Defence Science Journal, Vol. 69, No. 5, September 2019, pp. 510-516, DOI : 10.14429/dsj.69.14471

THz Communication Technology in India: Present and Future

M.H. Rahaman[#], A. Bandyopadhyay[#,*], S. Christopher[$], K.P. Ray[@], and S. Pal[&]

[#]*Joint Advanced Technology Centre, IIT Delhi, New Delhi -110 016, India*
[$]*Department of Electrical Engineering, IIT Madras, Chennai - 600 036, India*
[@]*DRDO-Defence Institute of Advanced Technology, Pune - 411 025, India*
[&]*D S Kothari Chair, DRDO, Office of DGECS, Bangalore, India*
[*]*E-mail: loveofconcept@gmail.com*

ABSTRACT

As the communication industry is currently undergoing a major overhaul to accommodate greater bandwidth and higher data-rate to meet the rapidly growing data demand; terahertz range of frequencies from 100 GHz to 3 THz are being investigated as a possible replacement of the conventional mm-wave technology. In this paper, the technological readiness of Indian research community in this specific direction have been examined. The research development strategies that are required to gain momentum towards achieving a viable technology standard in THz communication in India are discussed. Technology recommendations towards product development required for initiation and advancement in THz communication are presented. We have also introduced a design of a short-range THz communication configuration in conclusion, based on recent reports of successful realisation of THz communication which could be utilised for immediate realisation using commercially available resources.

Keywords: THz communication technology; THz range; Implementation issues; Technology enablers; Development strategy

1. INTRODUCTION

Worldwide THz communication research has gained momentum driven by the need to support high capacity wireless data transmission using the THz range. Several groups have used several specific THz transmission windows, mostly below 500 GHz, for short range (well below 100 m mark), indoor wireless systems and have been successful in attaining a data rate of 100 Gbps or more[1,2,3,4]. However, the most important challenges remain; which are, the development of compact and efficient THz sources providing continuous wave output power levels up to 100 mW and the development of compact electronically steerable antenna arrays to minimise wireless link loss[5]. In the recent past, many researchers have reported about transceiver technology, working close to the 300 GHz mark[6,7,8], pushing the operating frequency towards THz communications.

Contrary to this intense global research thrust[9,10,11,12,13], advancement of THz communication technology in India is still very limited. The main reason for the same is that, the present status of enabling technologies for THz communication is very poor in India. There are many groups working in related areas of wireless communication, RF communication and optical communication across India in various academic and national level research facilities. However, these research initiatives are not in synergy with the technology requirements of a viable THz communication network. Most of the work done in this frequency range are parametric modelling and simulation based. The modelling and simulation done are also not oriented towards an implementable communication network: these are fragmented model and simulation of various active and passive components meant for THz communication. However, most of these components under consideration are either technologically challenging or a mere software reproduction of the state-of-the-art THz components realised elsewhere in the world.

In this review, some of these pertinent issues hindering the growth of THz communication technology in detail in India are discussed. A chart of application viability of THz range in communication in terms of link lengths is organised. Critically reviewed the technology readiness of India in implementing THz communication technological which is followed by a Vision 2040 Technology Roadmap, both in terms of a chart comprising a list of key technology enablers and research directions, as well as, a info graphic depicting the projected phases of technology development in India. Apart from this, the issue of 'data safety' and the upcoming quantum key distribution technology, which is the necessary component in reorienting traditional 'classical' digital network into highly secure 'quantum' network are brought out. Finally, in conclusion, a system configuration to attain short-range THz communication using frequencies over 100 GHz with 0.1 Tbps data-rate or more is proposed.

