MAC Protocols for Terahertz Communication: A Comprehensive Survey

Saim Ghafoor, Noureddine Boujnah, Mubashir Husain Rehmani and Alan Davy

***Abstract*—Terahertz communication is emerging as a future technology to support Terabits per second link (Tbps) with highlighting features as high throughput and negligible latency. However, the unique features of Terahertz band such as high path loss, scattering and reflection pose new challenges and results in short communication distance. The antenna directionality, in turn, is required to enhance the communication distance and to overcome the high path loss. However, these features in combine negate the use of traditional Medium access protocols. Therefore novel MAC protocol designs are required to fully exploit their potential benefits including efficient channel access, control message exchange, link establishment, mobility management, and line-of-sight blockage mitigation. An in-depth survey of Terahertz MAC protocols is presented in this paper. The paper highlights the key features of the Terahertz band which should be considered while designing an efficient Terahertz MAC protocol, and the decisions which if taken at Terahertz MAC layer can enhance the network performance. Different Terahertz applications at macro and nano scales are highlighted with design requirements for their MAC protocols. The MAC protocol design issues and considerations are highlighted. Further, the existing MAC protocols are also classified based on network topology, channel access mechanisms, and link establishment strategies as Transmitter and Receiver initiated communication. Some open challenges and future research directions on Terahertz MAC protocols are highlighted.**

***Index Terms*—Terahertz band, Terahertz communication network, Terahertz technology, Terahertz physical layer, Terahertz MAC layer, Terahertz Channel model, Terahertz Propagation model, Terahertz Antenna, Terahertz Transceivers.**

I. Introduction

The demand for wireless data traffic has increased significantly since the evolution of Internet and Mobile Technology and is projected to exceed Petabytes by 2021 [1]. The existing wireless technology although reaching the capacity of wired technology, still it is not meeting the demands of future ultra-high bandwidth communication networks. The communication networks using lower frequency bands below 60 GHz cannot go more than 10 Giga bits per second (Gbps) [2]. The spectrum at and below 60 GHz still orders of magnitude below the targeted Terabits per second (Tbps) link. The Free space optical (FSO) which operates at Infrared (IR) frequencies also have several issues which limit the practicality of these systems for personal wireless communications [2], [3]. In this perspective, the Terahertz (THz) band from 0.1 to 10 Terahertz has a potential to provide up to Tbps link speed to satisfy beyond fifth generation (5G) communication requirements such as high throughput and low latency [2], [4]–[6]. The Terahertz bands offer much larger bandwidth (up to 1 Tbps) than the existing milimeter wave (mmWave) systems (up to 10 Gbps)) [7].

Saim Ghafoor, Noureddine Boujnah, and Alan Davy are with Emerging Network Laboratory, Telecommunication Systems & Software Group, Waterford Institute of Technology, Ireland. email: s.ghafoor,bnoureddine,adavy@tssg.org.

Mubashir Husain Rehmani is with Cork Institute of Technology, Ireland. email: mshrehmani@gmail.com.

While, the technology is rapidly advancing with new transceiver architectures, materials, antenna design, channel/propagation model, and physical layer techniques, there still exist several research challenges which needs to be addressed before achieving the Tbps links. Among these different fields of interest, Medium Access Control (MAC) are least explored area of research in Terahertz communication networks. The existing MAC protocols of traditional networks cannot be directly applied, because they do not consider the unique features of Terahertz band like path and molecular loss, multi path, reflection, and scattering. Therefore, novel and efficient MAC protocols are required which should consider the features of Terahertz bands and antenna requirements. Therefore, in this paper a comprehensive survey on Terahertz MAC protocols is presented with classification, design issues and considerations, requirements for different application areas and challenges. The acronyms used commonly throughout this survey are shown in Table I.

A. Terahertz Communication: Related survey articles

Table II highlights and summarise the overall survey papers on Terahertz communication without MAC layer protocols. These survey papers covers different application areas, however covers mostly the device, antenna, channel, and physical layer aspects. These include the nano-communication networks [8]–[10], Internet of nano-things [11], [12], molecular communication network [13], [14], nano-sensor network [15], in-body nano networks [14], [16], [17], broadband communication [18], vehicular networks [19], wireless indoor/outdoor communications which include the office/data-center or small cells deployment [20], [21] and Terahertz Communication Networks [5], [6], [21]–[28]. Whereas, Table III highlights the survey papers which discusses the MAC layer aspects to some extent and the differences with our work.

In [18], [22], the joint impact of Ultra-Dense Network (UDN), Multiple Input Multiple Output (MIMO), mmWave and Terahertz communications is discussed for supporting the demands of mobile broadband services. Particularly, the indoor and outdoor environments are analyzed for noise levels and signal to interference and noise ratio (SINR). The challenges are mentioned for signal power enhancement and interference mitigation. In [19], the challenges, and opportunities are mentioned but only with the perspective of Terahertz vehicular networks. It also describes briefly different aspects including transceiver design, MIMO antenna arrays, channel modeling and estimation, interference management, MAC layer design, and standardization. For Nano Communication Networks, the survey articles are discussed in [8]–[10], [13], [16], with physical layer aspects, propagation models, security, in-body communication, and biomedical applications, materials and antenna design, and channel modeling. The Internet of nano-things (IoNT) for interconnecting devices at the nanoscale is discussed in [12], [17]. Although, a brief discussion on architecture, channel modeling and challenges related to MAC and Network layer are mentioned, but only for a specific scenario of the IoNT . An in-body nano communication is also mentioned in [12] with challenges related to the IoNT. A multimedia approach for the IoNT with few MAC and Network layer challenges is presented in [11]. A network architecture for wireless nano-sensor networks is given in [15]. It discusses briefly the challenges related to channel modeling, information encoding and protocols for nano-sensor networks. The molecular communication network survey is given in [14] for the body area networks. These works although provides a good survey, they represent the architecture, models, and challenges related to the specific application scenario.

The Terahertz communication is still in its design and development stage and therefore looking at the advantages like ultra-high bandwidth and negligible latency, the research directions should be identified in a manner to advance the technology and enhance the system performance. The work so far on general aspects of Terahertz communications from channel model to material/transceivers and communication layer design are mentioned in [2], [5], [20]–[22], [25]–[31]. In [20], the Terahertz recent progress is reviewed but only for the propagation models, antenna and testbed design, and an implementation roadmap is mentioned. In [22], the propagation models are discussed with open challenges. For opportunities beyond 5G paradigm, an architecture is discussed with possible application areas in [5]. A survey related to MIMO is given in [26]. Some standardization related work is mentioned in [25]. Some other survey papers on the usage of Graphene material, weather impact on Terahertz bands and Terahertz antenna are mentioned in [29]–[31]. A guest editorial is also published recently on Terahertz communication [32].

With these related survey articles, there are some articles which discuss the Terahertz MAC protocols but not with required detail, as shown in Table III. In [33], a survey on MAC schemes for mmWave and Terahertz wireless communication is presented. The MAC protocols overall related with Terahertz band communication are not fully covered and mostly MAC strategies related with mmWave are discussed. Only few challenges and design issues are mentioned. Whereas, in this survey paper, detailed work on existing Terahertz MAC protocols with classifications, band features, design issues and considerations, challenges and application requirements and challenges is discussed.

TABLE I: Acronym definitions used throughout this survey.

Acronyms	**Definitions**
5G	Fifth generation
ACK	Acknowledgement
AoA	Angle of arrival
AP	Access point
BER	Bit error rate
BP	Beacon period
CA	Collision avoidance
CAP	Channel access period
CSMA	Carrier sensing multiple access
CTAP	Channel time allocation period
CTR	Critical packet transmission ratio
CTS	Clear to send
DEV	Device
DL	Downlink
DMDS	Distributed Maximum depth scheduling
DSSS	Direct sequence spread spectrum
EMF	Electromagnetic fields
ESaware	Energy and spectrum aware
FHSS	Frequency hopping spread spectrum
FSO	Free space optical
FTDMA	Frequency and time division multiple access
HBT	Heterojunction bipoloar transistor
HD	High definition
IR	Infrared
IR-UWB	Impulse radio ultra wide band
LOS	Line of sight
LTE-A	Long term evolution advanced
MAC	Medium Access Control
MIMO	Multiple input multiple output
mmWave	Millimeter wave
MRAMAC	Multiradio assisted MAC
NI	Node information
NLOS	Non line of sight
OFDM	Orthogonal frequency division multiplexing
PAM	Pulse amplitude modulation
PNC	Piconet coordinator
PPM	Pulse position modulation
QoS	Quality of service
RA	Random access
RD	Rate division
RTDs	Resonant tunnelling diode
RTR	Request to receiver
RTS	Request to send
SDN	Software defined network
SINR	Signal to interference and noise ratio
TABMAC	Terahertz assisted beamforming MAC
Tbps	Terabits per second
TC	Transmission confirmation
TCN	Terahertz communication network
TDMA	Time division multiple access
THz	Terahertz
TLAN	Terahertz local area network
TR	Transmission request
TS-OOK	Time spread On-off Keying
TTS	Test to send
TPAN	Terahertz personal area network
UDN	Ultra dense network
UL	Uplink
UTC-PD	Uni-travelling carrier photo diodes
UV	Ultraviolet
VL	Visible light
WLAN	Wireless local area network
WPAN	Wireless personal area network

TABLE II: General survey papers on Terahertz bands, devices, and communications.

Year	Reference	Network Area/Type	Brief description of main topics covered
2004	[34]	Terahertz Communication Network	An overview of communication and sensing applications is given with sources, detectors, and modulators for practical Terahertz Communication systems.
2007	[28]	Terahertz Communication Network	The developments in the fields like Terahertz quantum cascade lasers, quantum well photo-detectors, time domain spectroscopy system and materials are discussed with measurements of atmospheric propagation.
2010	[9]	Nano Communication Network	Propagation models for molecular and nano-electromagnetic communications are discussed with challenges.
2011	[21]	Terahertz Communication Network	Different aspects of Terahertz communication are discussed with transistors, mixers, antennas, and detectors.
	[27]	Terahertz Communication Network	Progress on Terahertz wave technologies is discussed.
2012	[31]	Terahertz Communication Network	Terahertz antenna technologies are discussed with different substrate integrated antennas and beamforming networks.
	[10]	Nano Communication Network	An overview on biochemical cryptography is discussed with requirements related to security and challenges.
	[35]	Terahertz Communication Network	An overview on demonstration of data transmission is given with standardization activities.
	[36]	Terahertz Communication Network	The Terahertz technology is discussed with challenges for spectroscopy and communications.
	[14]	Molecular communication networks	The elementary models for intra body molecular communication channel and their extensions are discussed with challenges.
2013	[13]	Nano Communication Network	Issues of Nanonetworks are analysed and discussed with particular focus on communication via microtubules and physical contact.
	[37]	Molecular Communication Network	A review on bacterial communication and neuronal networks is given with application areas in body area networks.
2014	[7]	Terahertz Communication Network	Summarizes the research projects, spectrum regulation, and standardization effort for Terahertz band.
2015	[17]	Internet of Nano-Things	A survey is presented for connecting body area networks and external gateway for in-body nano communication. Network architecture, requirements, and simulation based performance evaluation are also discussed.
	[38]	Terahertz Communication Network	A survey on Terahertz technology is presented including devices, antennas, and standardization efforts.
2016	[30]	Terahertz Communication Network	A review is presented for impact of weather on Terahertz links, attenuation, and channel impairments caused by atmospheric gases like water vapor, dust, fog, and rain.
	[29]	Terahertz Communication Network	A survey on graphene based devices for modulation, detection, and generation of Terahertz waves is discussed.
2018	[22]	Terahertz Communication Network	A review is presented for channel modelling for Terahertz band including single antenna and ultra massive MIMO systems.
	[39]	5G Femtocell Internet of Things	A survey on low Terahertz band circuit blocks is presented with focus on energy consumption using best modulation schemes and optimizing hardware parameters.
	[5]	Terahertz Communication Network	A review is presented for deployments of Terahertz wireless link and opportunities to meet future communication requirements.
2019	[40]	Terahertz Communication Network	A review is presented on development towards Terahertz communications with key technologies.

B. Contributions of this survey

The existing work, although covers a detailed survey on devices, antenna, channel and physical layer aspects. Only limited work is available which summarises the Terahertz MAC protocols and their challenges with future research directions. No survey paper discusses in detail the Terahertz applications and their requirements towards the design of an efficient MAC protocol. Terahertz band features, MAC protocol design issues and considerations in general and for specific applications with decisions and challenges. Therefore, the main objective of this paper is to highlight, discuss and summarise the literature on Terahertz MAC protocols, thier requirements in general for different applications and functionalities. It will help also the researchers to be aware of the gaps in the existing work on this particular topic. Main contributions of this survey paper are:

- A comprehensive survey of existing Terahertz MAC protocols is presented.
- Classification of existing Terahertz MAC protocols based on network scale and topologies, channel access mechanisms and transmitter/receiver initiated communication.
- The unique features of Terahertz band are highlighted to be considered for Terahertz MAC protocols.
- The design issues are highlighted which should be considered while designing efficient Terahertz MAC protocols with decisions which should be taken at MAC layer for performance enhancements.
- The requirements and design challenges for Terahertz

TABLE III: Survey papers discussing the Terahertz MAC layer.

						MAC protocols classification			MAC functionalities											
Network type	Year	Reference	MAC layer discussed	Application areas	Challenges	Network topologies and scale	Rx/Tx Initiated communication	Channel access/sharing	Interference	Error control	Packet size	Device discovery	Handshaking	Tx distance	Data rate	Antennas	Beamforming	Modulation	Cross layer
Nano networks	2008	[41]	Partially	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	2010	[12]	Partially	X	✓	X	X	✓	X	X	X	✓	X	X	X	X	X	X	X
	2010	[15]	Partially	✓	✓	X	X	✓	X	X	X	X	X	X	X	X	X	✓	X
	2010	[42]	Partially	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	2011	[8]	Partially	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	2012	[43]	Partially	X	✓	X	X	X	X	X	X	✓	X	✓	✓	✓	X	✓	✓
	2012	[11]	Partially	✓	✓	X	X	X	X	X	X	✓	X	✓	✓	✓	X	✓	✓
	2016	[16]	Partially	✓	✓	X	X	X	X	✓	X	X	X	X	X	X	X	X	X
	2017	[44]	Partially	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Vehicular networks	2017	[19]	Partially	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Terahertz networks	2014	[2]	Partially	✓	✓	X	X	X	✓	✓	X	X	X	X	X	X	X	X	X
	2014	[4]	Partially	X	✓	X	X	X	X	✓	✓	X	X	X	X	X	✓	X	X
	2016	[26]	Partially	X	✓	X	X	X	✓	X	X	X	X	X	X	✓	✓	X	X
	2016	[25]	Partially	✓	✓	X	X	X	X	X	X	X	X	X	X	✓	✓	X	X
	2019	[33]	Partially	X	✓	✓	X	✓	X	✓	X	X	X	X	X	✓	✓	X	X
This work	2019		Detailed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

MAC protocols for different application areas are discussed.
- Different challenges and future research directions are also highlighted.

C. Organization of survey

The paper is organized as, Section I, presents the introduction and literature review. Section II, presents the background on Terahertz band standardization efforts, health and safety requirements, comparison with different wireless technologies and ongoing projects of Terahertz communications. In Section III, different applications of Terahertz band communication are discussed with respect to macro and nanoscale communication with their requirements. Section IV, highlights the unique features of THz band, issues which needs to be considered with decisions while designing efficient Terahertz MAC protocols. Section V, mentions the topologies so far focused for Terahertz communication networks. Different channel access mechanisms are discussed in Section VI. The transmitter and receiver initiated communication are classified in Section VII. The challenges and future research directions are discussed in Section VIII. Finally, in Section IX, the survey paper is concluded.

II. Background of Terahertz band, communication and standardization

A. Terahertz bands

The Terahertz can be termed as a unit of frequency (one trillion cycles per second or 10^{12} Hz) or electromagnetic waves within ITU designated band of frequencies. The Terahertz frequency range (0.1 - 10 THz) is the last span within the whole electromagnetic wave spectrum and is more commonly referred to as Terahertz Gap. They appear between the Microwave and Infrared bands, as shown in Figure 1. The wavelength of radiation in Terahertz band range from 1 mm to 0.1 mm (or 100 μm). It is sometimes also referred as sub-millimeter band, as it begins at a wavelength of one millimeter and proceeds into shorter wavelengths.

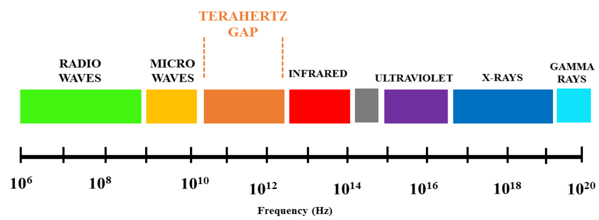


Fig. 1: Terahertz gap in the electromagnetic spectrum.

For nearly two decades, the Terahertz bands are been efficiently used for imaging applications because these waves are non-ionizing and able to penetrate through materials and absorbed by water and organic substances. These waves are unique as they do not harm biological species which is not the case with X-rays and so far considered to be safe for humans as well. Their properties allows them to be used in communication networks to provide higher data rates up to Tbps. The Terahertz Gap is still the least explored bands for its potential use in communication networks and to achieve higher data rates. Table IV, enlist the features of different frequency bands closest to Terahertz frequency bands. Its unique potentials motivate its usage for broadband wireless communications.

B. Comparison between Terahertz band and other wireless technologies

A brief comparison between existing wireless communication technologies and Terahertz band communication including mmWave communication is presented below and shown in Table IV.

The traditional 802.11 protocol is mainly designed for 2.4 GHz WiFi, which uses frequency-hopping spread spectrum

TABLE IV: Different types and features of wireless communication technologies [5].

Technology	Frequency range	Wavelength	Data rate	Transmission range	Power consumption	Topology	LOS/nLOS	Noise source	Weather effect
mmWave	30GHz-100GHz	3cm-1mm	10 Gbps	Short	Medium	PTP, PTmP	both	Thermal	Robust
Terahertz	100GHz-10THz	3mm-30μm	upto 240 GHZ: 10 Gbps [45] upto 300 GHz: 64 Gbps [46] 300-500 GHz: 160 Gbps (single channel) [47] 300-500GHz: > 160 Gbps (multiple channels) [48]	Short/Medium (1-10m)	Medium	PTP, PTmP	both	Thermal	Robust
Infrared	10THz-430THz	30μm-3 μm	2.4 kbps to 1 Gbps	Short, upto 1 m	Low	PTP	LOS	Sun/Ambient	Sensitive
Visible Light	430THz-790THz	0.3μm	100 Mbps to Gbps [49], [50]	Short	Low	PTP	LOS	Sun/Ambient	
Ultra Violet	790THz-30PHz	100-400 nm		Short	Low	PTmP		Sun/Ambient	Sensitive

(FHSS) and direct sequence spread spectrum (DSSS). It provides a simple data rate of up to 2 Mbps. After that 802.11 (a and b) were published, operating at 5 and 2.4 GHz bands. The 802.11a is based on Orthogonal Frequency Division Multiplexing (OFDM) and can provide a data rate up to 54 Mbps, whereas 802.11b supports only 11 Mbps. The 802.11 ac was published which aimed at providing the data rate up to more than 100 Mbps. Other than those, the 802.11ad is developed for the carrier frequency of 60 GHz and it belongs to mmWave frequency bands. Based on different modulation schemes, it can support up to 7 Gbps and 4.6 Gbps, making it possible for various high definition audio and video transmission. Compare to WiFi protocols at sub 6 GHz, its coverage is much smaller due to poor diffraction and severe attenuation at 60 GHz [51], [52]. Although, by using 802.11ad the data rate increase, still it is much lower to handle the 5G and beyond traffic requirements (i.e., Tbps). That is due to the bandwidth provided by these technologies is much narrower and cannot alleviate the enormous pressure from the exponential growth of data traffic [53]. The detailed description and comparison are provided in Table IV. The smart technologies like OFDM and communication schemes like large-scale Multiple Input Multiple Output (MIMO) can be used for frequencies below 5 GHz to achieve higher spectral efficiency. In Long-Term Evaluation Advanced (LTE-A), the peak data of upto 1 Gbps is possible only when the 4x4 MIMO scheme is used over a 100 MHz aggregated bandwidth [54]. The Terahertz band can achieve a drastic improvement in the data rate, however new transceiver design and physical layer approaches are required to increase the spectral efficiency and the data rate.

The Terahertz and mmWave are neighboring bands but their properties are different. In comparison, the bandwidth at mmWave band is 10 GHz, which cannot support Tbps link speed, whereas the Terahertz band has distance varying transmission windows of up to Terahertz bandwidth. The free space attenuation increases as a function of frequency and molecular absorption loss occurs due oxygen molecules in mmWave, whereas in Terahertz band it occurs due to water vapors. The reflection loss are high for both mmWave and Terahertz band which results in severe loss of NLOS path compare to LOS path. The scattering effect also become severe when the wavelength decreases below 1 mm which results in increase of multipath components, angular spreads and delay. Due to much smaller wavelength many antennas can be packaged together to generate more narrower beams. However, the stronger directivity increases the difficulties and overhead of beam alignment and tracking, but reduce the interference. These all factors require novel MAC mechanisms for Terahertz network and introduces more challenges for beam alignment, mobility management, obstacle sensitivity, LOS blocage and multi band operation.

The frequency bands above 10 Terahertz cannot support Tbps links. Although very large bandwidth is available in FSO communication system which operates at IR frequencies, it still holds some issues which limit its use for personal wireless communication like the atmospheric effects on the signal propagation (fog, rain, pollution and dust); high reflection loss; misalignment between transmitter and receiver; and low power link budget due to health safety which limits both transmission range and achievable data rates for FSO communication. It can support up to 10 Gbps of data rate with proper line of sight (LOS) for Wireless Local Area Network (WLAN) [55]. For non LOS much lower data rate has been reported [56]. For longer distance, an FSO system were demonstrated in [57] to support 1.28 Tbps, however, requires typical fiber optical solution to generate and detect high capacity optical signals which are injected in the optical front-end and also does not include the signal generation, detection, modulation, and demodulation blocks. These constraints limit the overall feasibility to achieve higher data rates for 5G and beyond networks. Comparison of wireless and optical technologies is presented in [3] for wireless indoor environments. It is mentioned in [3], the wireless communication has overall better chances for penetration through obstacles in comparison with FSOs. Further, the IR and ultraviolet (UV) are not considered as safe for human and the Visible Light (VL) communication requires the visibility of light at all times.

C. *Effects of Terahertz band on health and safety*

For Terahertz band, it is still not completely understood the effect on human health and the safety limits of exposure. There are concerns regarding the safe power levels of radiation at 300-600 GHz; research is ongoing to establish safe limits. For example, research performed on lab-grown human skin suggested that short but powerful bursts of Terahertz radiation may cause both DNA damage and increase the production of proteins that help the body fight cancer. These findings resultant from a collaboration between physicists at the University of Alberta and molecular biologists at the University of Lethbridge in Canada were published in Optical Society's open-access journal Biomedical Optics Express in 2013. The research suggests that Terahertz pulses can induce DNA damage but also provide DNA repair mechanisms [58]. In 2015, the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) provided an opinion on the potential health effects of exposure to electromagnetic fields (EMF)[95]. At that time they stated that the number of studies investigating potential biological, non-thermal effects of Terahertz fields is small but has been increasing over recent years due to the availability of adequate sources and detectors. They summarized that in vivo studies indicates beneficial effects on disorders of intra-vascular components of micro-circulation in rats under immobilization stress, but did not address acute and chronic toxicity or carcinogenesis. In vivo studies on mammalian cells differed greatly with respect to irradiation conditions and endpoints under investigation. There were studies suggesting health effects of exposure, but these have not been replicated. Some theoretical mechanisms have been proposed, but there is no experimental evidence for them. The committee, considering the expected increase in the use of Terahertz technologies, recommended that more research focusing on the effects on the skin (long-term, low-level exposure) and cornea (high intensity, short-term exposure) be conducted.

D. Standardization efforts for Terahertz communication

The devices capable of operating at 275 GHz and above have recently made rapid progress. Currently, the propagation characteristics are being made in the Terahertz frequency bands for the short range and high-capacity communication systems to achieve a data rate of 100 Gbps and above.

One of the biggest challenges of Terahertz wireless network communication is standardization. The standardization efforts for Terahertz communication started in early 2008 by IEEE with an Interest Group (IG) on Terahertz communication (IGTHz) under the umbrella of IEEE 802.15. The primary focus of IGTHz was on Terahertz communication and related network applications operating on Terahertz bands between 275 to 3000 GHz. The applications include; machine to machine, component to component, human to machine and human to human, indoor and outdoor wireless communications. This interest group was upgraded to a Study Group (SG100) to determine the validity of standard on 100 G (100 Gbps over beam switch table wireless point to point links). The applications focused on SG100 include data centres, intra-device communication, and wireless backhaul.

