cannot be used for THz communication as transmission windows change according to the transmission distance. Modulation schemes should be distance aware for macro scale environment and should be compact and less power consuming for nano scale applications. Pulse based schemes, TS-OOK (time spread ON-OFF keying)[16], Mary-QAM, FSK etc. many modulation schemes for various different applications are found in the available literature.
2. *Channel coding schemes:*For this different error sources need to be characterised first. And also ultra low complex channel codes needs to be designed. It should also take the decoding power consumption parameter into consideration. Many channel codes are present but nothing is reliable or proven to be suitable for THz links. Some researchers have suggested LDPC, Turbo and Polar codes.
3. *MIMO architectures:* MIMO systems will enable THz links to provide high data rates but in turn it will increase the complexity. But ultra massive MIMO can become the proper candidate for THz links because it can combat the high path loss and power limitation problems[14]. Dynamic massive MIMO is suggested in the literature. 1024×1024 ultra massive MIMO suggested by *L. M. Zakrajsek et. al*. provides 8Tbps data rate but are not suitable for long distance communication. Some authors have suggested use of different transmission windows at a time. Similarly many other MIMO schemes are present and are currently under research.

3.6. Miscellaneous

Apart from broad level challenges discussed above there are many other factors also which needs to be considered while designing the THz link for wireless communication. They are MAC protocols, synchronization issues, handover mechanisms, beamforming and beam steering management etc. Though many issues are already under consideration, still few of them are unaddressed till date.

IV. CONCLUSION

The THz spectrum (0.1-10THz) supports wide bandwidth and Tbps data rates. It is envisioned as an appropriate candidate for beyond 5G wireless domain as it satisfies the requirements. This band will definitely address the spectrum scarcity as it has not been allocated for many application till now. It provides solution for many applications in wireless domain.

However, THz signal generation, hardware development, antenna design etc. are the major challenges in this domain. High path loss, transmission distance etc. issues are more challenging. Even though Graphene supports many requirements, it is still immature technology. Many aspects of Graphene are still untouched. This band of frequencies also ask for novel modulation, channel coding schemes to be developed to satisfy the needs. There is also a need for miniaturization making the design and development even more demanding.

This paper has surveyed various challenges and solutions in use of THz for beyond 5G communication.I hope this paper stimulates the research for the development in this area focusing on the surveyed challenges.

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