Received : 24 April 2019, Revised : 16 July 2019
Accepted : 31 July 2019, Online published : 17 September 2019

2. THZ RANGE

Founded in 1865 at Paris, International Telegraph Union (ITU) is responsible for issues concerning Information and Communication Technology[14]. Figure 1 shows the exact positions of various range of frequencies in the ITU communication band designation chart with respect to the EM spectrum. The bands, represented as extremely high frequency (EHF) and tremendously high frequency (THF) in Fig. 1, offers a total available bandwidth over hundreds of GHz. These bands (0.1 – 3 THz) in EM spectrum are in the Terahertz (THz) range which spans across the range between microwave and far-IR 'bridging the gap' between the 'electronics' and 'photonics', respectively. Consequently, THz range enjoys some attributes of both electronics and photonics area and offers some distinctive set of advantages and poses some fundamental challenges.

For most of the past century terahertz (THz) frequencies of electromagnetic radiation (approx. 100 GHz to 10 THz) were mostly referred to as sub-millimeter or far-infrared waves and were principally used by the astronomers and very select groups of spectroscopists. However, with the advent of laser-based THz time domain spectroscopy in last two decade of the past century THz technology has rapidly curved its niche in myriad areas of application, including security screening, medical diagnostics, material characterisation, communication and others[15]. In fact, THz technology has been promoted as one of the disruptive technologies changing the world. Specifically, with the availability of THz commercial systems as research spin-offs, non-invasive THz imaging has become an effective tool of application in many industrial and research sectors. The widespread utility of THz technique in many applications relies on its distinctive attributes of 'chemical signature', 'material transparency' and 'biological safety'[16].

However, widespread implementation of THz technology in strategic manner in various areas are very daunting; because of the following factors established by fundamental physics:

(a) THz waves are highly reflected by all metal surfaces, thus it cannot 'see past' metal
(b) THz waves are highly absorbed by water, so THz waves cannot penetrate deep into a material containing a lot of water
(c) THz waves being longer wavelengths than visible and IR waves will have a limiting spatial resolution of submillimeter in the far-field.

From the application perspective in communication technology, the second issue is, the high atmospheric attenuation of THz range and the frequency dependency of the same with highly non-linear nature, poses the greatest challenge against its widespread use in communication sector. A long-range THz communication wideband frequency channel in free space, is therefore, simply cannot be established. Figure 1 gives the atmospheric attenuation in THz communication range showing distinctive 'pass band' with very low or no attenuation.

These 'low-loss' transmission windows in THz range, as shown in Fig. 2, inevitably lead us to formulate the strategic viability plan of THz application in communication. It can be seen, that, contrary to traditional approach of long-range front-end communication channel THz range, and especially the higher frequency range with the capability of supporting high data rate, is suitable for short-range to very-short-range communication[17]. In these short-links, the 'atmospheric attenuation' issue of THz range becomes negligible and the advantages of 'material transparency' and 'high metal reflectivity' would enable us to configure communication channels based on the use of selected THz frequency windows coupled with strategic placements of active and passive material components (like, waveguides, filters and optical amplifiers etc.) to successfully implement THz communication system.

Table 1 gives a summary of all the different THz communication applications, in terms of their viability of application, expected operational conditions and locations, expected typical bit-rate achievable and most importantly, the expected typical link length for such specific application. It should be noted, that, as per this chart, the application of

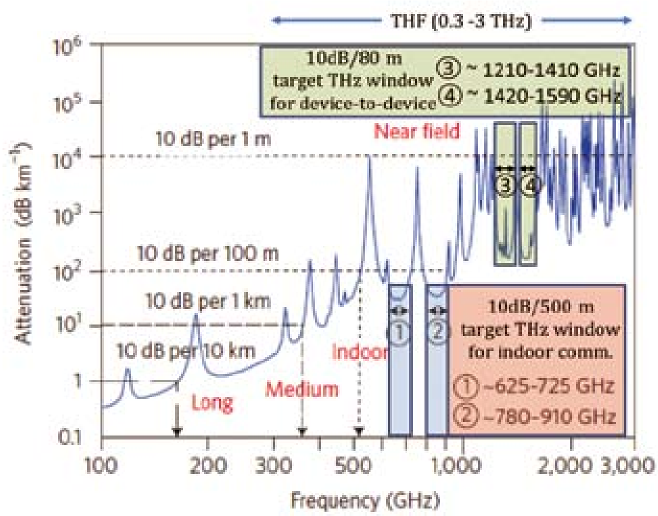

Figure 2. Atmospheric attenuation in terms of dB/km for THz frequencies.