In 2014, a Task Group 100G Wireless (TG100G, IEEE 802.15.3d for Wireless Personal Area Network systems) was established with the aim to design standard for Physical and MAC layers of Terahertz communications [68]. The applications of interest were kept same as in SG100. The IEEE standard 802.15.3d-2017 mainly defines an alternative physical layer at lower Terahertz frequency range between 252-325 GHz for switched point-to-point (P2P) links with MAC changes in support of Physical layer [68]. It inherits the changes from IEEE 802.15.3d-2016. Some of the key features of this standard are:

- Operation over Terahertz frequency bands including the satellite, land mobile and wireless communication over short ranges.
- Utilization of eight different bandwidths between 2.16 GHz and 69.12 GHz.
- Supporting data rates of up to 100 Gbps.
- Supporting wireless links for pairnet structure for applications including intra-device communication, short-range communication, wireless data centers and front/back-haul communications.
- Physical modes to achieve ultra high-speed communication or system simplicity by using either single carrier or On-off Keying.

Further, the Task Group was involved in the documents for the application requirements [69], technical requirements [70], the channel modelling [71] and the evolution criteria [72]. So far, the spectrum from 275 to 300 GHz is already regulated for data communication. Further, from higher frequencies, the transmission windows between 0.38-0.44 THz, 0.45-0.52 THz, 0.62-0.72 THz and 0.77-0.92 THz are also reported for possible communication with less absorption loss at distances higher than 1 meter [2], [7], [35]. Although due to spreading the path loss is still high above 10 dB/Km, the usage of directional antennas and massive MIMO motivates to achieve the desired transmission range and communication quality, which is being considered to become a part of Terahertz standardization and spectrum regulation. Some, recent standardization activities are also mentioned in [73].

More work is still required for spectrum regulations and communication windows to support high data rate for 5G and beyond networks including shared channel access, physical and MAC layer. For MAC layer specification, the current documents include MAC scanning for pairnet, frame and header format, channel access with Interframe spacing, multi-rate support and MAC sub-layer parameters [68].

The International Telecommunication Union (ITU) has also put some effort by their recommendation documents for spectrum management [74], radio wave attenuation [74]–[76] and noise in Terahertz bands [77]. It also recommends and progressing towards the usage of Terahertz band communication for different applications like IoT (ITU-R WP1B.AR,2017)), radio astronomy (ITU-R R15-WP7D.AR) and land mobile services (ITU-R WP5A-AR, 2018).

E. Projects focussing on Terahertz communications

The spectrum is a crucial resource which requires attention to alleviate the spectrum saturation. The Terahertz gap is recently emerged as a viable solution to increase the bandwidth efficiency which was previously limited using bands below 100 GHz. Therefore, it is crucial to develop a technology roadmap for a beyond 5G network using Terahertz communication to establish links with Tbps speed.

TABLE V: Projects related to Terahertz band and communication.

Project	Reference	Years	Funded by	Band	Distance	Mobility	Features	Target speed	Scenario	MAC layer considered	Focus
iBrow	[59]	2016-2018	EU-H2020	60 GHz - 1 THz	10 m	No	Wireless Transceiver architecture	10 Gbps	femtocell, wireless portable devices	No	low cost and simple wireless transeiver architecture, integrated semiconductors emitters and detectors with seamless fibre-wireless interface.
TERRANOVA	[60]	2017-2019	EU-H2020	300 GHz	1 Km	No	Fiber/wireless	100 Gbps	Backhaul	Yes, specific scenarios	Tbps Wireless Connectivity by TeraHertz innovative technologies to deliver Optical Network Quality of Experience in Systems beyond 5G.
TERAPOD	[61]	2017-2020	EU-H2020	300 Ghz	10 m	No	P2P, P2MP, re-configurability	100 Gbps	Data Centres	Yes, specific scenarios	Terahertz based Ultra High Bandwidth Wireless Access Networks for Data Centres.
ULTRAWAVE	[62]	2017-2020	EU-H2020	300 Ghz	1 Km	No	P2MP	100 Gbps	Backhaul	No	High capacity backhaul links to enable 5G cell densification by exploiting bands beyond 100 GHz.
EPIC	[63]	2017-2020	EU-H2020	-	-	-	-	1 Tbps	FEC	No	System architecture for embedding broadband Terahertz wireless links into fiber optic links for beyond 5G networks by exploiting 270 and 330 GHz band.
DREAM	[64]	2017-2020	EU-H2020	D-band	300 m	No	point to point	100 Gbps	Backhaul, Mesh		Exploiting radio spectrum bands like 130-174.8 GHz with beam steering functionality to reach optical systems speed.
WORTECS	[65]	2017-2020	EU-H2020	90 GHz	10 m	Yes	P2P	10 Gbps	VR	No	Optical wireless communication and radio over 90 GHz Proof of Concept with Gbps throughput.
ThoR	[66]	2015-2017	EU-Japan	300 GHz	1 Km	No	P2MP	100 Gbps	Backhaul	Yes, partially	To provide technical solutions for the data networks beyond 5G based on 300 GHz RF wireless links.
NTT & Tokyo Uni.	[67]		JAPAN	300 GHz	< 10 m	No	P2P	20 Gbps	Wirless downloading system	No	IC capable of 100Gbps at 300GHz. Target source is InP-HEMT. Single carrier.

There is a sharp increase in recent years in the research funding by the bodies like Horizon 2020 (H2020) of European Union and National Science Foundation (NSF) of USA and NTT of Japan. This funding ranges from enhancing research on the device technology to communication aspects including channel, physical, MAC and Network layer characterization. The projects related to these aspects are mentioned in Table V. Some of the projects are based on establishing the feasibility of communication windows within Terahertz Gap like Ultrawave [62], Dream [64], EPIC [63], and WORTECS [65].

The project which involves the research on advancing the communication methodologies while considering the MAC layer issues and challenges are TERAPOD [61], TERANOVA [60], and Thor [66]. Their aims and objectives include the device, channel and antenna characterization. They are also focusing on designing a simple and efficient MAC protocol for point to point and multipoint scenarios. However, each project is looking at a specific scenario. For example, the TERAPOD [61] project is aiming to design an communication methodology for a Data Centre environment, which involves potentially the channel, antenna and Physical layer considerations for an indoor environment only. The TERRANOVA [60] on the other hand focuses on the backhaul point to point scenario for outdoor long range environment including small cells. Each scenario requires a different modelling approach for antenna, channel and propagation model and therefore requires different strategies to access the channel and communication establishment. Similarly, Thor [66], is also looking at high speed link upto 100 Gbps over 300 GHz band for backhaul with partial involvement of point to point scenario for MAC layer channel access.

III. Terahertz band applications and their requirements

The heavy usage of mobile devices like smartphones, personal computers, digital cameras, and high definition (HD) video camcorders have accelerated the recent trends and pushed the global traffic expansion further. The existing steady progress in increasing the data capacity, cannot fulfil the future demands to support these trends for both industry and end-users. Further, the industry partners are expecting new applications, like virtual reality, tactile Internet, vehicular connectivity, and the Internet of Everything which will cause a major shift in key industrial applications. The requirements of these applications mainly include:

- high throughput to deliver and collect data from and to intelligent and connected devices.
- very low latency to support mission-critical wireless networks.
- massive level connectivity.
- high reliability.

The mmWave band can be used for high bandwidth, however their bandwidth can only go upto an order of magnitude. The Terahertz band, particularly the bands above 275 GHz are attracting a huge interest because of wider spectral bandwidth. Typically, the bands between 0.1 to 10 THz, generally considered as a Terahertz Gap is now being considered as a scientific breakthrough to support the requirement for 5G and beyond networks. Therefore, it is vital to explore the possible applications and extension of existing applications to deliver high-quality transmission including voice, video, and data, over Terahertz band communications. So far, the Terahertz band communication applications can be categorized mainly into applications for macro and nano scale networks. In this section, these macro/nano applications are further classified in indoor and outdoor applications because of difference in environment and coverage. Key applications areas are highlighted below and shown in Figures 2a,2b and 3. Some of the application areas are discussed here to show the suitability of Terahertz band in order to meet the 5G and beyond network requirements. Their design requirements are highlighted to emphasize on their particular necessities to progress in Terahertz MAC protocol design. Their performance target requirements are given in Table VI. Table VII, presents the details of these protocols based on different communication aspects and parameter aware Terahertz MAC protocols[1]. The MAC layer related design requirements, issues and considerations will be discussed in Section IV.

A. Applications for Macro Scale Terahertz Networks

The macro scale communication involve applications in which the transmission range is higher than 1 meter. The Terahertz bands although has huge bandwidth availability, but their distance highly depends upon the path and molecular absorption loss. These factor require further research on device and antenna characterisation including size and Tx power, and also requires new and novel MAC techniques for seamless communication with sufficient coverage, channel access, QoS and reliability.

1) Indoor applications: The indoor applications typically considered as the applications with limited transmission range (10-20 m) and therefore can go upto 100 Gbps with sustainable path and molecular loss. It includes applications which requires mobility as well as applications with fixed point to point or multipoint connections, like indoor small cells, TLAN and Data centres. These applications are different from the outdoor environment mainly due to reflections and scattering phenomenon with path and absorption loss. Therefore, requires new channel and propagation model to be considered for designing of Terahertz MAC protocol for different scenarios like office, home and data centres. The indoor applications are shown in Figure 2b and includes:

Data Centres network: The traditional architecture for data centre networks are mostly based on tree topologies [3]. In which each server rack contains number of servers (20-40) with a top of rack (ToR) Ethernet switch having individual connection for each server, aggregated back to a single end-of-row switch which in turn is connected to a core network [3], [106]. Currently, the bandwidth requirements for data center network are being planned to be fulfilled using fiber-optic solutions [107], [108]. However, still, they are incapable of reaching the future data traffic demands of Terabytes and exabytes [1]. Depending on the size of a data centre, these data centres acquire a complex wired connectivity. The study suggested and shown the performance improvement using wireless connectivity for the ToR replacement of wired connectivity with wireless [3]. A typical ToR scenario is shown in Figure 2b for Data Centre network. At one hand the technologies like FSO and mmWave are promising to fulfill the demands for 5G networks [3], [106]. However, they suffer from limited bandwidth up to 10 Gbps and environment losses with indoor obstacles penetration. Terahertz bands can be utilized efficiently to provide more than 100 Gbps or even Tbps links to realize future wireless data centers. The FSO and mmWave solutions are analysed in [3], for the wireless Data centre connectivity. However, requires careful alignment in case of FSO and lower practical bandwidth with interference management.

The Terahertz band has huge bandwidth to serve the future bandwidth requirements. Using the high capacity wireless Terahertz links can also help in re-designing the Data Centres geometry [109]. However, require careful communication protocol design like Physical, MAC and network layer, to be efficiently utilized for Data Centre network. The ToR Terahertz devices can connect using point to point and multipoint wireless links. However, requires directional antennas for inter rack communication for enhanced coverage for more than a meter. The intra rack communications can also use omni-directional antennas due to short distance between the routers. A fair and efficient channel access scheme is required for both inter/intra rack communication with scheduling (for directional antennas) and with collision avoidance (CA) techniques (for omni-directional antennas) due to multi user interference. To connect different ToR devices, the link establishment is very important however becomes challenging with directional antennas and energy minimization constraint. The Terahertz usage can surely provide a way to change the geometry of current data centres to save the physical space, and wires complexity which can hugely save the expenses and provide ease of management. The wireless topologies for data centres has shown performance improvement and are discussed in [3], [110]–[112] for 60 GHz band. The main advantages of using the Terahertz bands are alternate links and high-capacity wireless links for inter and intra rack communication; reduced energy cost; adaptable networks and communication; efficient load balance over alternate links; distributed connectivity to replace the existing centralized control; ultra-high bandwidth and very low latency. The main challenges include efficient channel access and scheduling, link establishment with directional antennas, flexible geometry, achieving high throughput and ultra low latency.

Touch-and-Go or KIOSK downloading system: The KIOSK data downloading system is an instant data transfer system, as shown in Figure 2b. It is a peer to peer communication system between a stationary transmitter and mobile receiver. The high power RF front end can be used at the fixed KIOSK point but the receiving mobile devices should be low power consuming mobile devices. Therefore, it should partially supports mobility, as the KIOSK system remains fixed all the time, however the user can be mobile with very slow speed. It can be imagined as a stationary terminal or point, which may be connected with a data center using fiber-optic, can provide the bulk amount of data to various users with mobile receiver terminal or mobile phones in few seconds. Typically, a GBs of data can be received on the devices within a few seconds without any delay. Other simple applications can be imagined as a data collection and delivery point for autonomous vehicles, instant video files delivery at the video shop, books download at a bookshop, stations or streets, city information pack for visitors including navigation information, instant information delivery for advertisements using their quick response or QR codes.

These systems should consider rapid user association and link establishment. As, huge data can be transferred in short

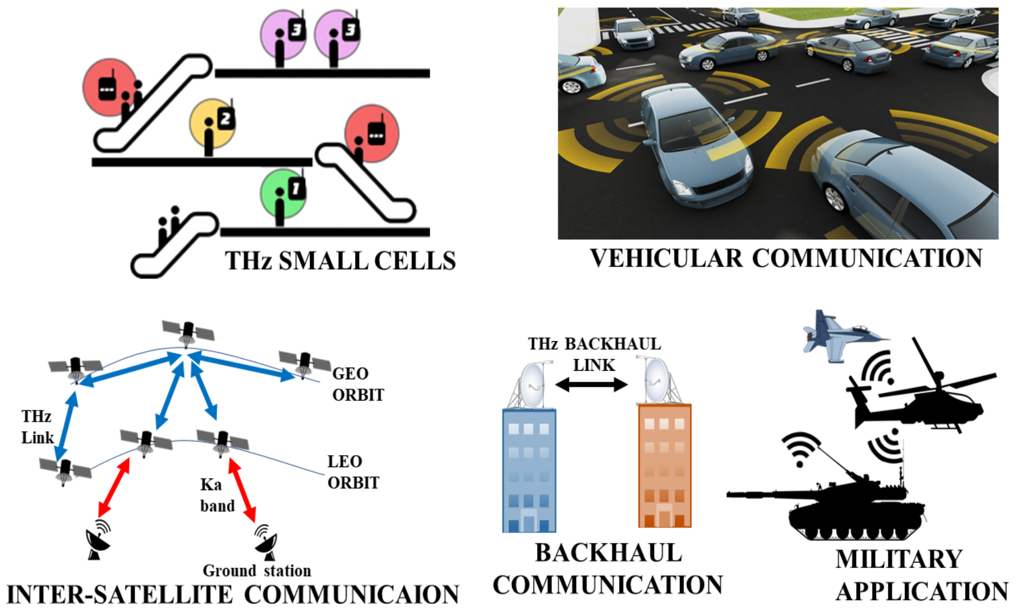
[1] 1) Channel aware: Nodes are aware of the spectrum information, 2) Physical layer: Nodes are aware of physical layer parameters like propagation loss and bit error rate, 3) Memory aware: Nodes are aware of the available memory at each node, 4) Position aware: Nodes are aware of the position of other nodes, 5) Nodes are aware of the bandwidth and adapt according to the available bandwidth.

TABLE VI: Terahertz applications features, requirements and some general MAC related challenges.

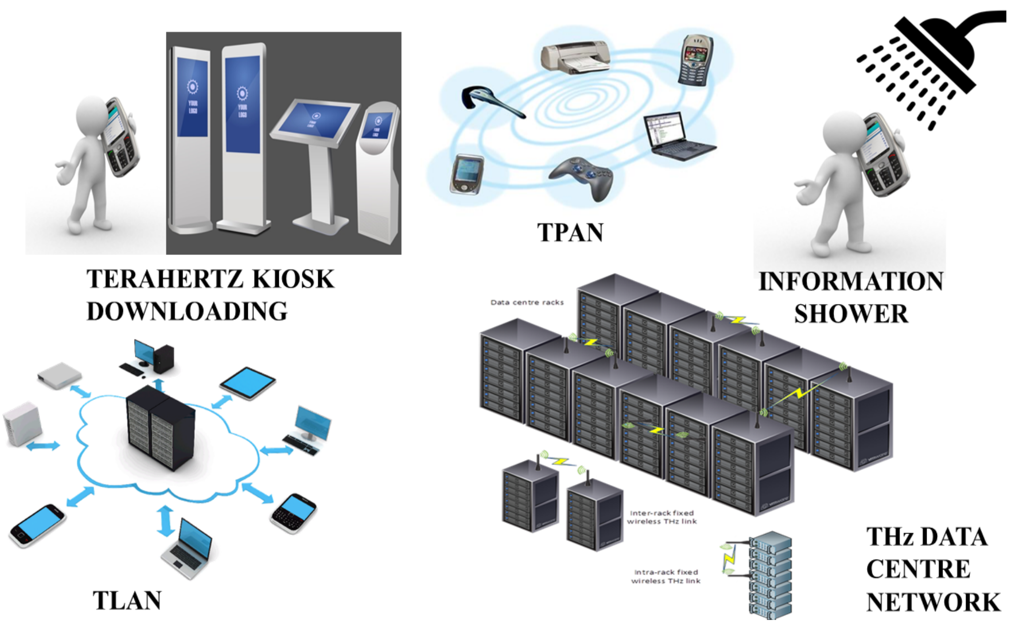
Network scale	Category	Application Areas	Coverage	Mobility	Data rate	Latency	No of connections	Link availability and reliability	Connectivity	Energy efficiency	Target BER	General and MAC related challenges
Macro	Indoor applications	Data Centre networks [3]	< 20 m	No	upto 100 Gbps	0.1-0.2 ms	large	99.99%	P2P,P2MP	Yes	10^{-12}	Efficient and shared channel access, error and flow control with link reliability, coverage, device discovery, beam management, coverage, high throughput and low latency, resource based link assignment, channel modeling to consider interference management for MAC.
		Terahertz Local Area Networks [20], [23], [78]	< 50 m	Yes	upto 100 Gbps	< 1 ms	medium	High	P2P, P2MP, Adhoc	Yes	10^{-10}	Efficient channel access, user mobility and density support, interference and collision avoidance, high reliability and throughput with the low latency, coverage, user association and beam handovers.
		KIOSK downloading system [79]	0.1m	No	1 Tbps	< 1 ms	small	99.99%	P2P	Yes	10^{-6}	Error correction algorithms, fast dadta delivery, user association and disassociation, short term link establishment.
		Terahertz Personal Area Networks [20], [23], [80], [81]	< 20 m	Yes	upto 100 Gbps	< 1 ms	meidum	High	P2P, P2MP, Adhoc	Yes	10^{-10}	Scalability, interoperability between multiple devices, high throughput and very low latency, mobility and coverage.
		Information Showers [69], [82]	0.1-5m	Yes	1 Tbps	upto few sec	small to medium	99.99%	P2P,P2MP	Yes	10^{-9}	High throughput and low latency, directional transmission, synchronization, error correction, mobility and coverage.
	Outdoor applications	Small and ultra dense cell technology [18], [20], [83]–[86]	10-15m	Yes	> 100Gbps	upto few ms	medium to large	High	P2MP	Yes	10^{-10}	High user mobility, frequent handovers, seamless connectivity, high data rate support, very low latency, ultra high reliability, usage of directional antennas, beam alignment and management.
		Vehicular networks and driver-less cars [19], [86]–[90]	> 100 m	Yes	> 100Gbps	upto few ms	medium	medium	P2P, P2MP, Adhoc	Yes	10^{-10}	Data cache system and scheduling, real time data transmission and optimization, autonomous and timely data delivery.
		Military applications [91]–[93]	> 100 m	Yes	10-100Gbps	upto few ms	medium	High	P2P, P2MP, Adhoc	No	10^{-10}	Security for data, user and to avoid jamming attacks, last mile connectivity, larger area coverage.
		Space Applications [94]	kms	Yes	10-100Gbps	upto few sec	small to medium	High	P2P,P2MP	Yes	10^{-12}	Modulation and multiplexing techniques, free space communication, signal attenuation study from space to ground communication, efficient frequency utilization, new antenna design.
		Backhaul connectivity [23], [95]	1 km	No	> 100Gbps	upto few ms	small	High	P2P	No	10^{-10}	Distance dependant bandwidth adjustment, beam management, link reliability, adaptive parameter adjustment.
Nano scale	In/On-body applications	Health monitoring [41], [96], [97]	0.5-2.5mm	Yes	100Gbps	1 ms	large	High	adhoc, P2MP	Yes		Efficient usage of Terahertz frequencies, safety constraints and heating problems, interaction between nano devices and surrounding environment, hybrid nano communication system, efficient communication protocols, nano network architecture, antenna design, channel/propagation model.
	Outdoor applications	Defence applications [98]		No	100Gbps	1 ms	large	High	adhoc, P2MP	Yes		Timely dissemination and gathering of data, Multiple access due to molecular communications, communication range, device scalability, channel/propagation model.
		Agricultural applications [99]–[101]	4mm	No	100Gbps	1 ms	large	High	adhoc, P2MP	Yes		High resolution monitoring of chemical, compound emissions from plants, obstacles detection and avoidance, efficient communication protocols.
	Indoor applications	Internet of Nano-Things [17], [102]	2m	No	90Gbps	1 ms	massive	High	adhoc, P2MP	Yes		Service or device discovery, information routing, reliability, channel sharing.
		Intra chip network [103]–[105]	0.03m	No	100Gbps	1 ms	small to medium	High	Ad-hoc	Yes	10^{-12}	Inter-core communication, high bandwidth, low delay.

time, efficient error detection and correction strategies are required. In case of non-public data transfer, authentication mechanisms will be required as well with secure user data protection system. For a meter coverage distance, the beam width should also be used properly to support the pencil beams with directional antennas. The approximate beam size is mentioned in [79] as 22 cm with 30 dBi as antenna gain for 1 meter distance. These directinal antennas can reduce the interference of side devices and can reduce the multipath effect. Multiple device support should also be considered for future KIOSK systems to save the waiting time. All these issues should be considered while designing an efficient MAC protocol, including the channel access and quick data delivery with minimum latency. An experimental demonstration of a prototype for KIOSK Downloading system using 300 GHz band is presented in [79] and [67], which include the channel and LOS analysis with comparison of error correction algorithms.

Information showers: It is one of the potential deployment strategies for Terahertz access points (APs) which can be deployed at the gates with high traffic such as metro stations, highway entrances or dense environments like shopping malls and airports to deliver information at a higher data rate of more than 100 Gbps [25], [82]. For future access technologies, higher frequency bands 0.1-10 THz can be used to achieve several Tbps transmission rates. However, the transmission or data showers currently can be possible only for the short distance. The short distance, mobility and user density per



(a) Outdoor scenarios



(b) Indoor scenarios

Fig. 2: Terahertz applications for Macro scale networks. a) Outdoor scenarios include small cells deployment, vehicular communication, satellite communication and military applications, b)Indoor scenarios include KIOSK downloading system, THz wireless local and personel area networks, Information shower and Data Centre Networks.

coverage area should be considered while designing a MAC protocol. Multiple users should be supported at the same time, as in heavy crowd scenario users can pass by very quickly and also requires the information they need. The timely, link establishment with user mobility, efficient channel access, synchronization and error correction schemes required attention for such kind of applications.

In comparison with small cells that are supposed to offload data, information shower aim for applications which supports prefetching of data like big files and video streaming. The devices in presences have restricted access to long range wireless networks especially at the time of connectivity to and information shower. The benefits of this application is also recognised by IEEE 802.15.3d (TG - 100 Gbps wireless) as one of the use cases for the Terahertz communication [69]. An information shower case with area density, number of users and mobility pattern is discussed in [82].

Terahertz Local Area Network (TLAN): The Terahertz band can potentially provide seamless communication between the fiber-optical links and wireless routers to extend the connectivity services to various wireless and mobile devices like laptops and mobile devices [20]. This can facilitate the bandwidthhungry applications such as video streaming, conferencing and online gaming. The interesting scenarios for TLAN are the indoor home networks and LAN [80], [113], as shown in Figure 2b. In home networks, the users as mentioned above can surf on internet with the highest possible speed of hundreds of Gbps or Tbps and can download the Blue-ray quality of video file in few seconds. In another type of scenario, it can pair up with other devices and can transfer Terabits of data within a few seconds. Multiple hotspots can be installed to support user mobility in a home network or in an ad-hoc manner.