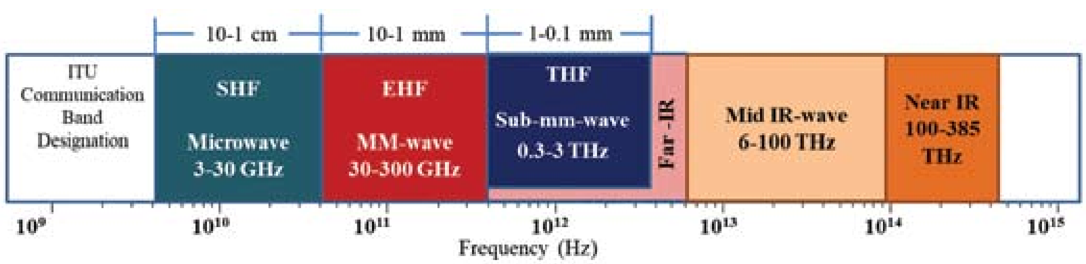

Figure 1. ITU Communication band designation chart showing the Terahertz high frequency band from 300 GHz to 3 THz (or 1 mm to 0.1 mm) as a subset of the Far-IR range (0.3 THz to 6 THz).

Table 1. Example of different THz communication applications

	Application	Typical link length	Location	Operational condition	Beam positioning	Typical bit-rate
Highly probable	Intra-chip	< 1mm	Monolithic	Line of sight nm sized THz transceivers	Fixed	1- 10 Terabyte per second
	Inter-chip	< 1cm	On single board layer	Same as above	Fixed	
	Inter-board	< 10 cm	Inside single device	LOS, THz transceivers with multiple reflections	Almost fixed	
Possible	Device to device	< 0.1 m	Indoor around desk	Same as above	Manual positioning	0.1 - 1 Tbps
	Kiosk 'data' shower	0.1 – 1m	Indoor can be across a wall	Same as above	Automatic positioning required	
	Inter ballistics	1 – 10 m	Controlled indoor	Same as above	Same as above	
	Short-range WLAN/WPAN	> 10 m	Indoor across rooms	LOS/Non-LOS, dynamic	Same as above	
Highly improbable	THz cellular connection	< 100 m	Mobile network indoor or outdoor	Same as above	Same as above	< 100 Gbps
	Fixed wireless access	100 m – few km	Fixed link outdoor	LOS, with very high gain T_x/R_x	Fixed, highly directional	

THz communication in traditional consumer sector is found to be limited. On the other hand, the scope of high-end research product (in computer technology etc.) and strategic defence (in military etc.) communication seems to be very much viable.

3. PRESENT STATUS OF THz COMMUNICATION IN ACADEMIC AND RESEARCH FACILITIES ACROSS INDIA

In India, no group has yet reported any working THz communication link; the main reason for the same is that, the present status of enabling technologies for THz communication is in its nascent stage in India. There are some groups of researchers working across the nation who have demonstrated THz communication enabling devices in practice. Though the performance and functionality of these components are far less than the target objectives. Table 2 enlists some of the institutes in India, along with their locations and current research activities geared towards THz communication (the list is neither exhaustive nor summarised).

4. THz COMMUNICATION IN INDIA– VISION 2040

Towards the initiation of a successful technology implementation, certain strategic research recommendations as follows:

(i) First and foremost, the development of high-power THz sources within the THz low-attenuation windows (as prescribed in previous section), as well as compatible high sensitivity detectors, and modulation hardware are to be prioritised in the very first phase.