The omnidirectional antenna is a road ahead with extended transmission range beyond few meters. Currently, in TLANs, the directional antennas can be used to extend the coverage area. However, using directional antennas increases the challenges of serving multiple users with mobility. The quick user association with link establishment is required. Due to huge bandwidth availability, shared channel access needs attention with scheduling. Multi-user interference can affect the performance with collisions when bulk data is transferred. The modulation schemes can also improve the efficiency of data transfer, however analysis is required for frequencies above 0.1 THz. A wireless link with its transmitter and receiver components and link performance is given in [78] with higher order modulation. The efficient channel access with high speed communications are still unexplored areas for TLANS. Further, the indoor scenarios require different channel and propagation model which should consider factors like multipath and reflections, techniques to reduce the signal attenuation should also be researched [113]. The main challenges include the shared and multiple channel access, user mobility and density support, interference and collision avoidance high reliability and throughput with the lowest latency. A road map for indoor Terahertz wireless network is highlighted in [20].

Terahertz personal area network (TPAN): The high speed and instant connectivity between multiple personal devices are possible using Terahertz communication links [80]. It could be an indoor office or home environment, where multiple devices can be connected with each other using a coordinator. A coordinator is mainly a device responsible for channel access, synchronization, scheduling and access control [81]. A scenario is shown in Figure 2b, in which portable devices can be connected with a laptop or mobile devices in a home or office environment. Further, a high capacity ad-hoc network between multiple devices can also be established. While designing a MAC protocol, the centralised architecture should be considered with channel access mechanism, scheduling, retransmissions and ACK mechanism, and frame architecture and error control. The Terahertz band features should also be considered while designing an efficient MAC protocol for TPANS.

2) Outdoor applications: The outdoor applications ranges from few meters to kilometers and includes vehicular, small cells and backhaul connectivity. Table VI, is showing the technical requirements for different Terahertz applications. It includes the fixed point to point, point to multipoint and mobility scenarios.

Small cells communications: The small cells deployment can utilize the huge bandwidth available in Terahertz band and can free up the lower frequency bands which leads to several Tbps of data transfer [25]. One of the possible and upcoming applications of Terahertz band is the small cell communication for mobile cellular networks, in which ultra-high data rate can be provided to mobile users within transmission range up to 20 m [54], [86]. The Terahertz small cell can be a fixed point installed to serve multiple mobile users. The mobility of users with higher data volume offloading needs to be supported. The users moving from cell to cell requires seamless handover for uninterrupted communication. The Terahertz directional antenna usage can increase challenges in user association and tracking with scheduled channel access. Therefore, the Terahertz MAC protocol should consider these requirements and the target performance to ensure the user satisfaction. Figure 2a, shows a scenario for small cells within a building, similarly this can be deployed in an outdoor scenario. The MAC layer protocol should also consider the environment factors in the indoor and outdoor small cells deployment to increase the coverage and throughput and to minimize the latency. The directional antennas, very large antenna arrays and massive MIMO are definitely the roads to look ahead, in future the device advancement support for omnidirectional antenna usage can highly support such application and make its operation much easier. An SDN based small cells with mmWave and Terahertz band is discussed in [86].

Vehicular networks and driver less cars: The future vehicle to vehicle and infrastructure high bandwidth connectivity will enable driverless cars with real-time information services involving bulk data downloads, ultra-fast data transfer for backhaul and large-scale traffic optimization for uploading massive data to clouds for processing. For example, Google's auto-driver cars generate the sensor data at the rate of 750 MBps [114] and are expected to generate 1 TB of sensor data in a single trip [115]. Such data can be used to remotely monitor the current status and to predict the best route for the vehicle. An on-vehicle camera can also be used to collect the route images to build detailed and accurate maps [116]. The limited sensing capability of vehicles can achieve great benefits from these precise maps when downloaded by being in contact with the nearest infrastructure. The challenge to transfer bulk amount of data is the high throughput links, which will not be required otherwise. The main challenges include vehicle scheduling, autonomous link establishment, handovers to provide control of transmission to vehicles in different zones, high processing capacity, capacity and map planning, and efficient usage of the Terahertz spectrum. A vehicular communication scenario is shown in Figure 2a. The Terahertz MAC protocol for vehicular network must consider the quick link establishment, autonomous relay and scheduling of resources and different links to enhance further the autonomous driving and performance of vehicle to vehicle and vehicle to infrastructure communication [88]. For larger distances, a distance dependant scheme can be used which requires efficient mechanism to switch between different frequency bands such as mmWave and Terahertz bands [88]. The quick connection establishment and buld data transfer also requires efficient error correction techaniques and optimal packet size [117]. As an alternative solution for fiber-based backhauling, the vehicles can also serve as digital mules to reduce the deployment cost and to transfer the data [118], [119]. These vehicles can be used to transfer bulk amount of delay-tolerant information between two data collection point, such as data centers [120].

Military applications: The Terahertz band can also be used in defense and military applications, some of them are shown in Figure 2a. These include detection of explosives materials without operator interpretation; personnel screening to detected metallic objects; mail screening without opening; detection of noxious gases; and radar communications [91]–[93]. During a battle, it can be used to communicate the bulk data between the military vehicles including tanks and fighter jets. Due to critical mission requirement reliable, secure and efficient data transmission needs to be prioritise. Typically, air to air and air to ground systems with variable distances are required and needs to be facilitated with high reliability, low delay and very high throughput. The imaging and explosive detection system with quick data transfer is high in demand using autonomous vehicles, for which higher distance coverage links, relaying and adhoc networks needs to be considered with new MAC protocols. Further challenges include security and authentication mechanisms to avoid jamming attacks and protocols to efficiently deliver large data at a larger scale in a timely manner. A physical layer security and transceiver to counter eavesdropping is highlighted in [121] for directional Terahertz wireless link.

Space applications: For many years, space agencies such as NASA and ESA, are developing sensors and instruments for space technology [94], space applications range from point to point communication, TV and radio broadcasting, telemetry and tracking [122]–[124]. Using THz link for satellite application can be feasible outside the atmospheric region, where the only free space loss is considered. A possible scenario can be an inter-satellite link within the same constellation or between low orbit and geostationary satellite, intra satellite communication between elements inside a satellite.

The satellite to earth propagation medium is layered and each layer is characterized by different physical properties, ranging from vacuum to plasma and finally gaseous layer. Signal undergoes additional deep fluctuations and distortions such as molecule absorption and scattering, for THz band, a realistic model is still unavailable and few works tackle the space to earth communication using THz band [125]. To mitigate space link attenuation, different transmission techniques can be deployed such as high antenna gain at satellite and ground station [94], deployment of dual polarization [126] and implementation of advanced signal processing.

Using THz band for space applications open the door to a new type of services provided by satellite operators characterized by ultra-high data rate, low latency, and high availability. From data link layer point of view, classical issues related to space application are challenging such as fast link establishment, mobility management, and synchronization problems. A typical scenario of space application is shown in Figure 2a, in which communication between Geostationary and Low earth orbit (GEO and LEO) satellites is shown with LEO to ground link using Ka band, which is proposed in [127].

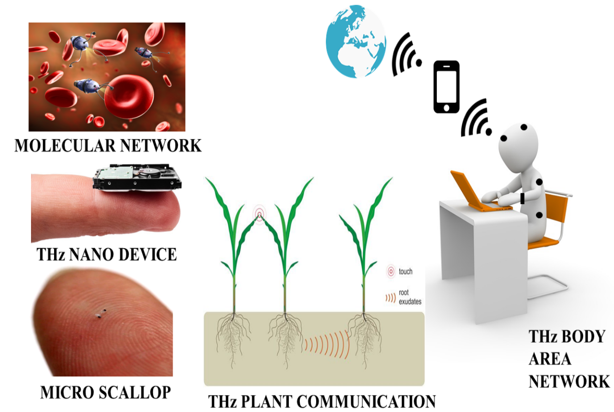


Fig. 3: Terahertz communication applications for nano scale networks.

Backhaul connectivity: The Terahertz band is emerging as the most promising way to realize Gbps link, due to increase in the current traffic demand [95]. A radio link over 120 GHz band for data transmission at the rate of 10 Gbps to the range of over 800 m is presented in [128]. The capacity of backhaul and fronthaul system should be sever times higher to provide reliable and timely data delivery from multiple users and a point to point link. The atmosphere loss is higher, however can be compensated by high antenna directivity. For capacity enhancement and larger bandwidth with Tbps transmission, the Terahertz band between 200 and 300 GHz has shown low atmospheric losses [129]. The wireless fibre extender is also an interesting scenario to extend the communication range and capacity of existing backhaul communication setup to provide reliable data communication with Tbps throughput for distance upto 1 Km in outdoor environments. A very large antenna array or Massive MIMO techniques can be used to transfer information between cells. The use of massive MIMO arrays can be used in an adaptive manner to modify the transmit and receive beams to accommodate the changes in the environment than to physically readjusting the arrays [95]. They can be used to communicate with multiple backhaul stations by electronic beam steering. The challenges for MAC include reliable data transfer, interference and atmospheric loss mitigation techniques and adaptive parameter adjustment including frequency switching, distance and bandwidth allocation mechanisms.

3) Summary of macro scale indoor/outdoor applications: The potential of Terahertz band opens the door for many future applications, some of them are mentioned above. Their requirements and MAC related challenges are highlighted in Table VI. For, most of the applications, only preliminary work is available on the MAC layer. As MAC performance and behavior changes according to different applications and their requirements. New and novel work is encouraged in this direction for Terahertz MAC protocols for different applications. Different MAC functionalities addressed in the literature are mentioned in Table VII.

Each application has their own requirements and requires different MAC strategies to establish link and channel access. These applications mainly require a wider coverage (> 1 m to few Kms) and high throughput (upto 1 Tbps) with low latency (< 1 ms). However, differ in terms of the environment in which they operate. These range from indoor scenarios like Data centres and office environments to small cells and long distance point to point and multipoint backhaul connections. Typically, both indoor and outdoor scenarios require different channel and propagation models, due to different obstacles, scattering and atmospheric losses. The operation requirements are mentioned in Table VI for both indoor and outdoor macro scale scenarios. The indoor scenarios can be static like KIOSK and information showers scenarios in which the aim is to transfer bulk amount of data in less time with high throughput. The range is very limited typically 1 to 2 meters. Therefore, the challenges occur due to mobility and high density does not really affect the design for their MAC protocols. However, quick user association and disassociation, physical layer security should be considered with sufficient user connection establishment. In these applications high throughput and reliable data transfer is highly required while the delay depends upon the amount of data transferred. But, the high throughput does not mean low delay, especially when error control is activated. The virtual reality (VR) device is an interesting application which requires at least 10 Gbps data traffic transfer. However, currently it relies on wired cord and needs to be shifted to wireless transfer with more than 10 Gbps data rate.

The medium range application scenarios like office or home environments are an attractive application scenarios for higher data rates and commercial application point of view. These applications typically require medium range from 10 to 20 meters. The frequent mobility and multi user interference needs to be considered while designing an efficient Terahertz MAC protocols. The shared channel access is required mainly in which collisions can also occur when the number of users increases and high amount of data is transferred. The huge bandwidth availability requires mainly the scheduling among different users. The channel access like time division multiple access (TDMA), frequency division multiple access (FDMA) and carrier sensing multiple access (CSMA) needs to be further explored for performance enhancement and requires further research in order to facilitate an efficient and timely channel access between different number of users with an efficient handshake mechanisms. For TPANs, the interoperability among the heterogeneous devices with user association and channel access with very less latency are required to be considered. Further, the use of highly directional antennas is required currently for extended coverage due to high path loss. The directional antenna usage requires efficient algorithm for beam steering, node discovery and association and scheduling. The mobility adds further challenges in this setup and requires novel MAC techniques. The omni-directional antennas due to high path loss can provide limited range. However, further research is required in devices and antennas to make it possible for higher communication range and minimized interference. The MAC protocols for these medium range indoor applications also requires to consider interference and noise for efficient channel access and to avoid the hidden node problem. The Data Centre networks is a scenario with huge cost benefit by replacing the wired technology with wireless. Typically, these are the static scenarios in which inter and intra rack communication needs to be established. Due to antenna directionality, the point to multipoint connectivity needs further research to schedule the communication among different racks. The MAC should incorporate the link establishment and antenna steering in a timely and scheduled manner for stable connectivity among different nodes. Further, the indoor channel and propagation models needs to be incorporated with communication protocols to realise their effect on the performance. The cross and simultaneous links among different racks can also cause multi user interference, which needs to be addressed. Further, an efficient channel access mechanism is required also to facilitate different nodes with high reliability, high throughput and low latency.

The outdoor macro scale application like small cells and vehicular communication introduces unique challenges when mobility is applied. These application requires control channel architecture to exchange important information to synchronise the users, initial channel access and resource allocation with interference considerations. Frequent decisions at MAC layer are required due to smaller channel coherence time and mobility of users [19], [84]. With other challenges, the NLOS communication exist in small cell deployment scenarios, which can be placed with macro cells to offload data traffic [84]. The requirements for these scenarios include the frequent user association, discovery, mobility, scheduling and handover management. This also include different channel and propagation model which should also be considered while designing a MAC protocols with path and molecular absorption loss optimization with respect to coverage. Few studies suggest also to use distance dependant spectrum switching to reduce message overhead and user discovery [18], [86], [130]. To increase the networks performance, the error recovery and packet aggregation should also be considered to enhance the throughput. The SINR can become a bottleneck in these scenarios for which the signal power enhancement and interference mitigation should be considered [18]. The networks with high density also requires novel MAC mechanisms to facilitate large number of users with high bandwidth, frequent user association, reliability, and mobility management.

The last mile access and backhaul point to point and multipoint are also very interesting scenarios which requires high throughput and low latency for longer distances upto a km. Currently, it has reached until 10 Gbps and is realized to reach beyond 100 Gbps using Terahertz band with high bandwidth availability [66], [131]. The MAC for these application scenarios should consider the beam alignment and management, transmission power and antenna gain, and efficient link establishment. The existing work on different MAC functionalities are mentioned in Table VII.

The indoor and outdoor applications require different communication techniques to achieve enhanced networks performance with high throughput and low latency. The atmospheric losses affect both type of applications differently and therefore the appropriate channel and propagation models should be considered. The indoor environments like Data Centres requires fixed links between the racks, very limited mobility is required for TLAN and TPAN scenarios. The outdoor environments like backhaul links involve fixed point to point links, however differ from indoor environments in terms of atmosphere, distance, reliability and link-budget requirements. The scenarios like vehicular and small cells requires high mobility and therefore involves frequent handovers and must support high user density and scalability for new MAC protocols. For both scenarios, efficient channel access mechanisms, reliable connections with error detection and correction are required with beam management.

B. Applications for Nano Scale Terahertz Networks

Nanotechnology enables the nano-components which are able to perform simple specific tasks, like data storage, computation, sensing, and actuation. These nano-components can be integrated into a device with only a few cubic meters in size and can enable the development of more advanced nano devices [2]. These nanodevices can exchange information to achieve complex tasks in a centralized or a distributed manner [132], which enable unique and interesting applications in the field of biomedical, industrial, military, health monitoring, plant monitoring, nanosensor networks, chemical and biological attack prevention and system-on-chip wireless networks. It mainly involves communication below 1-meter range or in centimeters. The main challenges include the novel transceiver design for nanoscale devices, channel models for different environment, physical layer solutions with information coding and modulation techniques, and communication protocols. This also includes the networks using electromagnetic radiation like nanonetworks and molecular networks in which transmission occur using the flow of molecules. The molecular communications use the absence or presence of molecules to digitally encode messages. It has many applications including the health monitoring and drug delivery [96], [133]. These applications are mentioned below shown in Figure 3 and their challenges are also mentioned in Table VI. It can also be categorised in indoor, outdoor and in-body networks. A general description of these kind of applications is given below, highlighted in Table VI and shown in Figure 3.

1) In/On-body or Health monitoring applications: New devices are being invented to perform health care tasks using nano communication [2], [96], [133]. Different diseases and the presence of different materials like glucose, cholesterol in the blood can be monitored by using nanoscale sensors [134]–[137]. The applications are being built for health monitoring including in-body, on-body and off-body communications [16], [138], as shown in Figure 3. The nanosensors can be used to detect an early disease by using molecular communication by gathering heart rate. The gathered information that can be transmitted over the Internet using a device or mobile phone to a healthcare provider. Other applications are nano-scallop to swim in a biomedical fluid [139], a bio-bot which is powered by skeletal muscles [140], on board drug delivery system [141], a magnetic helical micro-swimmer to deliver single cell gene to the human embryonic kidney in a wireless way [142]. The MAC layer protocols should consider energy consumption and harvesting trade-off, error recovery, scheduling of transmissions among different nodes and efficient channel access. Other challenges include the efficient usage of Terahertz frequencies, safety constraints, the interaction between nanodevices and the surrounding environment, hybrid nano communication system, timely delivery of data, distributed connectivity, efficient communication protocols, architecture, antenna design and channel/propagation model.

2) Indoor applications: : The indoor applications include the industrial applications, office applications, system on chip communication applications and Internet of Nano-things.

Internet of Nano-Things: The Internet of Nano-Things is a new phenomenon which can be referred when different nanoscale devices are connected to the Internet via a communication network [11]. It can be imagined as a connection of different devices in an office or a room area to keep track of different things by using a nano-transceiver and a nanoantenna. For example, it can be attached to keys, wallet, and medicines and connected to mobile devices, so that a user will not forget to take them before leaving a room. The MAC layer protocol should consider high number of device connectivity, their link establishment, efficient channel usage with scheduling strategies to avoid collision and interference. Other challenges include autonomous service or device discovery, information routing, and reliability.

On-chip communication: Terahertz band can be used for interior communication and also for wireless on-chip networks [104], [143]. It can be used at the very small scale to connect two chips due to its high bandwidth and low area overhead. The MAC should consider supporting maximum number of cores by addressing MAC performance by specifying input traffic and interface characteristics [103]. The tolerable delay should be analysed among different layer architecture and analysis of maximum cores supported for throughput delay [103]. The challenges include efficient channel access mechanism for intra chip communication with scheduling, efficient inter-core communication, small-scale antennas to provide high bandwidth and low delay.

Software defined metamaterials: The software defined materials (SDM) emerge from the merging metamaterials with nano networks, which are artificial materials with special structures. They act as reconfigurable metamaterials, whose properties can be changed by programming bia ac omputer interface, which can be controlled by a network of nanomachines incorporated into the structure of metamaterial. The nanomachines receives instructions from the user and can perform tasks to geometriclaly alter the behavior of metamaterial structure. These are the class of programmable materials, whose electromagnetic properties can be controlled via software. The applications emerges from it are, electromagnetic invisibility of objects (cloaking), radiation absorption, filtering of light and sound, and efficient antenna for sensors and implantable communication devices [144]. Its applications include also the monitoring of nuclear reactor [145] in which the exposure of nuclear material can be monitored. A flooding based approach for monitoring is also presented in [146]. For a MAC layer protocol, it mainly looks into interference mitigation issues, due to dense network, queuing models and reliability which covers the error resiliency and security issues.

3) Outdoor applications: It mainly includes agricultural monitoring, industrial plant monitoring and biological attack prevention applications.

Agricultutal monitoring: The plants have shown the ability to communicate with each other through their biological systems like through roots or using germination and pollination process [147] (Figure 3). The nano and molecular communication network can be used to understand and enhance the working of plant communication and the monitoring to detect the plant's growth and their diseases. Particularly, the sensitivity to moisture levels of Terahertz band can be used for monitoring and data dissemination [101]. A review of Terahertz applications for food and agriculture is presented in [99]. The MAC layer protocol requires efficient energy consumption mechanism, cross layer optimization, path loss considerations, efficient deployment strategies and channel access. Other challenges include high-resolution monitoring of chemical compound emissions from pants, obstacles detection, and avoidance and communication protocols.

Industrial/Defence applications: At the nanoscale, the chemical and biological nanosensors can be used to detect harmful chemicals and biological weapons. The nanonetworks can work in a distributed manner to detect these threats ahead of time in a faster way at molecule level than classical sensors [15]. The challenges include the timely dissemination and gathering of data, multiple access due to molecular communications, communication range, device scalability, and channel/propagation model. To progress in research the development of new materials their manufacturing process and quality control process is required. The possible application scenarios are shown in Figure 3.

4) Summary of Nano scale applications: The different nano scale communications scenarios are discussed above include body networks, indoor and outdoor applications. Mainly, these all scenarios requires efficient energy consumption and harvesting mechanisms to address limited energy issues while considering nonbatteries/nanogenerators/nontransreceivers architecture and performance enhancements. The timely dissemination of data from nano sensors to external network. The antenna technology and new channel/propagation and noise models with tools to estimate path loss for different nanoscale network environments. Tools for efficient simulation of nanoscale communication environments. Efficient communication protocols such as modulation and coding techniques, power control, routing and MAC strategies for nanoscale communications. Their MAC protocols also requires to support scalability to support connectivity among high number of devices. The limited capacity nano device cannot handle complex tasks. Some architectures for nanonetworks to handle complex task by combining it with current technologies like SDN, IoTs, virtual network and fog computing are presented in [16].

IV. Design issues and considerations for Terahertz MAC protocols

This section discusses the feature of Terahertz band which needs to be considered while designing efficient MAC protocols, the design issues and challenges related to Terahertz MAC protocols.

A. Feature of Terahertz band communication related to Terahertz MAC protocol design

By using frequencies above 0.1 THz, new propagation phenomena can appear such as reflection, wave absorption by some molecules and channel noise generation [180]. The understanding of Terahertz band seems to be crucial to design systems exploiting this frequency, hence, researchers are focusing on the behavior of Terahertz wave traveling under different environments and in the presence of items such as walls, concrete or grass. The Terahertz wave can follow different paths. At the receiver side, it can be processed as a sum of the line of sight and non-line of sight. To strengthen the reflected and scattered signals, a metal reflector with goof reflection properties can be embedded and to reduce the power absorption the temperature and humidity can be maintained at a certain level for a particular indoor environment. However, for outdoor environment, novel mechanisms are required to overcome the effect of absorption loss. Following are the Terahertz band features which can affect the MAC layer performance including throughput and delay.

1) Path loss: To realize the Terahertz band and its characteristics, it is important to understand its propagation phenomenon and to analyze the impact of molecular absorption on the path loss and noise [181]–[183]. The current efforts are mainly focused on channel characterization at 300 GHz band [184]–[188]. As Terahertz wave propagates, it suffers from different types of attenuation due to absorption, scattering, and refraction [189]. It can follow different paths at the receiver as the sum of non-/line of sight. The path loss includes the spreading as well as the absorption loss. The spreading loss occurs due to the expansion of waves as it propagates through the medium, whereas the absorption loss occurs when a Terahertz wave suffer from the molecular absorption at the medium [190]. These losses make a Terahertz band a frequency selective. The spreading loss can be given as [191],

$$a_1(f,d) = \left(\frac{c}{4\pi f d}\right)^2 \tag{1}$$

whereas the absorption loss depends upon the parameters such as the temperature, pressure, and distance, and can be demonstrated as,

$$a_2(f,d) = e^{-K(f)d} \tag{2}$$

where $K(f)$ is the total absorption coefficient and d is the distance between transmitter and receiver [75]. $K(f)$ can be calculated using the HITRAN database [182].

For a particular transmission distance, the path loss increases with frequency due to spreading loss. For a few meters distance, the path loss can increase up to 100 dB. Further, the molecular absorption defines several transmission windows depending upon the transmission distance. For 1 meter distance, the transmission window behaves like a 10 Terahertz wide transmission window due to negligible absorption loss. However, for distance more than 1 meter the

TABLE VII: Summary of existing Terahertz MAC protocols with MAC aspects and parameter awareness.