(ii) Secondly, demonstration of device performance to highlight the potentially major benefits of THz communications (wide bandwidth) should be emphasised over the next several years. Additional hardware systems that take advantage of the 100 GHz of available bandwidth, such as modulator/demodulators, amplifiers and guided channels also need to be realised in tandem. Specifically, low-noise and wide-bandwidth THz amplifiers for both transmitters and receivers ends are a key research priority in second phase.

(iii) Aside from the actual hardware functionalities, the attenuation and scintillation properties of the atmosphere, including the effect of fog, rain, and smoke, need to be experimentally quantified in a systematic manner as and when THz components/systems are developed for communication purposes working in a certain frequency range[18].

(iv) Finally, photonic and electronic integration is a key factor that needs to be pursued for increased efficiency, compact size, lower power consumption and heat-dissipation and

Table 2. Indian research geared towards realisation of THz communication

	Institutes	Research Area
Source and detectors	IIT Delhi	mm-wave electronic transmitters, spin-based THz sources, time domain and CW THz set-up, THz waveguides
	IISER Trivandrum	Semiconductor hetero-structure alloys as THz sources
	TIFR, Mumbai	SI-GaAs THz sources, THz-ultrafast studies
Channels	CEERI – Pilani	THz waveguides in Silicon for short range communication channel, multiplexer/demultiplexer
	CEERI – Chennai	mm-wave remote and atmospheric sensing, atmospheric transmission
Signal processing and devices	IIT Guwahati	THz metamaterial structures for active/passive THz devices
	IIT Bombay	mm-wave signal processing

high stability of THz communication system which is the ultimate milestone of this technology pyramid[19].

Table 3 shows a technology roadmap to achieve a viable and efficient THz communication in short-range and very short-range span in terms target technology requirements and research directions to be implemented to attain the same.

Figure 3 shows a projected multiphase technology implementation timeline starting from 2019 to the year 2040 following the technology roadmap as described in Table 3.

5. LONG-TERM TECHNOLOGY IMPLEMENTATION CONSIDERATIONS

Asymmetric encryption, now widely used, both for authentication and for data transmission, relies on the difficulty of solving prime-number factorisation problem. The recent advancement in developing effective quantum computers would turn these tasks straight forward enough; thus, currently deployed asymmetric cryptography would become obsolete[20]. This would potentially lead to a fatal breakdown of current infrastructure in terms of secure data transfer in communication system. An optical quantum key distribution (QKD) which relies on fundamental physical principles of ‘prepared’

Figure 3. Time line of technology implementation to realise viable THz communication in India.

Table 3. Technology roadmap to realise THz communication in India

Component	Aspect	Target	Technology Options	Research Direction
Transmitter	Data rate	(0.1 – 1) T bit/s	Multi-band (multi-carrier) system	Photonic-electronic integration
			Ultra-wideband (more than 100 GHz) optical modulators	Comb generation of a single laser line with phase stabilisation, monolithic integration of DFB lasers
	Fast switching with high output power	10 mW or more	III–V semiconductor photonics and Si photonics	InP or GaAs uni-travelling carrier photodiodes
			All-electronic source	SiGe heterojunction bipolar transistors
	Efficiency and cost		Wideband passive devices (filter, coupler, diplexer, absorber)	Basic material research for metamaterials, graphene, functional thin films
			Mitigate dispersion-induced propagation loss	Ultra-wide bandwidth single sideband modulator
Channel	Free-space	Short range (Loss < 0.1 dB/m)	Use of amplifiers and integration	Low-noise and wide-bandwidth THz amplifiers for both transmitters and receivers integration
			Atmospheric propagation and interference testing	Drone fitted with THz set-up for continuous monitoring of indoor/outdoor conditions
	Guided	Device to device (Loss < 0.05 dB/m)	Low-loss waveguide and interconnect	Hollow-core waveguide, photonic crystal omnidirectional fiber, plasmonic waveguides
Receiver	Low NEP	Error-free operation BER<10^{-8}	Schottky barrier diodes, interband tunneling diodes	Resistive-mixer-type FET detectors for mm to THz detection
		Less than 10 pW/√Hz at high frequency (> 1 THz) or broadband operation	Wideband, low-loss and reconfigurable PC antennas	Cleanroom fabrication of photolithographically grown photonic structures, parametric studies of thin films and surface quality optimisation
			Quantum dots and quantum wells	
	High Responsivity	> 10^4 V/W	Superconducting transition edge sensor, Hot-electron bolometer	Room temperature operation, using various structural set-up, graphene-based bolometers
			Edge metal-semiconductor metal junction	
	Response time	ns to ps	Plasmon based detectors	Si-CMOS, Graphene FET

quantum states which cannot be 'copied' or 'eavesdropped' without causing alteration is a viable long-term solution and which is very much compatible with THz communication methodology and its potential data-capacity. In fact, it was 29 September 2017 when the first intercontinental video conference using quantum encryption took place between the presidents of the Austrian and Chinese academies of science. The cryptographic key pair used by the stations in Vienna and Beijing had been generated using QKD payload aboard the Chinese satellite Micius—part of the QUESS (Quantum Experiments at Space Scale) mission, which was brought into orbit in August 2016. In India, especially in defence sector, where the security of data is of paramount importance, specific research on development and application of quantum encrypted communication system should be initiated promptly. This would ensure that the long-term communication technology implementation is viable and compatible with the global trend and upcoming technology shift in larger scope.

6. SHORT-TERM TECHNICAL IMPLEMENTATION CONSIDERATIONS TOWARDS VISION 2040

As mentioned previously, immediate physical realisation of THz communication system, even with limited capability, should be considered as one of highest priority, especially for its potential use of THz range as high-data rate carrier. Therefore, as the first marker in the long list of milestones, the most achievable task would be to set up a THz communication link of 10 m or more with a data capacity of 100 Gigabyte/s or more in 0.2 THz to 0.3 THz range. This range of THz frequencies offer an average of 1 dB/km atmospheric attenuation in 40 per cent relative humidity at 20°C temperature[21].

Table 4 provides the system specifications of recently reported THz communication with the above scenarios.

Most of these recent work shares some commonality in using UTC-PDs (Uni-travelling carrier photodiodes) as the source; because of their large bandwidth and high power. Commercially available mixer diodes are favoured as the detectors in these systems and the modulation scheme used was quadrature phase shift keying (QPSK). There are few notable features common to the hardware used in those experimental realisation, which are:

(i) All of the systems rely on the combination of photonic and electronic techniques

(ii) UTC-PD is one type of source (which is commercially available) which is heavily favoured in these reported works

(iii) Mixer diodes are also favoured as the detector (which are commercially available) in these reported works and

(iv) Quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) are also favoured as the modulation scheme in all these reported works.

Figure 4 is a proposed system configuration based on the above considerations for establishing a short-range THz communication link over 100 GHz frequency with 0.1 Tbps data-rate.

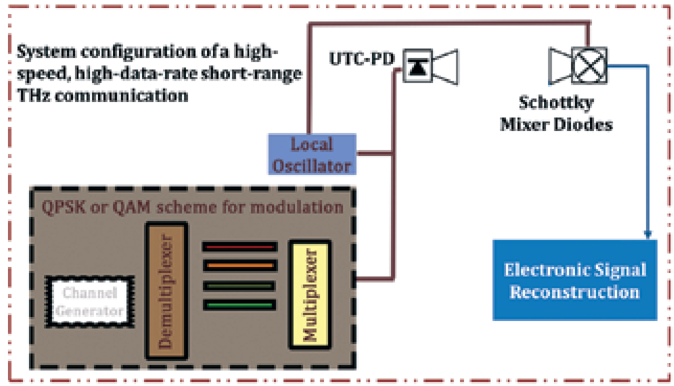

Figure 4. Proposed system configuration for short-range THz communication.