		Parameter aware MAC protocols					MAC layer aspects																
Paper	**Year**	**Channel**	**Physical layer**	**Energy**	**Memory**	**Position/Distance**	**Bandwidth adaptive**	**Hand shake**	**Synchronization**	**Neighbor discovery**	**Channel access method**	**channel selection**	**carier sensing**	**Scheduling**	**Cross layer MAC design**	**Collision and congestion**	**Interference**	**Packet size and structure**	**Data transmission**	**Error Control**	**Delay and throughput**	**Multiplexing**	**Beam forming and scanning**	**Protocol Description**
[148]	2011	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	✓	X	X	X	X	X	Effects of congestion and traffic generation intensity are analysed for nano-networks through competition among bacteria for conjugation at nano gateways.
[149]	2012	✓	X	✓	X	X	X	✓	✓	X	X	✓	X	X	✓	✓	✓	✓	✓	X	✓	X	X	The communication and coding schemes are jointly selected to maximise the decoding probability and minimise the interference while considering energy limitations.
[150]	2012	X	X	X	X	X	X	X	✓	X	✓	X	X	✓	X	✓	X	✓	X	X	X	X	X	An energy efficient, scalable and reliable MAC protocol is proposed for dense nano networks with control and data packet structures.
[151]	2013	✓	✓	✓	X	X	✓	X	X	X	✓	X	X	✓	✓	✓	X	X	X	X	✓	X	X	An energy and spectrum aware MAC protocol is proposed to achieve fair throughput and optimal channel access by optimising the energy harvesting and consumption in nano-sensors.
[152]	2013	X	X	X	X	X	X	X	✓	X	✓	X	X	✓	X	X	X	✓	X	X	✓	X	X	A MAC protocol based on IEEE 802.15.3c is proposed for Terahertz ultra high data rate wireless networks is proposed with super frame structure and timeslot allocation scheme.
[153]	2013	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	✓	X	X	X	X	A MAC protocol is proposed for health monitoring for nanosensor network with anlaysis of node density and Tx range with routing strategies.
[154]	2013	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	✓	X	X	X	X	A MAC protocol for Terahertz communication is proposed with channel access and data rate analyses with superframe structure.
[155]	2014	X	X	✓	X	X	X	X	X	✓	X	X	X	✓	X	X	X	X	X	X	X	✓	✓	A MAC design is proposed for macro scale communication at 100 Gbps for pulse-level beam switching and energy control with focus on neighbor discovery and scheduling.
[156]	2014	X	X	✓	X	X	X	X	X	✓	X	X	X	✓	X	X	✓	X	X	X	X	X	X	A technique to utilize the harvested energy in wireless nano=networks is presented with focus on optimal energy consumption for transmission and reception with packet scheduling.
[157]	2014	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	A frequency hopping scheme is presented to overcome the problems of molecular absorption.
[158]	2014	X	X	✓	X	X	X	✓	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	A receiver initiated MAC protocol is proposed based on distributed and probabilistic schemes for adaptive energy harvesting nanonodes with scheduling.
[132]	2015	X	X	✓	X	X	X	✓	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	A distributed receiver initiated MAC protocol is proposed with scheduling scheme to minimize collisions and maximize the utilization of energy harvesting.
[159]	2015	X	X	X	X	✓	X	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	An Rx initiated handshake based link layer synchronization mechanism is proposed to maximise the channel utilization with analysis of delay, throughput and packet transmission rate.
[160]	2015	✓	X	X	✓	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	X	X	X	X	A scheme with logical channel information is proposed in which information is encoded in timings of channel. It supports low rate communication in an energy efficient and reliable manner.
[161]	2015	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	✓	X	X	A cross layer analysis of error control strategeis is presented for nanonetworks with trade-off between bit error rate, packet error rate, energy consumption and latency.
[162]	2015	X	X	✓	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	✓	X	X	X	X	An intra-body disease detection is proposed for wireless nanosensor network using on-off keying and TDMA framework for analysing the data transmission efficiency.
[163]	2016	X	X	✓	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	✓	X	✓	X	X	A fully distributed low-computation scheduling MAC protocol is proposed for maximising network throughput by jointly considering the energy consumption and harvesting.
[164]	2016	X	X	X	X	✓	X	X	X	✓	X	X	X	X	X	X	X	✓	✓	X	✓	X	✓	An assisted beam-forming and alignment MAC protocol is proposed with neighbor discovery, data transmission, delay and throughput analysis.
[165]	2016	X	X	✓	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	A synchronization mechanism is proposed for nano sensor network based on TS-OOK with analysis of consumed energy, collision probability, delay and throughput.
[146]	2016	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	A networking approach for static and dense topologies is presented with flooding, network density, data dissemination and broadcast analysis.
[166]	2016	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	X	X	A link throughput maximization problem is discussed. An optimal packet size is derived with combined physical and link layer peculiarities.
[167]	2016	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	X	X	X	X	Different MAC protocols are compared and analysed in terms of transmission distance, energy consumption and collision probability.
[101]	2016	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	Four frequency selection schemes are analysed for throughput and energy utilization.
[168]	2016	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	X	X	A high throughput low delay MAC is proposed to reduces the delay with super-frame structure.
[81]	2017	✓	X	X	X	X	X	✓	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	A high throughput low delay MAC is proposed with on-demand retransmission mechanism based on verification, reserved timeslots based channel condition and adaptive retransmission mechanism.
[169]	2017	X	X	X	✓	X	X	X	✓	X	X	X	X	X	X	X	✓	X	✓	X	✓	✓	X	A memory assisted MAC protocol with angular division multiplexing is proposed with multiple antennas for service discovery, coordination, data communications and interference.
[170]	2017	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	✓	X	X	X	A hardware processor for 100 Gbps wireless data links is presented. A light weight FEC engine, BER, frames fragmentation retransmission protocol is also presented.
[171]	2017	X	✓	X	X	X	X	X	✓	✓	X	X	X	X	X	X	X	X	✓	X	X	X	✓	A distributed multi radio assisted MAC protocol is proposed with multiple antennas for signal control mechanism with beam-forming.
[172]	2017	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	✓	X	X	X	X	A relay based MAC is presented which considers communication blockage and facing problem. It further presents a neighbor discovery mechanism and data transmission.
[173]	2017	X	✓	✓	X	X	✓	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	An adaptive pulse interval scheduling mechanism based on pulse arrival pattern is presented.
[174]	2017	X	X	X	X	✓	X	X	X	✓	X	X	X	X	✓	X	X	X	X	X	✓	X	✓	Optimal relaying strategies with cross layer analysis.
[86]	2017	✓	X	X	X	X	X	X	X	X	X	✓	X	✓	X	X	X	X	✓	X	X	X	X	Channel handoff mechanism for mmWave and Terahertz channels, high bandwidth data transfer, scheduling and channel capacity modelling.
[175]	2017	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	An energy efficient MAC with clustering and TDMA scheduling for mobility and collisions.
[88]	2018	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	An autonomous relay algorithm is presented for vehicular networks.
[176]	2018	✓	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	X	A secure and intelligent spectrum control strategy is presented with fixed channel.
[117]	2018	X	X	X	X	✓	X	X	X	X	X	✓	X	X	X	X	X	X	X	✓	✓	X	X	Channel switching based on distance, signalling overhead, throughput maximization and error recovery.
[177]	2018	X	X	✓	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	✓	X	X	Throughput maximization with molecular absorption, interference, energy harvesting, and link capacity.
[178]	2018	X	X	X	X	X	X	X	✓	✓	X	✓	X	✓	X	X	X	✓	✓	X	X	X	X	Performance of energy consumption with dynamic super-frame durations and packet lengths.
[179]	2018	✓	✓	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	X	X	✓	A MAC Yugi-Ada antenna is presented for frequency and beam direction reconfigurability.

TABLE VIII: Summary of Section IV. Terahertz band features, Design issues and considerations for Terahertz MAC protocol and decisions to be taken at MAC layer.

Terahertz Band features	Physical layer related issues and considerations	MAC layer related issues and considerations	Decisions at MAC layer
Path loss	Antenna Technology	Channel access, scheduling and sharing	Bandwidth and frequency selection
Noise (Molecular abosption, Sky, Black body)	Interference model and SINR	Neighbor discovery and Link establishment	Modulation and coding scheme selection
Scattering and reflections	Link budget and capacity	Mobility management and handovers	Power management
Multi path	Physical layer features	Collision avoidance and interference management	Beam steering and management
Transmission windows	Channel model	Reliability	Neighbor management and handovers
	First generation devices	Throughput and latency	Channel access schedule
		Energy efficiency and harvesting	
		Coverage and connectivity	

resonance become significant which narrows down the transmission window. Such extreme path loss results in reduced bandwidth and only a few transmission windows. Different transmission windows are marked as feasible in [2] showing up to less than 10 dB of Path loss due to negligible impact of molecular absorption. However, due to the spreading loss, the path loss remains higher, which motivates the usage of highly directional antennas and MIMO techniques [2]. The Terahertz wave can be absorbed by raindrops, ices, foliage and grass and any medium containing water molecule [192].

2) Noise: Within Terahertz band, the molecules presented in the medium are excited by EM waves at specific frequencies. These excited molecules vibrate internally where the atom vibrates in a periodic motion and the molecule vibrates in a constant translational and rotational motion. Due to the internal vibration, the energy of the propagating waves is converted into kinetic energy partly. From the communication perspective, it can be referred to as a loss of signal. Such molecule vibration at given frequencies can be obtained by solving the Schrodinger equation for particular molecular structure [193]. A model for computation of attenuation by gases in the atmosphere is also described by International Telecommunication Union, which considers the water vapor and oxygen molecules over Terahertz band from 1-1000 GHz [76]. A High-Resolution Transmission Molecular Database (HITRAN) database is also found useful for the computation of attenuation due to molecular absorption in Terahertz band [182].

The molecular absorption is an important issue to consider along with free space path loss, as it also causes the loss to the signals due to partial transformation of electromagnetic energy into internal energy [181], [194]. Such transformation in Terahertz band can introduce noise which can be due to atmospheric temperature or the transmission in the radio channel. The noise occurs due to atmosphere temperature (such as Sun) can be referred as Sky-noise [77], [195], [196], where the noise introduced due to transmission in the radio channel can be referred as the molecular absorption noise [181], [190], [197]. A noise model for Terahertz wireless nanosensor networks with individual noise sources that impact intra-body systems is presented in [198], with noise contributions of Johnson-Nyquist, black body and Doppler-shift induced noise.

Molecular absorption noise: The molecular noise is the result of radiation of absorbed Terahertz energy by molecules which depends on the propagation environment. The fundamental equation of molecular noise under different assumptions, such as medium homogeneity or scattering properties, can be directly derived from radiative transfer theory [199]. The absorption is generally caused when the transmitted EM wave shifts the medium to higher energy states, where the difference between the higher and lower energy state of a molecule determines the absorption energy which is drawn from the EM wave. It has a direct impact on the frequency as the absorbed energy us $E = hf$, where h is the Planck's constant and f is frequency [193]. It can also be described stochastically using the absorption coefficient $K_a(f)$, which describes the average effective area of molecules per unit volume and depends upon frequency due to which Terahertz band has a unique frequency selective absorption profile. Similarly, the amount of radiation capable of penetrating through the absorption medium is known as transmittance, which can also be defined by the Beer's Lambert's Law [181], [194], [199] (2). Further details on the calculation of molecular absorption coefficient and model can be found in [181], [194], [200],

[201].

Sky noise: The Sky-noise is independent of the transmitted signals and can be known as background noise. It is caused by the temperature of the absorbing atmosphere and can be termed as an effective blackbody radiator or grey body radiator for non-homogeneous atmosphere medium. Several papers have described the Sky-noise, like [195], [196], [199], [202], [203]. It is identified in satellite communication and is mostly affected by the antenna temperature which is an additional temperature which accounts for the radiation from the absorbing temperature. The atmosphere can be considered as a dynamic medium with decreasing temperature and pressure as a function of elevation. In general, it depends upon the absorption coefficient and the distance due to the variable temperature and pressure in the atmosphere [190]. When the distance is small and the atmosphere is more likely homogeneous the absorption coefficient can be given as $K_a(s, f) = K_a(f)$ where s represents the distance.

Black body noise: A body with temperature T radiates energy, the energy can reach its maximum value for a given wavelength according to the Wien displacement law [204]. This phenomenon is known as black body radiation and it contributes for a specific range of temperature to the total noise of the Terahertz system [198], [199].

3) Terahertz scattering and reflection: Reflection and scattering are two physical properties that characterize electromagnetic wave, the region between transmitter and receiver can contain a large number of scatters with different size and are distributed randomly. There are two types of scattering: elastic scattering in which only the direction of the wave is changed, and inelastic scattering in which the scatter introduces a change to the energy. The scattering processes include Rayleigh scattering which occurs when the dimension of scatter diameter is larger than the Terahertz wavelength and Mie scattering otherwise. Mie and Rayleigh scattering can affect received Terahertz signal [205]–[207]. In [208], a statistical model for Terahertz scatters channel is proposed, based on indoor measurements of a point to point link and transmitter and receiver were equipped with directional antennas, at $300GHz$ window and a bandwidth equal to $10GHz$.

Radio wave reflections occur commonly in indoor scenarios. The reflected ray depends on the electromagnetic properties of the reflector, the surface roughness and the location of the reflectors with respect to the transmitter and receiver. The received signal at the R_X side is the sum of direct ray and all reflected rays. In [209], a demonstrator is set up for four frequency windows: 100, 200, 300 and 400 GHz, to characterize reflections in each window. The reflection coefficient is given by:

$$r = \frac{Zcos(\theta_i) - Z_0 cos(\theta_t)}{Zcos(\theta_i) + Z_0 cos(\theta_t)} \quad (3)$$

Where, $Z_0 = 337\Omega$ is the wave impedance in free space and Z the impedance of the reflector. Z depends on frequency, material relative index and absorption coefficient. θ_i is the angel of incidence and θ_t is the angel of transmission. The reflected wave can be reduced using phased array antenna [208], [209].

4) Multi-path: In the presence of reflectors and scatters, non-line of sight (NLOS) can be generated by the channel for Terahertz waves. In Terahertz communication, where the line of sight (LOS) and NLOS exist together, the NLOS can interfere with the main signal in LOS at the receiving side [210]. The advantage of NLOS component is when the LOS is obstructed, the receiver can still decode the transmitted signal. The magnitude of the received signal at the receiver depends on parameters such as reflector permittivity which characterizes the material, reflector roughness coefficient, incidence angle, and wave polarization and finally its position toward transmitter and receiver [75], [151]. The magnitude of the NLOS signal is also affected by the antenna properties, the distance between the source and receiver, and the plane containing the reflector.

Both LOS and NLOS propagation scenarios exist in indoor environment [211] where the presence of NLOS is mainly due to scatters and reflectors. The channel attenuations and delays can be estimated using NLOS and LOS components of channel impulse response $h(f, t)$ by:

$$h(f, t) = \sqrt{l(d_0, f)}\delta(t - t_0) + \sum_{j=1}^{N_{NLOS}} \sqrt{l'(d_j, f)}\delta(t - t_j) \quad (4)$$

where, N_{NLOS} is the number of NLOS paths, d is the distance, f is frequency, δ is the Dirac function, and l is the total attenuation and can be written as,

$$l(d_0, f) = a_1(d_0, f) * a_2(d_0, f) \quad (5)$$

and,

$$l^{'}(d_j, f) = r^2 a_1(d_j, f) * a_2(d_j, f) \quad (6)$$

Delay parameters in Equation 6 affect some of MAC decisions such as modulation and coding selection module, antenna beam steering module, then estimation of delay parameters can help selecting or switching to the path that give the lowest attenuation for the link. Presence of NLOS and LOS components can be used as an alternative for link communication outage in which if LOS is blocked the NLOS can be used as an alternate path.

5) Terahertz transmission windows: The path losses which occur in Terahertz wave communication gives these bands a frequency selective behavior in which some chunks of bands can be used to provide higher bandwidth due to less amount of losses. Terahertz windows for communication depends on many parameters, such as communication range and technology requirements. The distance-dependant bandwidth is given by [151]:

$$B_{3dB}(d) = \{f | \frac{a_1(f, d) a_2(f, d)}{N(f, d)} \geq \frac{a_1(f_0, d) a_2(f_0, d)}{N(f_0, d)} - 3dB\} \quad (7)$$

where, f_0 is the central frequency, a_1 is the spreading loss, a_2 is the absorption loss and $N(f, d)$ is the total molecular noise.

Typically, four Terahertz windows can be exploited within the band $[0.1 - 1THz]$ for a communication range of $1 - 10m$.

The optimal compact window with low attenuations and high bandwidth is the one centred around $0.3THz$. The $300GHz$ window is characterized by an available bandwidth of $69.12GHz$, subdivided into separate channels or sub-bands. The supported channels for Terahertz communication for the frequency range from $F_{min} = 252.72$ GHz to $F_{max} = 321.84$ GHz were proposed by IEEE 802.15.3d wireless personal area networks (WPAN) working group and summarized in Table IX [68], [180]. In [212], transmission windows are selected based on the distance between the nodes because of higher attenuation in channel impulse response due to molecular absorption at longer distance.

TABLE IX: Bandwidth and maximum achievable data rate for sub bands of 0.3 THz window for single career using high order modulation [68].

Bandwidth(GHz)	Index range	Data Rate (Gbps)
2.16	$1-32$	9.86
4.32	$33-48$	19.71
8.64	$49-56$	39.42
12.96	$57-61$	59.14
17.28	$62-65$	78.85
25.92	$66-67$	118.27
51.84	68	236.54
69.12	69	315.39

B. Design issues and considerations for Terahertz MAC protocols

The Terahertz band can provide high bandwidth for future high-speed networks. However, possesses unique features as discussed in the above section which can affect the communication performance. These features do not affect the MAC performance directly but impact hugely the Physical layer design, antenna and link capacity, which affects the MAC layer performance, throughput and latency.

These features are highlighted and discussed below and have a significant impact on MAC layer protocol design and are highlighted in Table VIII which describes the main parameters that affect Terahertz MAC design and their impacts on the physical layer and MAC layer performances. It includes features of the Terahertz band, such as atmospheric parameters, physical properties of scatters and reflectors. Choice of physical layer functionalities can also affect the MAC layer design such as antenna technology, modulation and coding scheme, and waveform. MAC functionalities include frame size, error control overhead, transmission time interval, and modules to monitor physical layer transmission. Each MAC functionality depends on channel characteristics, device technology, and physical layer features. There are several design issues related with Physical and MAC layer features which should be considered for designing an efficient MAC protocol for different applications. These issues and considerations are highlighted in Table VIII with Terahertz features and decisions to be taken at MAC layer. Table X also highlights the exiting Terahertz MAC protocols with these design issues and Terahertz features.

1) Physical layer and device related issues and considerations:

Antenna technology: The transmitted Terahertz signal undergoes several impairments due to the propagation through a medium, ranging from free space loss caused by high frequencies to molecular absorption noise and scattering. To cope with this issue, high gain antennas are required to strengthen signal in one particular direction and to compensate losses [214]. In communication networks, many nodes try to access the shared channel, it will be challenging to simultaneously serve all of them if we assume antenna is directional.

The antenna technology endowed with fast beam switching capability can determine the way nodes access the shared channel using narrow beams and by assigning each node access to the channel for a given time slot assigned by the MAC layer [215], and MAC layer should include antenna steering module to rapidly steer beams toward the receiver. For example, the switching can be performed at the pulse or packet level. However, the MAC and antennas of different nodes should be well synchronized in order to reduce errors and delays. With optimized antenna gain, it is possible to reach high data rate and good signal quality. Massive MIMO antenna is also envisioned for Terahertz applications, an antenna footprint can be optimized in the Terahertz band. Massive MIMO can enhance MAC performance by increasing the data throughput and by serving more nodes in the network using spatial multiplexing techniques [216] where the number of small antennas can reach 1024, in macro scale communication it is still an open challenge for deep investigations.

In nano-scale communication, the range is short and the antennas are assumed to be isotropic and non-complex design of antenna technology is required. Efforts to design terahertz antennas goes back to some few years, radiation is possible at this frequency band for antennas consisting of materials such as InGaAs and graphene taking advantages from their chemical and electronic properties [217]–[220]. Antenna dimensions are in the order of micrometers as the frequency is around $300Ghz$. The second issue to be considered is materials to be used for antenna design and feeding. Some interesting results achieved for nano-antenna industry [218], [221], [222], power consumption and radiated power, operating band and directivity are the main properties of antenna [223]. The mutual coupling is also an important challenge to address due to ultra dense integration of multi band nano antenna arrays. A frequency selective approach is proposed in [224], to reduce the coupling effects for mult band ultra massive MIMO systems.

MAC performance can be enhanced via beam steering technique by using a phased array. Phased array is characterized by the high gain at a given direction, antenna gain can be tuned using a phase shifter. Phased array antennas can produce directional beams(beamforming), it is also possible to steer beams towards a particular receiver(beam steering). Mathematically, the antenna gain for a uniform planar array at a specific angular direction (θ, ϕ) describes both functionalities of beamforming and beam steering and can be calculated

TABLE X: Terahertz features, design issues and considered in existing Terahertz MAC protocols.

Network scale	Ref.	Application area	THz band features					Terahertz MAC design issues and considerations: Physical layer & device related								Terahertz MAC design issues and considerations: MAC layer related							
			Path loss	Noise	Scattering & reflections	Multi path	Transmission windows	Channel model	Antenna	Interference and noise	THz device	Waveform	Modulation and coding	Link budget	Channel capacity	Channel access	Neighbor discovery and link establishment	Mobility management and handovers	Collisions and multi user interference	Throughput and latency	Reliability	Coverage and connectivity	Energy considerations
nano	[166]	Wireless Nanosensor Networks	✓	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	✓	X	X	✓
	[173]	Wireless Nanosensor Networks	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	✓	✓	✓	X	✓
	[146]	Software defined meta-materials	✓	X	✓	X	X	✓	X	✓	X	X	X	✓	X	X	X	X	✓	✓	✓	✓	✓
	[144]	SDM	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	X	✓	X	X	X	✓
	[161]	Nanonetworks	✓	✓	X	X	X	✓	X	✓	X	X	✓	✓	X	X	X	X	X	✓	✓	X	✓
	[150]	Nanonetworks	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	✓	X	✓	X	✓	X	✓
	[156]	Nanonetworks	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓
	[158]	Nanonetworks	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	✓	X	✓	✓	X	X	✓
	[213]	Nanonetworks	X	X	X	X	X	X	X	✓	X	X	✓	X	X	X	X	X	✓	✓	✓	X	✓
	[153]	Health monitoring	X	X	X	X	X	X	✓	X	✓	X	✓	X	X	✓	✓	✓	✓	X	X	X	✓
	[162]	In-body Nanonetworks	✓	✓	X	X	X	X	X	X	X	X	X	X	✓	X	X	X	X	X	X	X	✓
	[178]	Health monitoring	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	✓	✓	✓	X	X	X	✓
	[157]	Industrial monitoring	X	✓	X	X	X	✓	X	✓	X	X	X	X	✓	✓	X	X	X	X	X	X	✓
	[101]	Agriculture monitoring	✓	✓	X	X	X	✓	X	✓	X	X	X	X	X	✓	X	X	✓	✓	X	X	✓
	[179]	Wireless Nanosensor Networks	X	X	X	X	✓	X	✓	X	X	X	X	X	X	✓	X	X	X	X	X	X	X
	[172]	Nanonetworks	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X
	[160]	Nanonetworks	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	✓	✓	✓	X	✓
	[148]	Health monitoring	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	X	X	X
	[159]	Nano/Macro-networks	✓	✓	X	X	X	✓	✓	X	X	X	X	X	X	✓	X	X	✓	✓	X	X	✓
	[167]	Wireless Nanosensor Networks	X	✓	X	X	X	X	X	X	✓	X	X	X	X	✓	✓	X	✓	✓	X	X	✓
	[163]	Internet of Nano-Things	✓	✓	X	X	X	X	X	X	✓	X	X	X	✓	✓	✓	X	X	✓	✓	X	✓
	[132]	Health monitoring	✓	X	X	X	X	X	X	X	✓	X	X	X	X	✓	✓	X	✓	X	✓	X	✓
	[177]	Nanonetworks	✓	✓	X	✓	X	X	X	X	X	X	X	X	✓	✓	X	X	✓	✓	X	✓	✓
	[149]	Nanonetworks	✓	✓	X	X	X	X	X	✓	X	✓	✓	X	X	✓	✓	X	✓	✓	X	X	✓
	[151]	Wireless Nanosensor Networks	✓	✓	✓	X	X	✓	X	X	X	X	X	X	✓	✓	✓	X	✓	X	X	X	✓
macro	[171]	THz communication network	✓	✓	X	X	✓	✓	✓	✓	X	✓	X	X	✓	X	✓	X	X	✓	X	✓	X
	[81]	THz Wireless Personal Area Networks	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	✓	X	X	✓	✓	X	X
	[86]	THz Vehicular networks and small cells, SDN	✓	✓	X	X	X	✓	X	✓	X	X	X	X	✓	✓	✓	✓	X	✓	✓	✓	X
	[170]	THz communication network	X	X	X	X	X	✓	X	X	✓	X	✓	X	X	X	X	X	X	✓	✓	X	✓
	[174]	THz communication network	X	✓	X	X	X	✓	X	✓	X	X	X	X	X	X	X	X	X	✓	X	✓	✓
	[152]	THz Wireless Personal Area Networks	X	X	X	X	X	X	X	X	X	X	X	X	X	✓	✓	X	X	✓	✓	X	X
	[164]	THz communication network	X	✓	X	X	X	✓	✓	✓	X	X	X	X	X	X	✓	X	✓	✓	✓	✓	X
	[88]	THz Vehicular network	X	X	X	X	X	✓	X	X	X	✓	X	X	✓	X	X	✓	X	✓	✓	✓	X
	[169]	THz communication network, indoor networks	✓	✓	X	X	X	✓	✓	X	X	✓	X	X	X	X	X	X	X	✓	X	X	X
	[155]	THz communication network, indoor networks	✓	✓	✓	X	X	✓	✓	X	X	X	✓	X	X	✓	✓	X	X	✓	✓	X	✓

by [225]:

$$G(\theta,\phi) = G_{max}\frac{sin(Ma(sin(\theta)cos(\phi)-\nu_0))}{Msin(a(sin(\theta)cos(\phi)-\nu_0))}\frac{sin(Nb(sin(\theta)sin(\phi)-\nu_1))}{Nsin(b(sin(\theta)sin(\phi)-\nu_1))} \quad (8)$$

Where a and b are two parameters related to vertical and horizontal separation between antenna elements and also a function of Terahertz frequency. ν_0 and ν_1 are two horizontal and vertical steering parameters. MAC layer should select properly ν_0 and ν_1 to establish a communication link with a node, G_{max} denotes the maximum antenna gain.