7. CONCLUSIONS

Based on the intellectual expertise available in India, it is indeed possible to demonstrate and implement a viable and efficient THz communication as greater research infrastructure and direction are being commissioned across India. As we have discussed in this review, that, physical realisation of key technology enablers, such as, high frequency and high power photonic and electronic sources; receivers with low noise and high sensitivity and other functional components including high-speed electronic and optical modulators are required to be accomplished for successful implementation of this critical technology target. Therefore, the research thrust must stress more on realisation of functional prototype of device rather than modelling or simulation of device performance. At the same time, since the realisation of this critical components, and the technology implementation as well, encompasses several multidisciplinary and sometimes overlapping research directions, there must be coordinated research initiative across the nation. That central platform would then ensure a synergistic approach to acquire and maintain the intense research momentum in progress and in performance towards a fast turn-around in timeline towards our proposed Vision 2040 of THz Communication in India.

Table 4. Specification of reported THz communication system over 100 GHz with 0.1 Tbps or more.

Data rate (Gbps)	Link (m)	Frequency (GHz)	Multiplexing	Modulation	T_x	R_x	BER	Ref, year
160	0.5	300 – 500	8 channels (25 GHz/ch)	QPSK	UTC-PD	Schottky mixer diode	4×10^{-4} - 7×10^{-3}	[1], 2016
108	0.7	100	2 channels	QPSK	PD	Sub-harmonic mixer	3.8×10^{-3}	[2], 2013
106	0.5	300 – 500	16 channels	16 QAM	UTC-PD	Schottky mixer diode	3.8×10^{-3}	[3], 2018
100	20	237.5	Single channel	16 QAM	UTC-PD	HEMT	4.5×10^{-3}	[4], 2013

Thus, in conclusion, in this paper we have analysed the possible technology elements to strengthen THz technology, especially in India, as futuristic high-speed communication carrier having possible tactical application with an aim to optimise the overall payload configuration of various strategic system components in defence.