The Terahertz MAC scheduler maps traffic data to each antenna beam as depicted in Figure 4, the diagram shows an example of mapping between user data traffic and antenna beams. MAC selects, based on traffic requirements, for each transmission time interval $[(n-1)T, nT]$, a destination node and its associated beam to transmit data traffic. Many scheduling algorithms can be used such as Round Robin, maximum throughput or minimum delay algorithms. The switching operation of the beam can be performed at a pulse, symbol or frame level.

Interference model and SINR: Interference exists in Terahertz communication system and it can be generated from nodes using the same frequency band at the same time or from the signal itself. Interferences can be caused also by reflected and scattered signals [85], [130] for either fixed or mobile users. Research works on interference modeling are not sufficient, as a signal to interference ratio depends mainly on

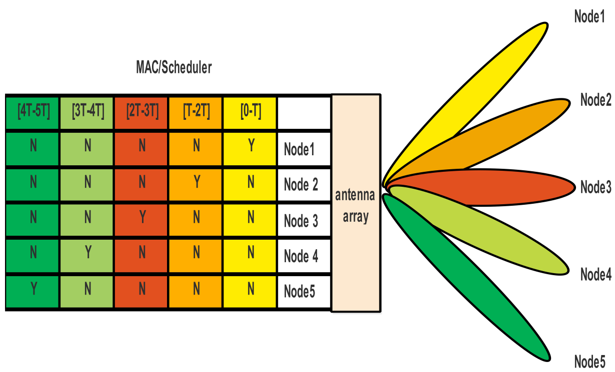


Fig. 4: MAC scheduler with antenna array. The figure shows the MAC scheduler module and how it is linked to the antenna system, if the current node i needs to send data to node j, then MAC sends a command to the antenna system, coded to steer its beams toward node j using a digital to analog module interfacing between MAC and the physical layer. The beamsteering operation can be repeated for each frame period to schedule a new transmission.

the channel model. Interference level affects the signal quality and leads to higher BER. The design of MAC should be aware of interference level by enhancing nodes synchronization or adopting channelization methods to access the channel. Access methods define the way each node transmits its data, then elaborating an interference model will help deeply selecting the right access technique.

Link budget and capacity: A communication link is characterized by link budget and system capacity. Link budget includes transmitting power, all gains, and losses. Link quality is good when the link budget value is higher than the receiver signal to noise ratio threshold, this threshold characterizes the receiver device as well as the bandwidth. Link budget gives the information of all power gains and losses that should be present in one Terahertz link, Terahertz link budget depends on many factors such as antenna gains, atmospheric attenuations, available bandwidth, distance, temperature, total noise, and the Terahertz source output power. The link budget should higher than a fixed threshold, mainly depending on device technology, to guarantee reliable Terahertz communication. Enhancement of link budget leads to increase in reachability, and reduce data loss. The link budget is used as a reference metric to determine the link range. Shannon capacity is derived from the mutual information maximization between sender and receiver for a particular channel model, it indicates how much data can be transmitted for a given bandwidth and SINR for different scenarios.

Most of the studies on Terahertz capacity analysis derived for the nanoscale Terahertz network [181], [226], [227], and macro scale networks [228] are based on theoretical assumptions and deterministic propagation channel. In realistic scenarios, additional properties of the Terahertz wave should be considered such as scattering, dispersion, atmospheric factors, and Terahertz statistical model.

Capacity increases with bandwidth and SINR, as a result, MAC layer design should take into consideration the achievable channel capacity for different channel models, as throughput is bounded by the maximum data rate. MAC layer should be aware of link quality: link budget and capacity; frames should be protected against errors, moreover, frame length and transmission duration should be tuned. For MAC design, link requirements should be considered, for example, in data center use case, the data rate can exceed $100Gbps$, then efficient tracking of link fluctuation is required. Knowledge on channel capacity and link budget enhances MAC awareness of the channel and the physical layer via frame optimization and transmission scheduling. In [228], the impact of the outdoor channel on fixed link capacity is studied at a 1 km distance. The channel capacity and BET performance for data transmission is analysed in [229].

Physical layer features: Physical layer design should adress a couple of issues related to the channel and should also guarantee high data rate transmission with low BER. Physical layer for a Terahertz system is still immature because of lack of efficient Terahertz devices. The Terahertz signal is generated by either optical such as UTC-PD or electronic devices such as E-RTD using the heterodyning technique. Ongoing works are still progressing on Terahertz power amplifier and low noise amplifier. Waveform generation is also still an issue, the signal form contributes to the Terahertz channel effect mitigation, for example, inter-symbol interferences and symbol detection. The Terahertz channel is characterized by high free space loss, molecular absorption, and noise, as well as limitations of transceivers capabilities. To mitigate the signal quality issue, modulation and coding are the main features envisioned. The modulation guarantees an adaptive data rate for fluctuating channel, high order modulation for low bit error probability can increase data rate [230], in [231] it is possible to reach $100Gbps$ using 16-QAM optical modulation and BER equal to 10^{-3} and using UTC-PD source for heterodying; coding helps to reduce errors. MAC layer can be designed to support variable throughputs and fits frame length to channel conditions via information from the physical layer. More works should be addressed to modulation and coding techniques to enhance main MAC layer performance and to design MAC protocols physical layer aware. For nanoscale communication, basic modulation techniques were used, such as On-Off Keying (OOK) and pulse position modulation (PPM) together with femtosecond pulses [232]–[234].

Terahertz Channel model: Terahertz channel model affects physical layer choices, for example, antenna pattern shape and device design. It affects also the MAC layer in term of transmission time choice and transmission window selection. Terahertz users are assigned short frame size in harsh propagation conditions, therefore, MAC should sense channel fluctuations to transmit data with less error and high throughput. Terahertz channel model is related to the propagation environment, for instance, modeling of indoor Terahertz channel within the data center using ray tracing simulations is proposed in [235] where NLOS and LOS coexist, Terahertz statistical model for short-range THz D2D communication for randomly distributed scatters in the area between transmitter and receiver is described in [236]. In-body communication, the nano-network consists of autonomous tiny devices with energy harvesting capabilities, the propagation channel is also different from macroscale communication, as Terahertz medium will be heterogeneous, a channel model is proposed for this particular communication channel [237]. Performance evaluation for indoor as well as outdoor Terahertz channel was evaluated in [238] for reflections.

A channel measurement study was carried out for LOS and NLOS link in [209]. The indoor links are observed as robust even with few NLOS reflections, whereas the scattering losses due to surface roughness are relatively low due to diffractive effects. A good BER performance can be achieved by tuning the receiver direction and high quality links can also be established with an obstruction in the beam path. The results were taken with data rate of only 1 Gbps, further measurements for higher data rates still required with multipath effect and ray tracing phenomenon because with increasing data rates requirements the path loss can also increase. Mainly, BER performance is only moderately affected within indoor and outdoor links. However, due to presence of multipath and absorption loss separate MAC mechanisms are required for indoor and outdoor applications. The indoor applications are most likely to be affected with walls, ceiling and other materials, which can cause multipath and scattering effects and can result in wring estimation of received information about another user's location or transferred data and can also result in hidden node problem. However, the outdoor scenarios can be affected due to external environmental features like rain and humidity, obstacles like trees and buildings, and distances. Although, by using reflector NLOS beam can be used, but for higher performance highly directional antennas with narrow beams are mostly required. Whereas, in indoor scenarios, due to short to medium range NLOS communication can also be used for sufficient performance, in which NLOS beam communication can enhance the network performance. In [20], an indoor scenario (WPAN) is discussed with implementation phases as Ethernet extension, handovers within multiple Terahertz plugs, interference management and integration with HetNets for B5G networks. A three dimensional time varying Terahertz channel model using Kalman filtering is presented in [239], for modelling and tracking access point to user equipment link in an office scenario to analyse the system capacity.

First generation Terahertz devices: Due to high attenuation, devices with good performance such as higher output power and low noise level are required to optimise the link budget and increase the link data rate. Terahertz transceivers based on electronics were developed, for example, Silicon-Germanium (SiGe) based heterojunction bipolar transistor (HBT) and Gallium-Nitride (GaN) based monolithic mmWave integrated circuit (MMIC) and also transceiver based on photonics such as quantum cascade laser QCL for high frequencies applications. Resonant Tunnelling Diode (RTD) based on InGaAs/AlAs are also promising for Terahertz applications [240], RTDs convert mm-wave to Terahertz wave.

Two kinds of devices that perform conversion to terahertz signal: electronic devices such as E-RTD and photonic devices such as Uni-Travelling Carrier photo-diodes (UTC-PD). Works on both technologies, photonic and electronic devices, are in progress to choose the best one of each scenario based on the required data rate, distance, and sensitivity. For some application, replacing the high capacity wire, such as optical link, by Terahertz bridges is promising as it adds more flexibility to the network and reduces deployment cost. Terahertz devices are responsible for signal emission and reception. They can affect the link quality such as link budget and the received power spectral density, and can also affect bit error rate (BER) and outage probability. Therefore, to design a MAC protocol with high data rate, devices with low system noise level and variable output power are required while maintaining the SINR in the network. SINR of the network is the results of deviceâĂŹs transmitted power, channel and system noise. MAC layer, aware of device technology capability, can monitor power emission, antenna pattern shape and beam orientation. The antenna technology and device performance can also enhance the node discovery functionality and reduce delay caused by this operation.

2) MAC layer related issues and considerations:

The issues and considerations related with MAC layer are discussed below. These issues are also highlighted based on Terahertz applications in Table X.

Channel access, scheduling and sharing: For short range coverage like in nano networks, we assume the use of isotropic antennas, due to high path loss and high transmission power requirements. On the other side, for macro scale communications, a higher range is required which is not possible using isotropic antenna. Therefore, directional antennas are being used to enhance the coverage. However, due to antenna directionality, beam alignment is required before any transmission should take place. Because, if they are not aligned and facing towards each other, they cannot receive the transmission, which could introduce deafness problem. In centralised networks, a central controller is required to manage the beam alignment with scheduled transmissions and for Adhoc networks TDMA based approaches can be used to avoid collisions and manage beam alignment, so that each node should know when to transmit, to which node to transmit and to which direction. Shared channel can be used among different nodes, but interference can be increase. An alternate band should be used, which can introduce synchronization and coordination problem among different nodes to access the channel.

Neighbor discovery and Link establishment: For any communication to occur, a link must be established first to discover the nodes, which needs to be considered while designing an efficient MAC protocol for nano and macro scale networks. For nano scale networks, due to constraints energy storage and generation, mechanisms with low message overhead are required. For this purpose, receiver initiated communication is mostly used in nano communication networks, in which a receiver asks for a message whenever, it has sufficient resources to receive a packet. For macro scale networks, the antenna directionality and mobility adds extra challenges to establish a link between the nodes, which requires a node to track and locate other nodes for stable link maintenance.

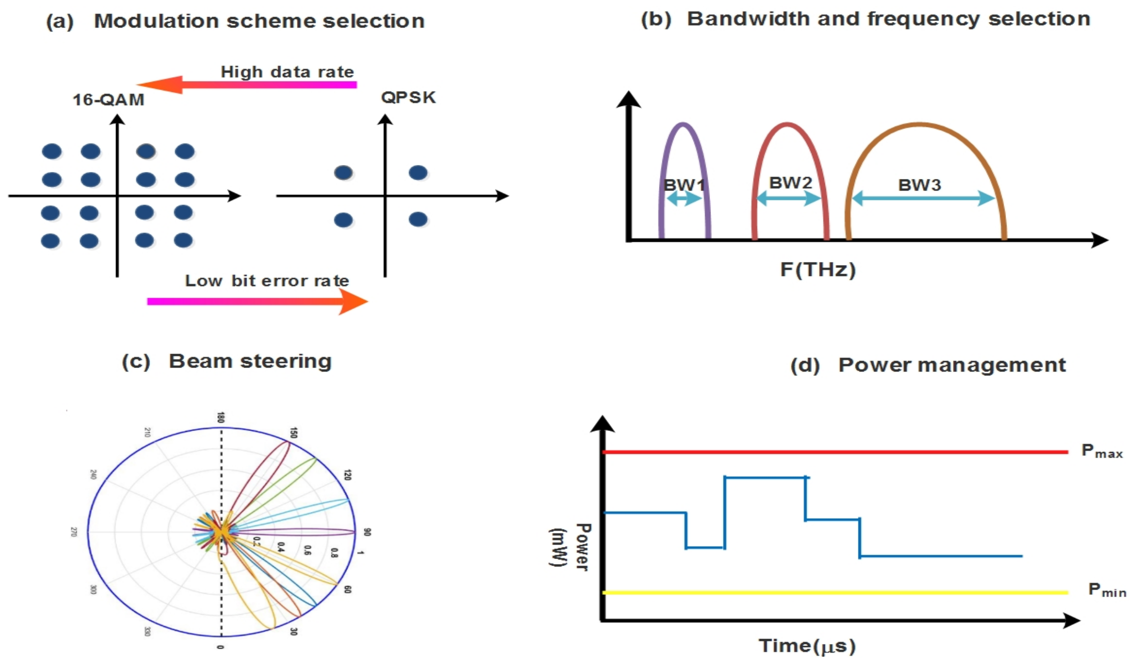


Fig. 5: MAC layer decisions to enhance the communication performance, like (a) Modulation scheme selection: MAC can select a modulation scheme suitable to the link requirement, (b) Frequency and bandwidth selection: it select from available frequencies for transmission, and an associated bandwidth to reduce interference and increase throughput, (c) Beam selection: MAC can direct a Terahertz antenna beam to establish a link between two nodes, (d) Power management: it can select the amount of power to transmit, in order to increase SINR in other nodes or reduce power consumption in the current node.

For seamless communication, a stable link is required at all times. Efficient beam steering mechanisms are required to reduce the handshake time and to reduce the overall neighbor discovery time in an adhoc networks. Further, due to short range and mobility frequent link association and handovers may be required, which should also be supported in MAC protocol design.

During the discovery process or data transmission, the directional antennas can also cause the deafness or hidden node problem due to unknown interference from hidden nodes, which can affect the reliability and transmission performance [90], [241]. In this problem, a node cannot communicate with another node because the other node can face towards a different direction. For example, Node 1 wants to send a packet to Node 3 via Node 2. After receiving a packet from Node 1, the Node 2 must then beamform its direction to Node 3 to forward the packet. If Node 1, remains unaware of this directional change of Node 2, it can starts its next transmission to Node 2 which is pointing towards Node 3. It can create interference for the transmitting node.

Mobility management and handovers: Mobility and coverage are two mutually correlated concepts, for mobile Terahertz system [87], [242] in which radio coverage should be guaranteed to decrease link outage probability. MAC layer should support mobility management functionality to guarantee the service continuity. The handover is a technical concept for mobile network to describe changing of the serving base station without interruption of the traffic flow. Its process involves;

- Handover preparation: if measurement in serving node or the mobile show that quality of the signal became critical then start the procedure of handover preparation by looking at the neighbor nodes.
- Handover execution: when a candidate node is selected to guarantee the communication continuity, a message is sent to the mobile node to steer its antenna toward the new node or base station ahead of time.
- Handover termination: mobile node is assigned to a base station and the previous link is released.

In Terahertz network, the MAC protocols have to operate with narrow beams, which should incorporate fast handover procedures with time for localization and tracking functionalities. This combination is required only in higher frequency bands above 60 GHz.

Collision avoidance and interference management: Due to high bandwidth availability and antenna directionality, it is unlikely that a collision might occur in Terahertz communication. However, it can occur when two node pairs beam directions and crosses each other and perform frequent and long transmission. The multi-user interference can also occur in a scenario with large number of nodes and with mobility. Therefore, a collision detection and avoidance mechanism should be considered while designing an efficient Terahertz MAC protocol. New interference models are required to capture the effect of Terahertz band features and multi user interference [243]. The directional communication can decrease the multi-user interference but it requires tight synchronization between Tx and Rx to overcome the deafness problem [244]. Further, reduced channel code weights can also result in lower channel error probability and can also help in avoiding the multi-user interference and molecular absorption [245].

Reliability: Most of wireless systems require a reliable communication, where the degree of reliability defers from one application to another. The problem becomes more complicated when the channel conditions changes with time and causing time varying absorption [97], [245]. For Terahertz systems, mainly low frame loss and high throughput are required. In Terahertz systems, the eror control module is mainly responsible for frame protection and retransmission to reduce frame losses where frame error depends on channel model as well as on frame length. Error control module is required especially for harsh channel conditions such as outdoor channel with dynamic conditions. It is less important for point to point link where the channel is indoor and stable. For nano sensor network, a cross optimization method is proposed in [166], to adapt with the frame transmission and size with the channel conditions. Further, for efficient usage reliable wireless links and beam tracking should be considered in a MAC design. With interference minimization and frequent handovers, providing reliable fornthaul and backhaul links is also a challenge [25].

Throughput and latency: Terahertz band is endowed with large bandwidth, due to which it is possible to reach a throughput exceeding 100 Gbps. For some applications like Terahertz data center scenario, bandwidth is shared between many nodes and therefore a MAC should support and guarantee high data rate and low delay. Fast scheduling algorithms, appropriate MAC techniques and buffering should be implemented to meet application specific QoS requirements.

Energy efficiency and harvesting: For some Terahertz applications, power of nodes is a limiting factor to transmit continuously, a power management module should be implemented on MAC to reduce power consumption without degradation of the system quality of service. For example switching from active to idle state if the node has no data to transmit and applying the power control strategy depending on channel conditions and target QoS. The second alternative to save power and guarantee the battery life is to harvest and manage energy, for example for nano-sensors the energy harvesting is applied for more active nodes. Due to low storage constraint of nano devices, the tradeoff must be considered for the energy harvesting and utilization in an efficient way [8].

Coverage and Connectivity: Terahertz communication is characterized by low range connectivity and high available bandwidth. The coverage or range can be optimized using directional antenna, enhanced Terahertz devices, high output power and optimized sensitivity. MAC layer can also contribute to coverage and connectivity enhancement by utilizing data link relaying, path diversity and spectrum switching. For example, in vehicular Terahertz network, a mobile node can coordinated to more than one node to increase the data rate. In nano sensor network, for short range communication, each node can transmit to any node out of its range using relaying capabilities. Path diversity is also an alternative solution to increase connectivity when a LOS is temporary unavailable. With no direct LOS link and to support the seamless communication with less delay, reflectors can also be used to reach out far nodes with no LOS link [84]. A coverage and achievable rate performance analysis for multi user Terahertz with single frequency is presented in [246].

C. MAC layer decisions

MAC layer is responsible for traffic adaptation with the physical layer, adding sophisticated modules to optimize link performance which can be promising. Following are some of the decisions which can be taken at the MAC layer to enhance further the system performance.

- **Bandwidth and frequency selection:** MAC layer should continuously sense the physical channel as well as be aware of service requirements of each traffic flow, then, the selection of the appropriate bandwidth and carrier frequency can adapt the traffic to the channel as well as reduce interferences. Most of the actual Terahertz system uses a single frequency, a multiband antenna is also worth considering.
- **Modulation and coding selection:** The Terahertz channel is generally time dependent, the transmitted signal undergoes impairments leading to high bit error rate, to mitigate this issue, an adaptive modulation, and coding scheme can be adopted and controlled by the MAC layer. High order modulation selection can increase throughput and low order modulation is required to reduce the bit error rate.
- **Power management:** This module selects the appropriate power to increase coverage as well as reduce interferences when nodes coordinate between each other. Monitoring nodes using power control can reduce interferences as well as maintain an acceptable energy consumption value. Power management module, can adapt to its environment, for instance, the mean consumed power value in a humid environment will be different from a dry one.
- **Beam steering:** when using a directional antenna for Terahertz communication, beams should be steered appropriately to the receiving node, selection of the beams orientation coordinates can be performed at MAC layer based on the inputs from the physical layer beam parameters such as phases between elements.

Implementing the aforementioned modules in the MAC layer, will increase awareness of the physical layer and channel fluctuation as well as adapt the Terahertz link to the upper layers. In Figure 5, four physical layer functionalities can be monitored at MAC layer level, for instance, it is possible to change the modulation scheme from high order 16-QAM to low order QPSK to reduce bit error rate and from QPSK to 16-QAM to increase data throughput when channel condition is good, switching operation can be triggered using link quality statistics. Module responsible for beam steering can be also included in the MAC layer, for example using 3 bits to monitor 8 beams and establish a link with 8 neighbors. Monitoring frequencies and bandwidth can be also included in the MAC layer, for multi-band wideband antenna, to reduce interferences and increase data throughput. Finally, the power management module allows monitoring transmitter output power to enhance link budget if the link breakdown or channel attenuation increase. The power management module can take a decision based on collected measurement from the physical layer and also from other nodes to control signal to interference ratio. Modulation scheme, beams orientation, frequency, and power can be updated at frame level based on collected statistics from a physical layer as well as reports from the networking layer.

D. Discussion on Terahertz application scenarios

In Table X, different Terahertz MAC protocols are mentioned with their application areas. Terahertz band features and their MAC design issues and considerations are also highlighted. Mainly, these applications are categorised in nano and macro scale scenarios which are also discussed in Section III. The Terahertz communication research is still in its early stages and still there are lots of challenges to be addressed for device, antenna, channel and communication protocols. Due to unique band features, each MAC protocol of different applications require novel MAC mechanisms to accommodate the high bandwidth availability, path loss and noise. Table X, mentions only those Terahertz applications for which MAC protocol work is available. Still, there are applications for which the literature does not include any work, therefore they are not mentioned in this table. For nano scale networks, mostly omni directional antenna are assumed due to the short range and low path loss. For higher transmission range the path loss can severely damage the communication and affect the distance. The Terahertz MAC protocols for nano scale networks still do not consider the unique features like path loss, molecular absorption noise, multi path effect. For Physical layer functionalities, the MAC protocols are there as mentioned in the Table X, but they are not considering the antenna design, channel, propagation and interference model.

For macro scale applications, mainly there are indoor and outdoor applications. Each indoor and outdoor application has different requirements and therefore require different MAC mechanisms. Due to short range constraint, the Terahertz band suits the indoor applications like TLAN and TPAN, these involves mobility with communication over short distances. The scenarios like Data centres involves static links between different racks and so require point to point/multipoint communications. These scenarios require different channel models and scattering and multipath phenomenon can affect the communication in a different way. Therefore, while designing an efficient Terahertz MAC protocols, the features and design issues mentioned in Table X should be considered. To enhance the communication range, directional antenna should be used which requires novel mechanisms for beam management and tracking with MIMO support, reflectors to mitigate blockage and reach to more than one hop distance. The static points application like kiosk downloading system and information showers needs to support quick link establishment and reliability. These applications also required new mechanisms to access the Terahertz channel and link establishment, especially when frequent link establishment is required and where node density is high.

The outdoor scenarios like vehicular communication, backhaul and small cell are interesting scenarios, which involves mobile and static scenarios. However, the channel can be affected due to different environment factors like rain, wind, humidity and dryness. Therefore, new channel and propagation models are required which should also incorporate blocking factors like trees, humans and other physical equipments. Massive MIMO can be used to relay information between cells or with nearby networks. Adaptive beam management can be utilized by using cooperative massive MIMO and electronically steerable beams [19]. Further, due to different environment factors interference mitigation techniques are required for outdoor applications.

E. Summary

Currently, unused spectrum for wireless links operating at disruptive bandwidths of 100 GHz and above can be a critical key enabler for beyond 5G networks. In this regards, the MAC layer protocols play a very important role in making communication decisions. The environmental and band-specific effects can easily degrade the performance of Terahertz MAC protocols in terms of delay, throughput, packet reliability, and delivery ratio. Due to unique features of Terahertz band like noise and path loss, the Terahertz band communication can easily be interrupted compared to the interference phenomenon in other lower frequency bands like ISM or GSM. The molecular absorption noise or the atmospheric noise can easily affect the Terahertz communication link and the problem increases with increase in the distance between the transmitter and receiver. If not considered properly can also result in hidden node problem and multipath effect. Further, the additional environmental noise factors like Sky-noise can result in underestimation of noise or interference figure at the receiver and transmitter which can also affect the MAC protocol performance seriously. The modeling of these factors is very important in the sense that these factors can behave differently in different environments like indoor or outdoor environments, and should be modeled carefully depending on the scenario. Therefore, in designing the MAC protocols for short, medium or long range Terahertz communication, these environmental factors, and their modeling must be taken into account. The indoor and outdoor scenarios required different channel, propagation and interference models and they need to consider different physical and MAC layer design issues discussed in this section. To support ultra high bandwidth different applications require different MAC mechanisms which needs to be focus to advance further the technology.

V. Terahertz MAC protocols for different network topologies

In this section, the existing Terahertz MAC protocols are categorized mainly in network topology as centralized, clustered and distributed, as shown in Figure 6. Each topology design is then further classified based on the network scale. Different topological designs are considered in the existing literature based on the application area and its requirements and are discussed below. In general, the existing Terahertz MAC protocols are characterized and summarized in Table XI.

TABLE XI: Characterization of existing Terahertz MAC protocols.

Year	Paper	Band	Network type	Network scale	Topology	Simulator	Simulation parameters	Analytical Model	Tx/Rx initiated communication	Modulation Scheme	Channel access method	Antenna	Complexity
2011	[148]	THz bands	Nanonetworks	Nano	centralized	C++	delay, throughput, performance analysis based on distance, propagation time, packet lifetime	✓	Transmitter initiated	-	-	nano	-
2012	[149]	0.1 - 10 THz	Nanonetworks	Nano	distributed	custom	Energy consumption, Delay, Throughput	✓	Transmitter initiated	RD-TS-OOK	TDMA	nano	-
	[150]	THz bands	Nanonetworks	Nano	clustered	No	X	X	Transmitter initiated	-	TDMA	nano	-
2013	[151]	0.1 - 10 THz	Wireless Nanosensor Networks	Nano	Centralized	custom	Throughput, optimal channel access, network lifetime, critical transmission ratio	✓	Transmitter initiated	pulse based,TS-OOK	TDMA	nano	-
	[152]	0.1 - 10 THz	Terahertz Wireless Personal Area Networks	Macro	Distributed	OPNet	data trasmission rate, avg access delay, time for transmitting frames, access success rate	X	Transmitter initiated		Hybrid	-	-
	[153]	THz bands	Nanonetworks	Nano	Distributed	NanoSim - NS3	packet loss ratio, physical transmission		Transmitter initiated	OOK	Random	nano	-
	[154]	0.1 - 10 THz	Terahertz Communication Network	Macro	Distributed		-	-	Transmitter initiated	-	Hybrid	-	-
2014	[155]	0.1 - 10 THz	Terahertz networks	Macro	Distributed	custom	Data rate, throughput	✓	Transmitter initiated	TS-OOK	TDMA	directional	-
	[156]	THz bands	Nanonetworks	Nano	Distributed	Matlab	energy efficiency, harvest rate, packet balance	✓	Receiver initiated	OOK	TDMA	nano	-
	[157]	THz bands	Wireless Nanosensor Networks	Nano	Distributed	custom	SNR, BER, capacity	X	Transmitter initiated	pulse based	FTDMA	-	-
	[158]	0.1 - 10 THz	Nanonetworks	Nano	Distributed	NanoSim - NS3	Prob collision, RTR, fairness,	X	receiver initiated	OOK	TDMA	nano	-
2015	[132]	0.1 - 10 THz	Nano Networks	Nano	Distributed	NanoSim - NS3	Delay, energy consumption, utilization capacity	X	Receiver initiated	Pulse based modulation	TDMA	nano	-
	[159]	1.04 THz	Terahertz Communication Networks	Macro, Nano	Distributed	NS3	Delay, throughput, Packet delivery ratio	✓	Receiver initiated	PSK, TS-OOK	CSMA	omni and directional	-
	[160]	0.1 - 10 THz	Nano Networks	Nano	Distributed	custom	Failure probability, normalized energy per bot, number of retransmissions	✓	Transmitter initiated	-	TDMA	nano	-
	[162]	THz bands	Wireless Nanosensor Networks	Nano	Centralized	custom	Energy consumption, Delay, Throughput	X	Transmitter initiated	OOK	TDMA	nano	-
2016	[161]	0.1 - 10 THz	Nanonetworks	Nano	Distributed	COMSOL multiphysics	BER, PER, enerhgy consumption, latency, throughput	✓	Transmitter initiated	OOK	-	nano	-
	[163]	0.1 - 10 THz	Internet of Nano Things	Nano	Distributed	custom	delivery ration, debt, throughput	✓	Transmitter initiated	-	CSMA	nano-antenna	-
	[164]	2.4 GHz, 0.1-10 Thz	Terahertz Communication Networks	Macro	Distributed	custom	packet delay, throughput, failure probability,	✓	Transmitter initiated	-	Random, multiple radios	omni and directional	-
	[165]	0.1 - 10 THz	Wireless Nanosensor Networks	Nano	Distributed	Matlab	delay, throughput, collision probability	✓	Transmitter initiated	TS-OOK	TDMA	nano	-
	[146]	100 GHz	Nanonetworks	Nano	distributed	Any-Logic platform	Coverage, Packet Transmission rate, classification time, collision	X	Transmitter initiated	OOK	-	nano	$O(x)$
	[166]	0.1 - 10 THz	Wireless Nanosensor Networks	Nano	Distributed	COMSOL multiphysics	link efficiency, optimal packet length with distance	X	Transmitter initiated	OOK	-	nano-antenna	-
	[167]	THz bands	Wireless Nanosensor Networks	Nano	Distributed	Matlab	collision probability, energy consumption, transmission distance		Transmitter initiated	OOK	-	nano	-
	[101]	1-2 THz	Nanonetworks	Nano	Distributed	custom	Throughput, Transmission probability	✓	Transmitter initiated	OOK	FTDMA	nano-antenna	-
	[168]	0.1 - 10 THz	Terahertz Communication networks	Macro	distributed	-	-	-	Transmitter initiated	-	Hybrid	-	-
2017	[81]	340 GHz	Terahertz Wireless Personal Area Networks	Macro	Distributed	OPNet	delay,throughput, success rate, buffer overflow rate	✓	Transmitter initiated	-	Hybrid	omni	-
	[169]	0.06 - 10 THz	Terahertz Communication Networks	Macro	Centralized	custom	Throughput, Data rate, Delay, and outage probability	✓	Transmitter initiated	Pulse waveform modulation	Scheduled, multiple radios	omni and directional	-
	[170]	240 GHz	Terahertz networks	Macro		Matlab	probability of successful frame reception, goodput Gbps, percentage of lost headers, ACK frame size, energy per bit	X	Transmitter initiated	PSSS, OOK, PAM-16	-	-	-
	[171]	2.4 GHz, 0.1-10 Thz	Terahertz Communication Networks	Macro	Distributed	Monte Carlo	Delay, Throughput, outage probability	✓	Transmitter initiated	Pulse based communication	Random, multiple radios	omni and directional	-
	[172]	2.4 GHz, 0.1-10 Thz	Nanonetworks	Nano	Distributed	NS3	Throughput	X	Transmitter initiated	-	Random, mulitple radios	omni and directional	-
	[173]	100 GHz	Wireless Nanosensor Networks	Nano	Distributed	NS3	Bandwidth efficiency, pulse drop ratio, packet deliver ratio, fairness, energy consumption	X	Transmitter initiated	OOK	TDMA	nano	$O(N')$
	[174]	1.0345 THz	Terahertz Communication Networks	Macro	Distributed	custom	Throughout, optimal distance	✓	Receiver initiated	OOK	CSMA	directional antenna	-
	[86]	73 GHz and 0.86 THz	Vehicular Network	Macro	Distributed	custom	data transfer	✓	Transmitter initiated	-	Scheduled, multiple radios	directional	$O(V^k)$
	[175]	THz bands	Wireless Nanosensor Networks	Nano	clustering	NS3	pkt loss ratio, consumed energy, scalability		Transmitter initiated	-	TDMA	-	-
2018	[88]	0.1 - 10 THz	Vehicular Network	Macro	Distributed	custom	Channel capacity, PSD, number of links	X	Transmitter initiated	-	-	omni	-
	[176]	0.1 - 10 THz	THz Mobile Heterogeneous Network	Macro	Distributed	custom	Uniformity, Randomness, Hamming Correlation, throughput, BER	X	Transmitter initiated		FTDMA	-	-
	[117]	mmWave, 0.1 - 10 THz	Vehicular Network	Macro	Distributed	custom	data transmission rate	X	Transmitter initiated	-	Scheduled, multiple radios	directional	-
	[177]	0.1 - 10 THz	Nano Networks	Nano	Distributed	custom	Throughput capacity, interference power	✓	Transmitter initiated	Pulse based modulation (OOK)	TDMA	nano-antenna	-
	[178]	0.1 - 10 THz	Wireless Nanosensor Networks	Nano	Centralized	custom	slot assignment rate, energy consumption	X	Transmitter initiated	TS-OOK	CSMA	nano-antenna	-
	[179]	2.3 THz	Terahertz Communication Networks	Macro, Nano	Centralized	custom	Antenna directivity, antenna controller overhead	X	Transmitter initiated	DAMC	-	omni and directional	-

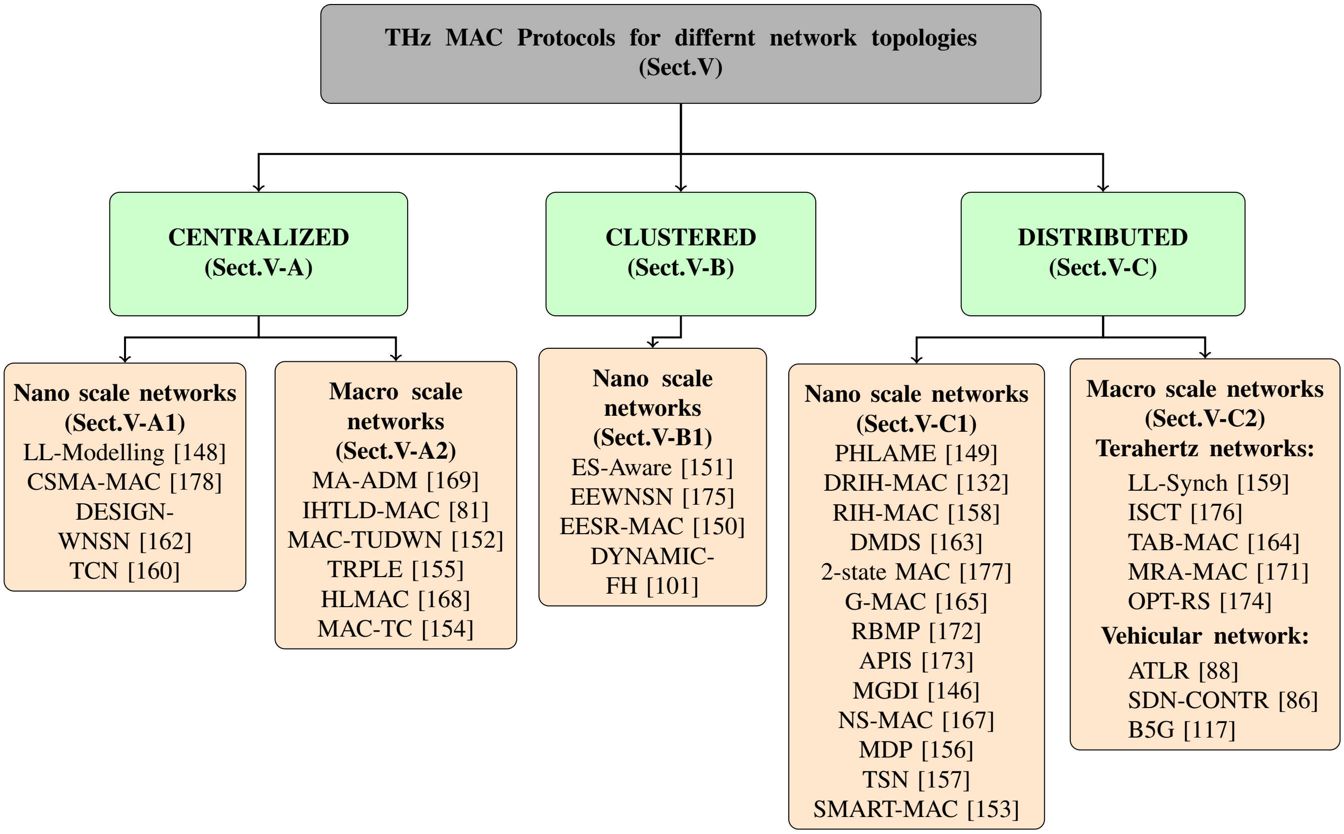


Fig. 6: MAC layer classification based on network topologies.

A. Terahertz MAC protocols for Centralized networks

The centralized architecture is mainly followed in nanoscale networks due to its limited coverage area and application in body area networks [148], [162], [178], [179]. However, the design is also followed in the picocell network for ultra high-speed wireless links in [169].

1) Nano scale networks: The nano networks include several nanodevices which work together to perform certain tasks. It has its application areas in in-body nanonetworks, industrial application, chemical detection, and disease detection. Most of the existing works in in-body networks use the centralized architecture, due to the limited capacity and capability of nanodevices. Certainly, the nano controllers are the devices assumed to be capable of performing heavy computation and transmission tasks, whereas the nanodevices are just able to perform a few simple computations or transmission tasks. They also require energy harvesting mechanism to store the energy first and then to use it. These nanodevices in turn send their data to the nano controller which is responsible to send the data to the application controller or the Internet via a gateway device. A general figure for such architecture is shown in Figure 7.

A Zigbee based channel access mechanism for MAC protocol is proposed in [178] for nanosensor networks. A centralized approach is followed by using nanosensor nodes, nano mucro interfaces and gateway nodes. Nano nodes can be implanted in a specific area to detect problems like defects or pollution, where each nano node can perform computational tasks with limited memory and transmits small data over a short range to the nano-controller. The gateway can collect the information and send to the Internet. This approach can also be used in a body area network to detect diseases or unusual behavior. A single hop delay-throughput performance is measured in [148] for the bio-nano communication network. In [148], bacteria packets travel towards the nano-gateways following the attractant particles emitted by the conjugate nano-gateway site. The distance-based delay and throughput are analyzed. Each gateway is then further connected to the nanodevice. Another nanosensor network for in-body networks is proposed in [162] to detect diseases. Several nanoscale devices are used in a body which can communicate a large amount of data to nano-controllers which are responsible to process and transfer the data to the Internet through a gateway device, as shown in Figure 7. Another work discussing the scheduled channel access for nano communication network using a centralized approach is presented in [160].

2) Macro scale networks: Besides, the nanonetworks, the centralized architecture is also used for the Terahertz communication at Picocell networks, where the coverage is assumed to be shorter than the macroscale. In [169], a centralized network with Terahertz links is presented which consists of an AP and multiple nodes, where the AP coordinates and schedules the transmissions among the nodes and is able to communicate directly to each node. The interesting issue in such networks will be synchronization among the nodes, where each node using a directional antenna needs to point towards

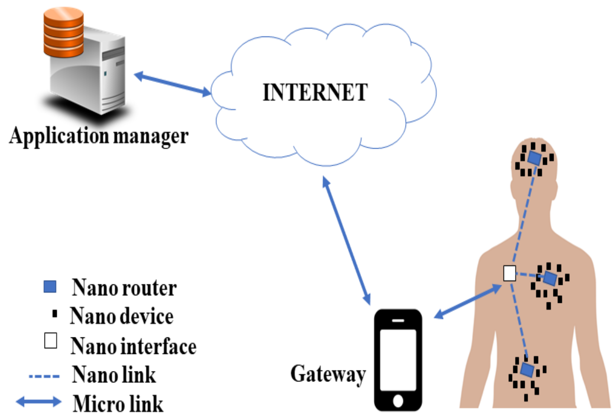


Fig. 7: Nano body communication network.

an AP and search it, which also increase the interference or collisions from the nearby nodes. In [169], directional antennas are used for both the cell discovery and the data transmissions without creating disparity problem [247]. The directional narrow beam from the AP is configured into a rectangular shape angular slot. The problem arises when the directional beams from the AP and the receiving node have to be well aligned. In this work, the AP is assumed to be equipped with directional antennas whereas the other nodes are using the omnidirectional antennas and are assumed to use the directional antennas after the establishment of initial discovery which can incur switching delays. A bloackage scenario is also discussed in [169]. High throughput and low delay access MAC protocol for wireless personal area network are discussed in [81], [152], [154], [168]. A piconet coordinator is assumed to provide time synchronization information to nearby devices and handles the scheduling and access control. The PNC also provides information like channel access, slot assignment, and synchronization to its nearby device. A MAC design for macro scale communication at 100 Gbps is discussed in [155] which utilize the pulse level beam switching with energy control. In this work, an indoor picocell is considered in which AP communication with a group of users using LOS and directed non-LOS to address neighbor discovery, transmission scheduling, and energy control.

B. Terahertz MAC protocols for Clustered networks

As a short-range communication usually between nanosensors which incurs reduced path loss, the clustered architecture is mainly used in only nano-networks so far, which is discussed below:

1) Nano scale networks: Hierarchical network architecture is mainly followed in nanonetworks, due to the limitations of nanosensor nodes in terms of computation capacity and available energy. In hierarchical architecture, the network is mainly partitioned in a set of clusters where each cluster is locally coordinated by a nano controller. The nano controller is a device which has more capabilities of processing complex tasks and has high energy availability. Since nanosensor nodes are not capable of processing and handling complex tasks, these tasks are pushed towards the nano-controllers which then coordinate their tasks in an efficient manner. A similar architecture is followed by in [151]. The nanosensor nodes are battery limited devices, which only can store enough energy to perform few simple tasks and therefore require energy harvesting mechanism to generate and utilize the energy in a balanced way, as nodes can either remain idle to generate energy or perform communication tasks. This tradeoff requires some efficient mechanism to reduce communication delay while maintaining the energy usage status. In [151], the energy consumption rate is analyzed for capacity optimal bandwidth adaptive communication. In this scheme, the transmission and harvesting slots are assigned among the different nanosensors within each cluster in a way that the harvested and consumed energy are balanced among the nanosensors. A cluster-based nano-network is also discussed for dense networks in [150], [175], in which inter and intracluster communications are carried out to reach gateway node. For plant communication, a clustered based architecture is followed in [101] which addresses the frequency selection problem in Terahertz band which are considered as frequency selective bands. The nanodevice clusters are used to monitor the chemical reaction in plants which schedules the transmission among themselves and transmit the data to microdevices which then transmit to the Internet via a gateway.

C. Terahertz MAC protocols for Distributed networks

Depends upon the application requirements, the devices both in nano and macro scale can perform communication task in a distributed manner. The details of the works following the distributed management are as follows,

1) Nano scale networks: The nanodevices are capable to perform different tasks in a distributed manner for different applications like intra body health monitoring, chemical detection, industry and military applications, and drug delivery system. In [149], a distributed architecture is followed in which the transmitter and the receiver jointly select the Physical layer parameters and channel coding scheme to maximize the decoding probability and minimize the multi-user interference. The work is aimed at the application which requires a distributed communication operations. To generate more scalable solutions, the work in [132], [158], discusses a distributed receiver initiated handshaking mechanism to minimize energy utilization, accessing medium, efficient scheduling and coordination. A fully distributed nano-network for bufferless nanodevices is discussed in [163]. The distributed scheduling mechanism is proposed in which every node takes decision locally based on its incoming traffic and channel sensing results. The proposed protocol is shown to be reliable in data delivery with optimal throughput and addresses the fundamental challenge of limited memory nanodevices. A multihop approach for nano communication network analyzing the tradeoff between the energy harvesting and data transmission is discussed in [177]. Another energy aware grid-based MAC protocol addressing the scheduling and relaying for nano communication is presented in [165]. An idea of combined usage of the omni/-directional antenna is presented in [172]. The work is addressing the facing problem, in which nanosensors which are in direct range can be communicated using an omnidirectional antenna, whereas to communicate with other message stations in presence of obstacles, relay nodes are used with directional antennas. The work is shown as to improve the throughput, however, due to the limited capacity of nano nodes, it can increase the message and energy overhead.

For scheduling the channel access between the nano sink and sensor nodes for an event based wireless nanosensor network is proposed in [173] as an adaptive pulse interval scheduling scheme. The proposed scheme schedules the arrival pattern of pulses transmitted by a nano sink based in the access bandwidth. It uses a distributed algorithm run by nano sinks in a small scale single hop network to detect the bursty events. It adapts to the access bandwidth and neighbor degree to schedule the pulses transmitted by a nano sink to the Internet of Things gateway node.

A flooding scheme for high node density ad-hoc nanonetworks is proposed in [146], in which a message from the external entity is broadcast in a nano-network with coverage in terms of percentage of receiver nodes. An internal node can also propagate the data towards the external entity of a gateway which is movable. An analysis of energy aware and receiver initiated MAC protocol is presented with a distributed environment in [167] in terms of transmission distance, collision probability, and energy consumption. An ad-hoc nano-network is discussed in [156], in which receiver initiated MAC protocol is optimized based on the energy consumption. A frequency hopping scheme is modeled in [157] to overcome attenuation and noise issue using multiple channels between two nanosensor nodes. A nanosensor network for health monitoring is used in [153] which uses the multihop links to transmit information to nano interfaces within an artery. In [153], a nano sim simulator is also presented.

2) Macro scale networks: Besides nanoscale networks, the Terahertz band promises the ultra high-speed wireless links for networks with coverage of more than 1 m to a km. However, at higher coverage areas, the free space path loss affects the throughput and results in reduced coverage areas. To extend the coverage and minimize the path losses the directional antennas have been encouraged to use. The use of directional antennas limits the flexibility to transfer, schedule and directionality of a transmitter and receiver. At higher ranges, the works following a distributed environment are discussed below.

Terahertz Communication Network: The Terahertz communication network with high-speed Terahertz wireless link is presented in [159] for macro scale communication. It addresses the problem of handshaking with antenna speed considerations as an important factor to consider while designing a MAC protocol. The number of nodes is placed within an area of 10 m circular area in a distributed manner. The mobile heterogeneous architecture is presented in [117], [176] for ad-hoc connectivity and WLAN to provide high-speed Terahertz links and broadband access using access points. With the inclusion of directional antennas for higher coverage new challenges appear like seamless communication while maintaining the throughput and connectivity. In [176], an intelligent and secure spectrum control strategy is proposed for indoor network model with different access subnets and anti-jamming strategy with adaptive frequency slot number selection.

A distributed Terahertz communication network with directional and omnidirectional antennas is proposed in [164], in which the anchor nodes are used with regular nodes. The anchor nodes are assumed to know their location in advance and regular nodes are equipped with beamforming antenna arrays. A similar work with Omni and directional antenna is used in [171] where control signals are used for beam alignment using 2.4 GHz link and for data transfer Terahertz links are used. Although, using 2.4 GHz band for control signalling reduce the handshaking delay between the nodes, it limits the coverage area and can leave isolated areas in a network, which further requires multihop strategies to increase the reachability of the network. A relaying strategy is proposed in [174] in a network with randomly distributed nodes. However, only few dedicated relays are used to transfer data and nodes are assumed as switching between the transmission and receiving modes, which can increase the delays. Further, due to the use of directional antennas, the initial synchronization is required which is not focussed in the paper.

Vehicular Network: A software-defined network (SDN) based vehicular network is considered with distance dependent spectrum switching, where mmWave and Terahertz band are used alternatively based on the data transfer usage [117]. It is argued that the universal coverage is not possible by using just Terahertz band and therefore a network architecture is proposed, which uses the microwave, mmWave, and Terahertz bands together to achieve the design goal of coverage and channel access period for each wireless technology used with the assurance of error recovery. Although, it can extend the coverage, the switching delay increases as nodes number increases and traffic between nodes increases. An SDN based architecture for vehicles is presented in [86], which discusses the handoff and MAC protocol to dynamically switch between the mmWave and Terahertz band for high bandwidth data transfer operations. An optimal procedure at the SDN controller is also proposed for scheduling multiple vehicles for access to a small cell using a greedy scheduling strategy. It is shown that the transfer of 100 Terabits is possible on a single journey by controlling the velocity of vehicles. Although, performance is shown to be improved the message overhead and switching delays are high. Further, the synchronization is not focussed for multiple vehicles. Another relay algorithm for autonomous vehicular communication using Terahertz band links to overcome short range and unstable links is presented in [88]. In [88], a multihop architecture is used while addressing the interference problem between multiple self-driving vehicles.