REFERENCES

1. Zhao, Y.; Lombardo, D.; Mathews, J. & Agha, I. All-optical switching via four-wave mixing Bragg scattering in a silicon platform. *APL Photonics,* 2017, **2**, 026102. doi: 10.1063/1.4973771
2. Li, X.; Yu, J.; Zhang, J.; Dong, Z.; Li, F & Chi, N. A 400G optical wireless integration delivery system. *Opt. Express*, 2013, **21**, 18812-18819. doi: 10.1364/OE.21.018812
3. Jia, S.; Pang,X.; Ozolins, O.; Yu, X.; Hu, H.;Yu, J.; Guan, P.; Da Ros, F.; Popov, S.; Jacobsen, G.; Galili, M.; Morioka, T, Zibar, D and Oxenløwe, L. 0.4 THz Photonic-Wireless Link With 106 Gb/s Single Channel Bitrate. J. of Lightw. *Technology*, 2018, **36**(2), 610-616. doi: 10.1109/JLT.2017.2776320
4. Koenig, S.; Lopez-Diaz, D.; Antes, J.; Boes, F.; Henneberger, R.; Leuther, A.; Tessmann, A.; Schmogrow, R.; Hillerkuss, D.; Palmer, R.; Zwick, T.; Koos, C.; Freude, W.; Ambacher, O.; Leuthold, J. & Kallfass, I. Wireless sub-THz communication system with high data rate. *Nature Photonics,* 2013, **7**, 977–981. doi: 10.1038/nphoton.2013.275
5. Armstrong, C. The truth about terahertz. IEEE Spectrum, 2012 (September), 36.
6. Boes, F.; Messinger, T.; Antes, J.; Meier, D.; Tessmann, A.; Inam, A. & Kallfass, I. Ultra-broadband MMIC-based wireless link at 240 GHz enabled by 64GS/s DAC. *In* 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), Tucson, AZ, 2014, pp.1-2. doi: 10.1109/IRMMW-THz.2014.6956202
7. Fritsche, D.; Stärke, P.; Carta, C. & Ellinger, F. A low-power SiGe BiCMOS 190-GHz transceiver chipset with demonstrated data rates up to 50 Gbit/s using on-chip antennas. *IEEE Trans. Micro. Theo. Tech.*, 2017, **65**(9), 3312-3323. doi: 10.1109/TMTT.2017.2677908
8. Hamada, H.; Fujimura, T.; Abdo, H.; Okada, K.; Song, H.; Sugiyama, H.; Matsuzaki, H. & Nosaka, H. 300-GHz 100-Gb/s InP-HEMT Wireless Transceiver Using a 300-GHz Fundamental Mixer. IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA, 2018. doi: 10.1109/MWSYM.2018.8439850
9. Nagatsuma, T.; Ducournau, G. & Renaud, C. Advances in terahertz communications accelerated by photonics. *Nature Photonics,* 2016, **10**(6), 371–379. doi: 10.1038/nphoton.2016.65
10. Merkle, T.; Tessmann, A.; Kuri, M.; Wagner, S.; Leuther, A.; Rey, S.; Zink, M; Stulz, H.; Riessle, M.; Kallfass, I. & Kürner, T. Testbed for phased array communications from 275 to 325 GHz. IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), Miami, FL, 2017, 1-4. doi: 10.1109/CSICS.2017.8240474
11. Rodríguez-Vázquez, P.; Grzyb, J.; Heinemann, B. & Pfeiffer, U. A 16-QAM 100-Gb/s 1-M wireless link with an EVM of 17% at 230 GHz in an SiGe technology. *IEEE Microwave Wireless Compon. Lett.,* 2019, **29**(4), 297-299. doi: 10.1109/LMWC.2019.2899487
12. Rodríguez-Vázquez, P.; Grzyb, J.; Neelanjan, S.;Heinemann, B. & Pfeiffer, U.A 219–266 GHz LO-tunable direct-conversion IQ receiver module in a SiGe HBT technology. *Int. J. Micro. Wireless Technol.*, 2018, **10**, 587-595. doi: 10.1017/S1759078718000302
13. Lee, S.; Dong, R.; Yoshida, T.; Amakawa, S.; Hara, S.; Kasamatsu, A.; Sato, J. & Fujishima, M. An 80Gb/s 300GHz-Band Single-Chip CMOS Transceiver. *In* IEEE International Solid- State Circuits Conference - (ISSCC), San Francisco, CA, USA, 2019, pp. 170 – 172. doi: 10.1109/ISSCC.2019.8662314
14. Official website of International Telecommunication Union (ITU) https://www.itu.int/en/Pages/default.aspx (Accessed on 24 May 2019).
15. Mittleman, D. Perspective: Terahertz science and technology. *J. Appl. Phys.,* 2017,**122** (23), 230901. doi: 10.1063/1.5007683
16. Dhillon, S.S., *et al.* The 2017 terahertz science and technology roadmap. *J. Phys. D: Appl. Phys.,* 2017, **50**(4), 043001. doi: 10.1088/1361-6463/50/4/043001
17. Ma, J.; Shrestha, R.; Moeller, L & Mittleman, D. Invited Article: Channel performance for indoor and outdoor terahertz wireless links. *APL Photon.,* 2018, **3**(5), 051601. doi: 10.1063/1.5014037
18. Yu, J & Zhou, W.Optimization of lens layout for THz signal free-space delivery. *Opt. Comm.,* 2018, **410**(3), 443-446. doi: 10.1016/j.optcom.2017.10.060
19. Seeds, A.; Shams, H.; Fice, M & Renaud, C.Terahertz photonics for Wireless Communications. *J. Lightw. Technol.,* 2015, **33**(3), 579 – 587. doi: 10.1109/JLT.2014.2355137
20. Khan, I.; Heim, B.; Neuzner, A. & Marquardt, C. Satellite-based quantum key distribution. OPN, 2018.
21. Slocum, D.; Goyette, T.; Slingerland, E.; Giles, R. & Nixon, W. Terahertz atmospheric attenuation and continuum effects. *In* Proceedings of the SPIE, Terahertz Physics, Devices, and Systems VII: Advanced Applications in Industry and Defense, 871607, 2013. doi: 10.1117/12.2015471