D. Summary and discussion

The network topology is an important aspect to consider for Terahertz MAC protocol for which the application scenario, target users, antenna directionality and coverage should be considered. Each application has different topology requirements. Typically, for Terahertz communication networks, the topology must account for many practical concerns like scalability, reconfigurability, LOS connectivity due to antenna directionality requirement, fault tolerance, and cost-performance index. An indoor scenario includes the TLAN and TPAN applications for home or office scenario. The distance between the APs and users with limited mobility support should be covered in the MAC protocol design while providing a fault-free and seamless communication. The distributed topology for Terahertz MAC protocol must accommodate the dynamic nature of the network while covering the whole network. The Terahertz Datacentre network, for example, requires top of rack nodes to transmit data among different racks. The short range limits the nodes connectivity, therefore, novel mechanism are required to approach far distance nodes within a Data Centre. Relays or reflectors can be used for this purpose. In nano-communication networks, the nodes are placed at a very small distance from each other. Due to this near node placement, the path loss is less effective in a nano communication network. The omnidirectional antennas can be used in nano-network due to the near placement of nodes. The Omni-directional usage of such scenarios requires a MAC protocol to include collision avoidance methods with efficient sensing mechanism to detect the interference. The path loss increases with increase in the distance, therefore to enhance the communication range directional antennas are required. The antenna directionality requirement clearly impacts on link establishment and channel access mechanisms. The transmission schedule can be easily managed in a centralized scenario, in which a central controller is responsible for overall transmission schedules. However, in distributed networks, scheduling the transmissions and resources is a challenge, especially when directional antennas are in use over the short distance.

VI. Channel Access Mechanism for Terahertz Communications

In this section, the existing channel access mechanisms for Terahertz band communications are presented and classified. They are classified as Random, Scheduled and Hybrid channel access mechanisms as shown in Figure 8 and discussed below.

A. Nano Scale Networks

As shown in Figure 8, the channel access mechanism in nanoscale Terahertz networks are classified here as a Random and Scheduled channel access mechanisms. In Nanoscale networks, the network size is considerably smaller than the macro scale networks. The nanoantenna which is of very small size is used which are generally considered as omnidirectional due to small coverage. The smaller coverage area also causes less path loss than the distances for more than 1 meter. In this section, different channel access mechanisms are discussed.

1) Random channel access: In Random access mechanisms, different nodes content for the channel access and acquire the medium in a random manner.

CSMA based: In [178], a slotted CSMA/CA channel access mechanism (CSMA-MAC) is adapted for event-driven nano applications. It fairly provides a chance for each node to communicate with a reasonable usage of the available energy. The proposed CSMA-MAC protocol follows Zigbee's MAC protocol with variable superframe duration and packet sizes. Three phases are presented as association, data transfer, and disassociation. Initially, a nanosensor node scans a channel to send the request to the nano-coordinator which responds the association requests by appending nano-sensors address in the beacon frame. Two types of data transfer are used as direct and indirect. In direct method, a nano sensor node finds the beacon to synchronize to the super-frame and transmits its data using CSMA/CA. In indirect data transfer the nano sensor node periodically listens to the beacon and transmits a MAC command request using slotted CSMA/CA. While in disassociation phase a nano sensor just withdraws is association with its nano coordinator. It is shown in the paper that the super-frame duration and packet sizes are predominant factors for controlling slotted CSMA/CA-based MAC protocols.

A fully distributed computational light scheduling/MAC protocol is presented in [163] which considers the limited memory of nano nodes and allows every nano node to locally make optimal transmission decisions based on its incoming traffic rate, virtual debts, and channel sensing results. Two scheduling algorithms for bufferless nanodevices are proposed with slotted CSMA approach in which time is slotted with size T. The T is assumed to be large enough due to the energy constraint and to allow sensors to recharge itself and transmit packets. The first scheduling algorithm is distributed maximum debt scheduling algorithm (DMDS), in which at the beginning of each timeslot t, each sensor i determines the length of its channel sensing period τ_i by independently generating an exponentially distributed random variable. However, if no transmissions are detected during that period, the sensor i transmits its packet until the end of the timeslot. In another algorithm $DMDS - \alpha$, the sensors with higher priority are assigned with a larger value of α and the devices with higher α values use small sensing times which leads to a higher chance to transmit.

CSMA with multiple radios: A similar approach based on the work in [164] is presented in [172] for nanonetworks using multiple radios as 2.4 GHz for control signal transmission and Terahertz for data transmission. The scheme as an extension considers the obstacles and relaying and consists of two phases as a control message exchange to solve antenna facing problem in phase 1 and phase 2 is the data transmission phase. The channel is accessed in a random manner for both control and data packet transmission.

Random Access based: A nanonetworks simulator and a MAC protocol are presented in [153] which are based on ALOHA protocol. In [153], a node performs initial handshaking to know about one-hop neighbors and transmits a packet in a random way to a randomly selected neighbor. Two MAC protocols are proposed as Transparent and Smart. In Transparent MAC the packets can directly be transferred from the Network to the Physical layer for transmission whereas, in Smart MAC, the packets will be enqueued at MAC before been delivered to the Physical layer. When there will be no neighbor to transmit the node will apply a random backoff delay prior to start again another handshake mechanism. Due

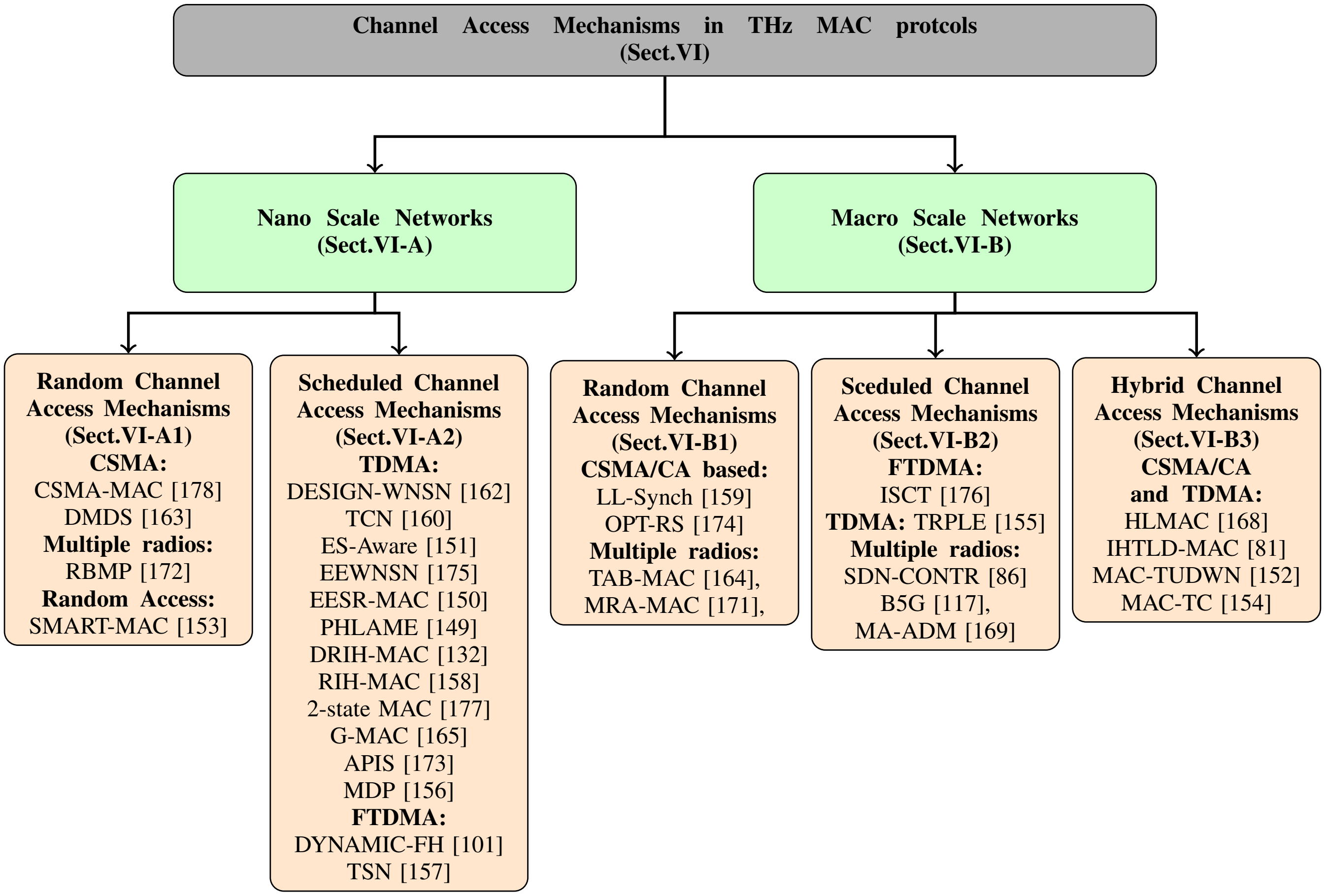


Fig. 8: Terahertz Channel Access Mechanisms classification.

to the presence of multiple enqueued packets at Physical layer, each new transmission is scheduled after a specific time interval which is computed through the same backoff mechanism which can reduce the probability of physical collisions. The receiving node verifies when there are any physical collisions. The collisions can occur when there is a higher number of nodes available, which is not addressed and the retransmission mechanism is not discussed. Another simulator which discusses the ALOHA protocols is presented in [248] as TeraSim for both nano and macro scale networks.

2) Scheduled channel access: TDMA based: A TDMA based approach is used in [162] in which a nano-router makes the decision for a nanosensor node to transmit the sensing data. The given framework follows a TDMA based scheduling using DL, UL, Multihop (MH) and Random Access (RA) phases. To avoid collisions in simultaneous transmissions a simple MAC is proposed with a scheduling scheme based on TDMA for the synchronization among the nano routers and sensors. A similar TDMA based approach is also used in [249].

A timing channel based MAC protocol (TCN) is proposed in [160] in which a timing channel is used. The timing channels are the logical channels in which the information is encoded in the silence period of two subsequent events. The network consists of nano nodes and gateways nodes where the nano nodes can only listen to the transmission of the gateway node and not of the other nano nodes due to limited receiver sensibility. The gateways node periodically broadcast a beacon containing a seed value to synchronize with other nodes and sends ACK for the packets received. The scheduling of beacons is important as part of the information is sent by exploiting the time instants in which individual transmissions occur. A packet is scheduled multiple times, however, when a gateway receives a packet correctly, it sends an ACK to the nano node which deletes the rest of the schedules for that packet.

An energy/spectrum-aware MAC (ES-Aware) protocol with an objective to achieve fair, throughput and lifetime optimal channel access by jointly optimizing the energy harvesting and consumption processes in nanosensors is proposed in [151]. In [151], the nano controllers are responsible to regulate the access to the channel of the nanosensors by using a TDMA approach. The nano controllers consider the data requirements and energy constraints of the different nano-sensors willing to communicate. The TDMA based scheduling schemes are given for two physical layers, a pulse based scheme and a bandwidth-adaptive capacity optimal physical layer. To balance the trade-off between the throughput and a lifetime an optimal scheduling strategy is proposed which aims to provide an optimal transmission order for the nano-sensors to maximize the throughput while maintaining the infinite network lifetime. A critical packet transmission ratio (CTR) is derived, which is the maximum allowable ratio between the transmission time and the energy harvesting time, based on which a novel symbol compression scheduling algorithm is proposed which is based on pulse-based physical layer technique. This algorithm utilizes the inter-symbol spacing for the pulse based physical layer to allow a large number of nanosensors to transmits the packets in parallel without introducing any collisions. Further, a packet level timeline scheduling algorithm based on theoretical bandwidth adaptive capacity optimal physical layer is also proposed to achieve balanced single-user throughput with infinite network lifetime. In this scheme, the nano-sensors are dynamically assigned with variable length transmission time slots, which depends upon the amount of data to be transmitted, the distance and channel conditions between nanosensors/controller, and the energy requirements. The energy harvesting is performed in both transmission and sleeping timeslots to replenish batteries. The main objective here is to optimally assign the transmission and sleeping timeslots to balance the harvested energy. The time frame structure considers the three fixed length sub-frames as, DL, UL, and RA. In DL, the nano controller broadcasts its information to nanosensors and the wake-up signals. In UL, the nano-sensors sends data to the controllers assuming each nanosensors have got their timeslots in DL phase. In RA, the nano-sensors can contact nano controllers for the next frame or can exchange information with other nanosensors in an ad-hoc manner.

In ES-Aware MAC [151], the nano-sensors communicate with the controller in a single hop manner. The TDMA based scheduling for multihop WNSN MAC (EEWNSN) protocol is presented in [175], which takes benefits of the clustering techniques to alleviate the mobility effects and transmission collision. The nano nodes send their packets to the nano routers based on the TDMA scheduling which then transferred to the nano-micro interface by aggregating the data. After selecting a nano router, the nano router allocates the specific time slots to the nano node according to a systematic allocation pattern by using a slot of time as,

$$slotTime = WLT_p + (L-1)T_i \tag{9}$$

where L is the packet length, W is a coding weight symbol (the percentage of logical 1), T_p and T_i are the pulse duration and pulse transmission interval. The timeslots are considered as fixed and due to the transmission to the closest nano router, the energy consumption can be decreased which can prolong the network lifetime.

Another work following a cluster-based architecture for nanonetworks (EESR-MAC) is given in [150], in which initially a master node is selected which then allocates the transmission schedules between the inter/intra-cluster using TDMA approach. The master nodes roles are periodically changed among different nodes to avoid long distance transmissions and to save energy.

A physical layer aware MAC protocol (PHLAME) for nanonetworks is presented in [149], in which a new modulation and channel access mechanism is proposed as Rate Division Time-Spread On-Off Keying (RD TS-OOK) for nanodevices. The RD TS-OOK is based on the asynchronous exchange of femtosecond long pulses, transmitted following an on-off keying modulation spread over time. The works in [226], [250] presents the simplified mechanism for this type of modulation and channel access mechanism. The communication mechanism works as a logical 1 is transmitted by using a femtosecond long pulse and a logical 0 is transmitted as silence where OOK modulation is chosen against the Pulse Amplitude Modulation (PAM) or Pulse Position Modulation (PPM) due to the molecular absorption. The time between the symbols T_s is longer than the pulse duration T_p and is fixed for the duration of the packet, as shown in Figure 9. The symbols are spread over time rather than transmitting as a burst due to the similarities/limitations to Impulse Radio Ultra Wide Band (IR-UWB) systems [251]. After determining the time between the symbols T_s and the detection of the transmitter pulses, the nanodevice does not need to continuously sense for the channel. The receiver during this time can proceed with other transmissions or remains inactive. To minimize the probability of multiple sequential symbol collisions in a packet, the time between the symbol T_s and symbol rate $\beta = T_s/T_p$ are chosen differently for different nanodevices for different packets. When all nanodevices are transmitting at the same symbol rate, a catastrophic collision can occur which can cause collision for all symbols in a packet. The orthogonal time hopping sequences can be used to avoid this condition [251].

The symbol collisions are unlikely to occur due to a very short length of the transmitted symbols T_p and because the time between symbols $T-S$ is much longer than the symbol duration T_p. In addition, not all types of collisions are harmful as RD TS-OOK provides orthogonal channels to nanodevices. Therefore, by allowing different nanodevices to transmit at different symbol rates, collision in a given symbol does not lead to multiple consecutive collisions in the same packet.

As an example, an RD TS-OOK illustration is shown in Figure 9 in which two nanodevices transmit to a common receiver with different initial transmission times as τ^1 and τ^2. A short pulse represents a logical 1 and a silence represents a logical 0. The device 1 plot shown a sequence "10100" and device 2 plot shows a sequence of "11100".

Another work on RD TS-OOK is presented in [132], [158] for centralized (as RIH-MAC) and distributed (as DRIH-MAC) nano networks including channel access communication scheduling. In [158] a scheduling mechanism is proposed using a probabilistic method whereas in [132] an edge coloring problem is modeled for the distributed nanonetworks. The edge coloring problem is considerably challenging in ad-hoc based networks due to the absence of a centralized coordinator. In DRIH-MAC [132], the medium access control relies on the receiver initiated and distributed scheduling for nano nodes in which each pair of nano node within a communication range will have an edge with different color. The main objective is to determine a minimum number of colors required to color the edges of a graph i.e., two edges incident on a common node do not have the same color, where each color represents a timeslot in which a nano node can communicate with one o its neighbors. The edge coloring problem is an NP-complete problem where the minimum number of colors required to

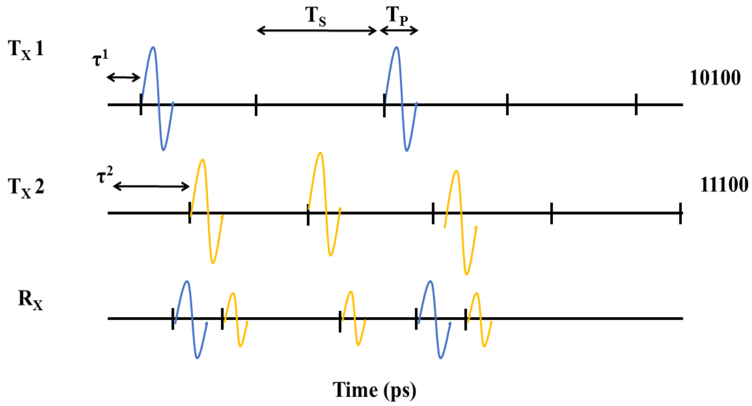


Fig. 9: An example of Rate Division Time-Spread channel access mechanism used for pulse based communication in Terhertz Nano communication networks [149].

edge color a graph is either its maximum degree δ or $\delta+1$. The given method runs in $O(loglogn)$ rounds, where n represents the number of nodes in a graph.

The graph is colored with $(1 + \epsilon)$ for $\epsilon < 1$, in which each edge $w = (u, v)$ between two arbitrary nano nodes u and v are initially given a palette of $(1 + \epsilon)\delta$ colors, locally based on received request packets. The new nano node which has no color assigned for its edges will transmit zero in the color field of its request to receive the packet. The coloring process runs in rounds, wherein each round each uncolored edge independently picks a color uniformly if no other edges of nodes are using that color. The palettes are updated at the end of each round and successfully assigned colors will be deleted from the current palette. The duration of each round is equal to the duration of the request-to-receive packet to announce selected color and receiving selected colors from the neighbors. At most $(\delta+1)$ timeslots are needed at least to reach an agreement/disagreement on color with all neighbors through RTR packet assuming no RTR packet failure. These works are shown to be efficient, however, the limited memory capacity of nano nodes is not considered in these works.

In [177], a two state MAC (2-state MAC) is proposed and an RD TS-OOK based channel access scheme is assumed while achieving optimal throughput in two different phases of nano nodes as harvesting only and harvesting transmit/receive. A Time-spread OOK based approach for grid-based nano-network is proposed in [165], as GMAC. In this communication scheme, the relay nodes are the next hop receivers and different transmitting nodes transmit their packet in a distributed manner on a symbol basis based on the diversity of the inter-symbol spacing of the nanosensors. The nodes can replenish their batteries both in sleeping and transmission modes. Two scenarios are discussed for the grid-based channel access. First, when the transmission ranges overlap the transmission is arranged according to the receiver's location. Second, when a receiver of two transmitters is in the same receiver grid, it can cause a collision. To avoid the collision, one of the colliding nodes will change its receiver to another neighbor receiver.

A distributed and adaptive pulse interval scheduling scheme (APIS) is proposed in [173] for bursty events in nanonetworks. This scheme schedules the arrival pattern of pulses transmitted by the nano sinks based on the access bandwidth. It has two scheduling steps such as transmission shifting and interleaving which are based on information collected from short channel sensing. When nano sinks start transmitting pulses, they are first shifted in sequence within interval of I_S. After which multi-user transmissions are interleaved by separating pulses with the interval that evenly shares the bandwidth among nano sinks and in response the pulses arrives at the gateway in an ideal pattern. Other works discussing the RD TS-OOK pulse based channel access are [153], [156].

Frequency and Time Division Multiple Access (FTDMA) based: In [101], dynamic frequency selection strategy (DYNAMIC-FH) is presented which uses FTDMA. An FT-DMA is initially considered and for a higher number of nano nodes multi-frequency is proposed with timeslots scheduling for a different number of users. Each node is assigned with different timeslots to avoid collisions in case of higher packet sizes (like multimedia traffic). The main objective of the frequency selection strategies is to minimize energy consumption and increase the channel capacity. In [157], also a Markov Decision Process based frequency hopping scheme (TSN) is proposed in which entire band is divided into K frequency sub-channels where the aim is to determine for each timeslot the sub channels to be used.

B. Macro Scale Networks

Figure 8, shows the classification of Terahertz band channel access mechanishms for Terahertz macroscale networks. The summary and details of each category are discussed below.

1) Random channel access: In random channel access mechanisms, a node access the channel in a random way. The examples of such mechanisms are ALOHA and CSMA techniques. Ideally, for the random mechanism, a node should sense a medium before accessing it. Since there is a large bandwidth available, the chances of collision occurrence are less. Therefore, the random mechanism is also being used followed by message confirmation strategies. However, the idea of collision and interference cannot be ignored completely as there could be many users accessing the same medium and might be transferring a large volume of data which could potentially generate collisions among the two nodes. The collisions avoidance schemes and recovery from collision schemes are very essential. The delay, on the other hand, can be minimized due to random access, however, further research is required for the collisions and delay parameters trade-off.

CSMA based: In [159], A MAC protocol is proposed to reduce the message overhead while achieving handshake between the two nodes (LL-Synch). The two-way handshake is reduced to one-way handshake and to increase the channel utilization the sliding window flow control concept is used in which multiple packets can be sent with a sequence number. The clear to send (CTS) packet is used followed by a data and an ACK packet. The node in receiving mode is intended to send a CTS packet to the receiver, upon receiving CTS packet, the node in the transmission mode can send data. The receiver can then send an ACK message to confirm the data reception. The node in transmission mode listens for CTS packet until one is received. As the directional antennas are used, the antenna facing problem can occur, however, it is assumed that the nodes know each others position. The proposed one-way handshake is compared with altered CSMA/CA with/without a handshake. To address the antenna facing problem, the work is extended in [174] by focusing on the use of highly directional antennas to overcome high path loss. In [174], the relaying distance is studied that maximizes the throughput by considering the cross-layer effects between the channel, the antenna and the physical, link and network layers. This work also focuses on control message exchange to establish nodes association and follows the random channel access, as in [159].

CSMA with multiple radios or hybrid system: In [164], TAB-MAC scheme is presented in whcih different antennas are used for control packets exchange and data transfer. For control packets, 2.4 GHz band is used with the exchange of location information to estimate the position of other nodes, while Terahertz band is then used with directional antennas to transfer the data. In the node discovery phase, the transmitter sends an extended request to send (RTS) packet with node information (NI) about node position. The receiver on reception of RTS can send and extended CTS packet with NI which includes the receive node position. Using the node position of each other, the two nodes can compute the LOS distance and use beamforming antennas to point towards each other. The frame headers are used as in IEEE 802.11ac. In data transmission phase using Terahertz band initially a Test to Send (TTS) packet is sent by a transmitter to check the condition of a channel and that the nodes are pointing towards each other. After receiving an ACK from the receiver the data transmission can start. Although using different antennas can potentially solve the antenna facing a problem, it increases the discovery delay in phase 1, antenna switching delay and the message overhead. Another work focusing on reducing the message overhead by cutting down the CTS packet exchange using the different antennas for control packet exchange and data transmission is mention in [171] (as MRA-MAC). Instead of sending CTS packet to the transmitter, the receiver estimates the angle of arrival (AOA) and sends TTS packet to the transmitter. The transmitter can then switch and adjust its directional antenna and starts pointing towards the receiver antenna to start the data transmission. Although the message overhead is shown to be reduced, the uncertainty of packet loss during user association phase is not considered, the difference is shown in Figure 10 in which one sceheme uses 4 transmissions until antenna direction alignement and other uses two transmissions. In these works, the mainly user association and antenna directionality problems are discussed for which CSMA based approach is followed with RTS and CTS packets. For antenna direction confirmation TTS packets with acknowledgment (ACK) are used before sending of data, which also access the medium in a random way. However, the Terahertz channel mechanism which is typically TDMA is not discussed. Another problem in [171] is that after sending an RTS the receiver packet might be lost, and the node switches without the consent of the other node. In both TAB-MAC and MRA-MAC [164], [171], the channel is being accessed randomly by including a backoff time in the beginning. TO avoid collisions, these works use the CTS and RTS packets, TTS and ACK for antenna direction alignment and for data transmission they use ACK packets after the data transmissions. In both works, the collisions and multi-user interference are not considered in the algorithm, which is the main task for CSMA based channel access mechanisms.

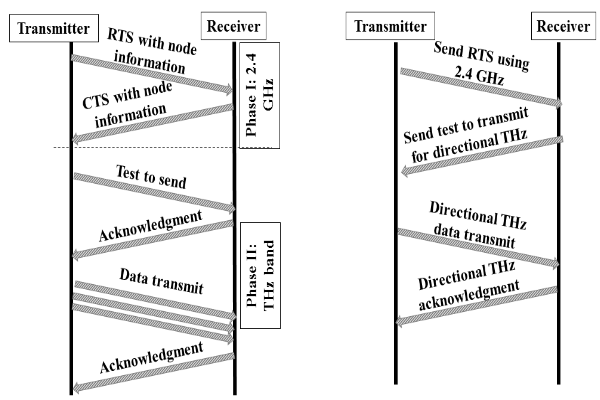


Fig. 10: Random channel access, node association with antenna direction alignment difference of TAB-MAC [164] and MRA-MAC [171] protocols.