CONTRIBUTORS

Md Hafizur Rahaman received his Master's in Radio Physics and Electronics from Burdwan University and MTech in Electrical Engineering from IIT Delhi. He worked in DRDO for 34 year and super-annuated as Director-General (HR and Technology Management) at DRDO. Presently, he is Director of Joint Advanced Technology Center at IIT Delhi and facilitating directed research in IIT Delhi for DRDO needs through various technology verticals, including advanced electromagnetic devices and THz technology.
Contribution in the current study was to overall conceptualisation of the manuscript and constructing the directions of roadmap of THz communication research with respect to Indian technology landscape.

Ms Aparajita Bandyopadhyay received her Master of Science in Physics from IIT Delhi in 2002. After a brief internship in IPR, Gandhinagar she joined doctorate degree program in Applied Physics in NJIT-Rutgers, New Jersey, USA and completed her thesis on THz propagation and detection methods for spectroscopy and imaging. She worked in Germany and in Washington State University as a post-doctoral researcher on THz imaging and pump-probe THz spectroscopy. Currently, she is working as a project scientist in JATC, IIT Delhi where she is involved in charting the technology roadmap for THz technology in India.
Contribution in the current study was the preparation of the manuscript including technical and graphical contents, literature survey and formulating the conclusions.

Dr Sargunaraj Christopher obtained his Bachelors in Engineering (Hons) from College of Engineering, Gundy, Madras followed by MTech at IIT Kharagpur and PhD at IIT Madras. He served in the Indian Defence Reaserch and Development Organisation and rose to the top and served as Secretary Department of Defence R&D & Chairman DRDO before he became professor at IIT Madras. His current interest is in Photonics and Radar systems.
Contribution in the current study was promoting the ideas of THz applications in defence and strategic research in India.

Dr Kamala Prasan Ray is M Tech in Microwave Electronics from University of Delhi and PhD from Department of Electrical Engineering IIT, Bombay. He has over 33 years research/academic experience in the areas of RF and microwave systems/components and was the Programme Director of SAMEER (MeitY) Mumbai and has executed over 48 projects sponsored by various Govt. agencies and industries. Presently he is the Head of the Dept of EE & CS, DIAT, Pune.
Contribution in the current study was to review the manuscript and providing guidance towards improvement of the same.

Mr Surendra Pal an alumnus of Birla Institute of Technology & Science (BITS), Pilani and Indian Institute of Science (IISc), Bangalore, India superannuated as Distinguished Scientist, Associate Director and Program Director, Satellite Navigation Program at ISRO Satellite Centre, Bangalore, India. He joined Indian Space Research Organisation (ISRO) in 1971 where he pioneered the Microwave, Antenna & RF communication activities at the ISRO Satellite Centre at the inception and is responsible for the development & fabrication of all spacecraft related telecommunication systems for India's all satellites beginning with Aryabhata to the present day. He is a Distinguished Fellow of IETE, Fellow of Indian National Academy of Engineering, National Academy of Sciences, India, and is a Fellow of the IEEE.
Contribution in the current study was helping in finalising the architecture of the proposed system configuration comprising electronic source/detector and other passive electronic devices.