2) Scheduled channel access: In scheduled channel access mechanisms, each node is assigned with a particular timeslot to access the channel. There are several variations in scheduled channel access which are mentioned below; like FTDMA in which frequency is divided into several sub-bands which can be assigned to different user with different timeslots; and time division multiple access (TDMA) which allows user to share the same medium by dividing the signal into different timeslots.

FTDMA: In [176], a secure and intelligent spectrum control strategy (ISCT) is proposed for a mobile heterogeneous network using Terahertz band. A control sequence is generated, which has the characteristics of adaptive frequency slot number, wide gap, and orthogonality. An FTDMA based techniques are used in which the available frequency of Terahertz band is divided into q frequency slots $f_1, f_2, ..., f_q$, wherein each time slot t_i $(i = 1, 2, ..., p)$ one of the f_m frequency can be used to transmit the information (m represents a frequency slot). The frequency used by any user in a particular time could be represented by a sequence S^k. To avoid jamming different sequence or transmission strategies are adopted by each user. For n users transmitting at the same time, the sequences used by each user must be orthogonal. The performance is shown to be improved for security and throughput, however, the unique features of Terahertz bands are not considered like path loss and noise.

TDMA: A fully directional MAC protocol for Terahertz network which relies on pulse-level beam-switching and energy control is presented in [155] (as TRPLE). The work follows the channel access scheduling than the traditional fighting-for-access. A MAC frame structure is presented in [155], which is composed of a POLL period, a Downlink (DL) period and an Uplink (UL) period. In the POLL period, the AP learns the traffic demands of the users and schedules the DL/UL transmissions. In DL and UL, each different users is assigned a separate timeslot to access the channel.

TDMA with Multiple radios: A TDMA based channel access scheme is used in [86], in which an SDN based controller (SDNC) is used to switch between mmWave and Terahertz band for vehicular communication for high bandwidth data transfer operation. An optimal procedure at the SDN controller for scheduling multiple vehicles for accessing a given small cell tower is also given using a time division approach. It is required that the SDNC schedules different vehicles at different times while considering the distance to the tower. The objective is to maximize the bits exchange between the cell tower and vehicle where the condition is to at least schedule one car in each timeslot. The greedy algorithm is proposed in which the vehicles which have already completed their communication needs are avoided. The objective is to schedule each vehicle in each timeslot, provided they have not completed their communication needs and they have not been scheduled before. For link switching, it is proposed that Terahertz band should be switched whenever the link between the vehicles and the cell tower is less than d_{th}, and to mmWave otherwise. Another work discussing the hybrid usage by switching between the mmWave, μW band, and Terahertz band is given in [117]. In this work, a higher capacity link like Terahertz band is used for data transfer and mmWave for ACK transfer. For error recovery stop and the wait is followed with data transmission using Terahertz band and ACKs using the mmWave band. However, this alternate bands usage can introduce excessive overhead, higher delay for receiving an ACK, and also introduces the beamforming overhead as the communication must be directional for the Terahertz band.

A memory assisted angular division multiplexing MAC protocol (MA-ADM) is proposed in [169]. Centralized architecture is considered in which an AP is responsible for coordinating and scheduling the transmissions to achieve fairness and efficiency. To overcome the node discovery and antenna alignment, the nodes are assumed to use omnidirectional antennas while the AP uses only the directional antenna. After the service discovery phase, the nodes can also switch to the directional antennas for data transmissions. A memory-guided message transmission is used by the AP, in which during the network association phase, a node establishes the connection with the AP using an angular slot and register it in the memory. The AP switches the narrow beam by checking the memory towards the registered angular slots for data transmissions to avoid the empty scanning of the unregistered angular slots. The initial use of omnidirectional antenna can limit the service range which can affect the connection of nodes with AP, which is not considered. In addition, the switching delay and cost are also analyzed. To maintain the fairness in which transmission completion is verified by the reception of an ACK message or repeated failure occurrence the service discovery phase is triggered to update the guided transmissions. The scheduling although is considered for data transmission but not focused in detail.

3) Hybrid channel access mechanism: A TPAN is discussed in [81] which is composed of devices (DEV) and a piconet coordinator (PNC) with an improved high throughput an low delay access protocol (IHTLD-MAC). The PNC is capable of performing more functions than devices and responsible for channel access in a network. The PNC provides the channel access, synchronization and time slot information to DEV using beacon frames. A hybrid channel access mechanism is used with CSMA/CA and TDMA based approaches in which the channel time is divided into multiple superframes. Each superframe consists beacon period (BP), channel time allocation period (CTAP) and channel access period (CAP). In each period, a hybrid access mode is used using CSMA/CA and TDMA together in which the PNC sends omnidirectional beacon frame during BP in each superframe with synchronization, timeslot, channel access and control information. The DEVs can synchronize themselves based on the synchronization information and obtain CTAP slot allocation information which is made by a series of channel time allocations (CTAs), and DEVs access channel in TDMA mode where each device transmits data in its allocated slot. The CSMA/CA is used to compete for the channel in CAP period in which the device which wants to transmit data need to send a channel time request command to PNC. The PNC broadcast slot assignment information in the net beacon frame according to request frame received. An on-demand retransmission mechanism is also proposed to decrease the message overhead with reserved slots mechanism based on channel condition. This work is an extension of the work presented in [168] which also uses a hybrid system and describes a high throughput and low delay Terahertz MAC protocol. It addresses the problem of not updating the timeslots requests in time, a new superframe structure is proposed which reduces the data access delay and provides the time slot allocation to devices in a piconet network. The throughput is also shown to be improved by updating the timeslot request numbers with a reduction in the latency efficiency by using the superframe. Although it improves the performance, the poor network conditions are not considered. Another work discussing the similar hybrid channel access mechanism with superframe are presented in [152], [154].

C. Summary and discussion

The traditional channel access schemes are based on continuous signals which cannot be used for nanonetworks due to the size and energy constraint. Instead, short pulses (100 fs) can be generated using simple devices (graphene antenna) and transmitted at the nanoscale. Therefore, novel channel access mechanisms are required for nanoscale networks. Mostly, scheduling based channel access mechanisms are used because of short pulses. The new mechanisms should consider the high network density and limited energy availability. The short pulses reduces the collision probability and therefore for high density network random channel access mechanisms can be used. But, in their MAC the collision avoidance mechanism should be considered to avoid any possible collision which can degrade the network performance. The problem with random mechanism is high control message overhead, therefore new mechanism should reduce the message overhead. By using isotropic antenna, a node at nano scale can communicaiton with more nodes in its communication range. Whereas, Terahertz signal can be generated using a reference laser wavelength and a carrier optical signal. At the macro scale, the directional antennas are preferred due to high path loss and coverage enhancement but requires antenna direction alignment. To solve the problem of antenna alignment different mechanisms are proposed in the existing literature which includes searching the space and adding an additional tuning phase [68]. But, these mechanisms can increases the link establishment delay. It can cause a hidden node or deafness problem (cf. Sect.IV-B2), in which a node remains unaware of the existence of the nearby node due to limited coverage or antenna misalignment. Therefore, new mechanism for fast antenna alignment with efficient channel access are required.

For Terahertz communication, mostly TDMA and pulse based communication are used. In pulse based communication, short Terahertz pulses can be generated using specific devices to reach higher throughput as a symbol which caries number of bits. Whereas, time division technique for Terahertz MAC is mostly related to the fact that antenna is directional and at a given time duration, a node can communicate only with one node or nodes within its beam length, where a beam orientation is equivalent to a timeslot. Therefore, the TDMA based approaches requires efficient scheduling schemes while considering antenna direction, beam alignment, multi user interference and Terahertz band features. To avoid tight synchronization requirement, asynchronous MAC protocols requires further research with energy efficiency. The channel access for macro scale relies more on beam steering. Therefore, an alignment phase should be considered at the MAC layer. For nano scale communication, a node can establish rapidly a communication link to its neighbor node in its range due to omni-directional antenna, short range and low path loss. The antenna pattern for nano scale is assumed as isotropic and directional for macro scale network for which the gain requirements are also high. Further, the high interference for nano scale due to isotropic properties of antenna requires efficient algorithm. Due to which the nano schemes cannot be applied to macro scale and requires new novel mechanism while considering the channel characteristics, antenna, gain and transmission power. New real measurement studies are also required for modelling of channel behavior for different indoor and outdoor applications at macro scale.

The Terahertz band offers high bandwidth availability with narrow transmission windows. This results in less channel contention and low collision probability. However, in networks with high density, and frequent transmission with jumbo packet sizes, the collision cannot be ignored. Therefore, the novel mechanism should consider the collision avoidance techniques to avoid performance degradation. For combined usage, medium sensing and scheduling based hybrid mechanisms can be explored for efficient channel access. In addition, the use of very large arrays and narrow directional beams can also reduce the multi-user interference, however, it increases the need for synchronization requirements [215]. Therefore, novel MAC mechanisms are required for efficient random or scheduled access of channel; alignment between the transmitter and receiver; and which should solve the deafness problem.

Some other challenges include, designing MAC with combined usage of Terahertz and lower frequency bands like microwave and mmWave bands. MAC will manage multiple bands, where control messages and antenna alignment in advance can be handled using lower frequency bands and high data transfer can be managed by Terahertz band. The RADAR bands can also be used with Terahertz band for localization and antenna alignment in moving vehicles. Another challenges is to design a MAC for massive MIMO systems with interfacing between MAC and the antenna system to increase the spectral efficiency and to assign schedules efficiently.

VII. Transmitter and receiver initiated Terahertz MAC protocols

The existing Terahertz band scenarios like nanoscale and macro scale networks require different MAC mechanisms. The nanoscale networks are energy constrained networks in which nanodevices have just enough energy to transmit a packet and therefore uses energy harvesting mechanisms to generate energy [8]. They require a balance between energy consumption and harvesting [252]. The macro scale networks, on the other hand, do not face energy issues, however, due to specific Terahertz band requirements, directionality of antenna requires attention in establishing communication. Depending upon the scenario and different networks, several transmitter and receiver initiated communications have been proposed in the literature, which is discussed in this section with their requirements and challenges.

Besides the nanonetwork communication, the literature also includes the usage of Terahertz band in other communication networks such as WPAN [81], vehicular networks [19], indoor and outdoor communication networks [4], [20], [38], which generally can be called as Terahertz communication networks. Due to the low transmission power of Terahertz transceivers and high path loss at Terahertz frequencies very high directivity antennas are required to establish wireless links beyond one meter. The directional antennas reduce the multiuser interference but it requires tight synchronization

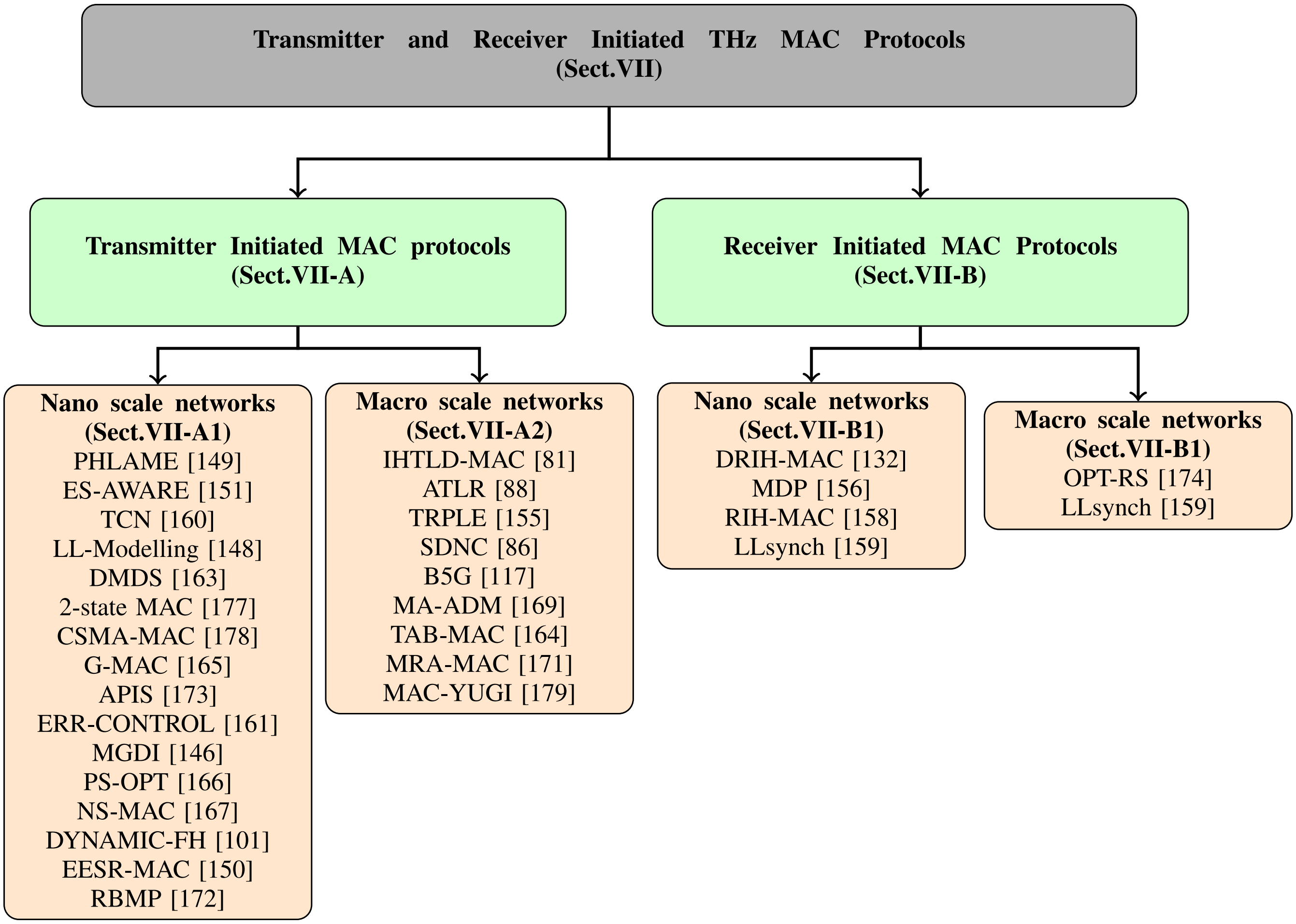


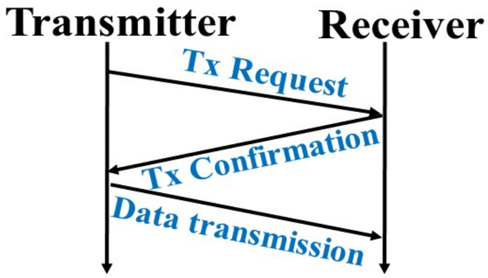
Fig. 11: Classifications of Terahertz MAC protocols based on Transmitter and Receiver initiated communications.

between the transmitter and receiver to overcome hidden node or deafness problem [244]. In addition, the high propagation delays result in low channel utilization. In particular, the Terahertz band provides large bandwidths and therefore do not need to contend for channel access. However, it introduces high bit rates and short transmission times which further reduces the collision probability. The existing MAC protocols cannot be directly applicable to TCNs due to higher molecular absorption which affects the distance and results in higher path loss and channel attenuation. There are solutions for directional antennas in traditional communication networks, however, they do not consider the Terahertz band properties.

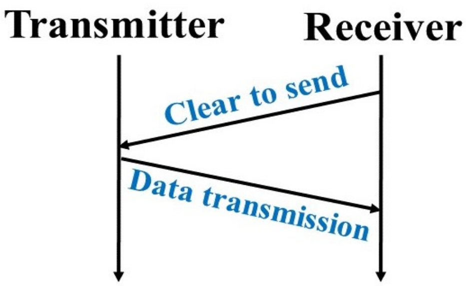
Different strategies for an efficient MAC communication are used in the literature namely, the receiver initiated [132], [156], [158], [159], [174] and transmitter initiated communication [81], [86], [88], [101], [117], [146], [148]–[151], [153], [155], [160]–[167], [169], [171]–[173], [177]–[179] mechanisms. Their difference is also explained in Figure 12. In particular, the receiver initiated MAC aimed at reducing the number of transmission in resource-constrained nano and macro scale networks. Whereas the transmitter-initiated communication focuses on the performance efficiency of the network in a traditional way. Typically, the directional antennas are used for transmitter initiated communication in TCNs due to its narrow beam requirement and distance-dependent bandwidth [149]. Other than directional antenna usage, some proposals use multiple antennas to establish initial coordination between multiple nodes. The solutions so far on receiver and transmitter initiated coordination protocols are mentioned below and are shown in Figure 11.

A. *Transmitter initiated MAC protocols*

In a traditional way, the transmitter is mainly responsible to exchange essential information to establish communication such as coding schemes, scheduling times and channel parameters. Most of the Terahertz MAC protocols are following the transmitter-initiated communication due to its simplicity and distributed nature. However, the distance dependent behavior of Terahertz band due to absorption and path loss; directional antenna usage; high bandwidth and throughput support, increases the challenges. These challenges include the facing problem introduced when the transmitter and receiver remain unaware initially about the position and antenna direction; the hidden node problem; and reliability of communication i.e., the packet is lost due to path loss or collision. A general example of transmitter initiated communication is shown in Figure 12, in which a transmitter or a node which has information can send a packet, a receiver which receives that packet can trigger



(a) Tx initiated communication



(b) Rx initiated communication

Fig. 12: Message transmission flow for handshake in Terahertz MAC protocols for link establishment. a) Transmitter initiated handshake mechanism which requires confirmation from receiver of its sent packet before starting a data transmission, b) Receiver initiated handshake mechanism in which receiver initiated communication when it required some information or have enough energy to receive a message, mostly used in nano communication networks.

an ACK or confirmation to send and after that, a sender can send the Data packet. The transmitter and receiver can agree on the common parameters like coding scheme, packet error rate etc to reduce the complexity of communication and to reduce the delay. Broadly, they are being used both in nano and macro scale networks, which are mentioned below:

1) Nano scale networks: In nanonetworks, mostly a nano controller is used to forward and collect data to/from nanodevices in a centralized fashion. The transmitter-initiated communication is used mostly to allow the nodes to forward the data on the need basis. The node which has data to send will initiate the communication and establishes the communication as well using handshaking mechanism. However, it can cause collisions between the nodes. To overcome these collisions different scheduling and channel access methods are used in the literature, as discussed in the previous section.

A transmitter initiated communication scheme is proposed in [149] for nanonetworks, which is built on top of RD TS-OOK and takes benefits of low weight channel coding scheme. The main aim is to negotiate between the transmitter and receiver the communication parameters and channel coding scheme to minimize the interference and maximize the probability of efficient decoding of the received information. The communication is established by sending a request by a node which carries information as Transmission Request (TR) and a node which receives it will agree to the communication parameters and generate an ACK and sends a Transmission Confirmation (TC) message. The TR contains the synchronization trailer, the transmission ID, packet ID, transmitting Data Symbol rate (DSR) and Error Detecting Code (EDC). Although, it offers benefits in terms of delay and throughput. It also has few limitations including the handshake process overhead which limits the Terahertz communication performance and limited computational power of nanodevices which requires optimal communication parameters. Due to its limited computational capacity, in [151] energy and spectrum aware MAC protocol (ESAware)is proposed, in which the computational load is shifted towards the nano controllers.

In ESAware [151], a nano controller follows the TDMA approach and a scheduling scheme is proposed in which variable lengths timeslots are assigned to each nanosensor by considering the data to be transmitted, channel condition and the distance between two devices. The time frame is also defined which consists of a downlink, uplink and random access subframes. In downlink subframe the nano controller broadcasts information, in uplink sub-frame, the nanosensors send data to the nano controllers, whereas in random access sub-frame the slot is required either by the nano-controller or can be used for information exchange in an Adhoc fashion. When a nanosensor has some information to send, it informs the nano controller in random-access sub-frame using a Transmission Request which includes the amount of data to be transferred, node ID and channel conditions. The nano controller processes the received request with channel condition and informs the nanosensor in the next downlink sub-frame about the optimal way to proceed.

The Terahertz bands are more about scheduling a transmission rather than fighting for channel access because of its high bandwidth. Different approaches are proposed so far for scheduling transmissions in nanonetworks [149], [151], [173]. For adjusting bursty traffic in nanonetworks, a pulse based scheduling mechanism is proposed in [173] for efficient data forwarding towards the access networks using nano gateways. An optimal scheduling strategy for distributed nanonetworks is provided in [163] which uses transmitter initiated communication to achieve optimal throughput by using transmission distance based on the local sensing information. In [177], a two-state MAC is proposed while considering energy harvesting and data transmissions in different states of busy and idle and a data dissemination approach is discussed in [146].

In the Terahertz domain, different approaches for the MAC layer are proposed which follows a transmitter-initiated communication approach. For example, an error control strategy using transmitter initiated communication is proposed in [161], a packet size optimization technique is also presented in [166], energy efficient and reliable MAC protocol is proposed in [150] with control and data packet structure. A CSMA/CA-based MAC protocol is also proposed in [178] for nanonetworks is proposed for medium access with variable packet size analysis. For interference and noise mitigation, a dynamic channel allocation mechanism is presented in [101] as a plant monitoring system at nanoscale where the performance is analyzed based on throughput and energy. A relay based MAC protocol for nanonetworks is presented in [172] in which multiple antennas are used. Other works which follow the transmitter-initiated communication includes [148], [160], [165].

2) Macro scale networks: At the macro scale, the main challenges are to achieve coverage with high throughput. To achieve this, directional antennas are being used to extend the distance. However, due to path loss and molecular absorption still, it is limited. Further, for macro scale network with directional antennas, the steerable narrow beam is essential to overcome the high path loss at the Terahertz band and to extend the communication range. The beam directions in TCN are switched at the pulse level, rather than the packet level as in the traditional wireless networks. A Terahertz based communication model and autonomous relaying mechanism for Vehicular communication are presented in [88], by considering the channel capacity, autonomous relaying and network establishment. For distance coverage, the propagation of Terahertz wireless link at 1 and 10 m decreases by 80 dBm and 110 dBm [2]. These communication systems are also proposed to offer 100 m transmission range by using directional antennas and less than 10 m links by using omnidirectional antenna [35]. A switching mechanism is proposed in [86], [117] for vehicular and small cells deployment using Terahertz band. For extended coverage mmWave and Terahertz, bands can also be used in combination. These works focus on extended coverage and adjustment of parameters for MAC protocol design with transceiver selection.

Besides, these approaches to using different transceivers for mmWave and Terahertz bands for extended transmission range. In [164], [169], [171], [179], multiple antennas are used to separate out the signaling and data transmissions. The 2.4 GHz band is proposed to use for signaling and antenna alignment using an omnidirectional antenna to overcome the facing problem. For data transmission at a higher distance beyond 1-meter directional antennas are used. Besides the high path loss, the directional antennas in these works are shown to be beneficial in reaching the distance beyond 1 meter. Although it is presented as beneficial it incurs higher switching overhead.

A MAC design is proposed in [155] for macro scale communication while exploring the pulse level beam switching with energy control at 100 Gbps. A CSMA/CA-based channel access mechanism is used in [81] with on-demand retransmissions mechanism for a TPAN which considers poor link conditions. A beacon transmission mechanism is used to synchronize and manage the scheduling between the devices and the coordinator. The beacon frames are used by piconet coordinator to provide information like channel access, channels slot assignment, and synchronization information. It is shown that network throughput decreases when the channel conditions are poor and proposed MAC protocol shows better performance in comparison with IEEE 802.15.3c and ES-MAC [151].

Although, the transmitter-initiated protocols are widely used as they incur less complexity and favors the distributed nature. It incurs several challenges due to the use of the directional antenna. At one hand these directional antennas increase the transmission distance. On the other hand, they introduce the antenna facing the problem. Other problems are beam forming and beam switching to reach out a maximum of the nodes. In outdoor scenarios where mobility is involved frequent beam switching occurs which requires a novel mechanism to minimize the synchronization and antenna alignment schemes. The WiFi technology is proposed to minimize the control messages overhead in works like [164], [169], [171], [179] and for antenna alignment which overcomes the facing problem. However, it introduces the high antenna switching overhead and requires efficient scheduling mechanism for seamless control information and data dissemination transmission.

B. Receiver initiated MAC protocols

A general example of the receiver initiated communication is shown in Figure 12, in which the receiver announces its existence and readiness to receive a packet from the sender. Different solutions are proposed based on the network type and scale, such as nano and macro scale networks. The design requirements for both networks are different which requires solution based on its network requirements. For example, the nanonetworks are limited in size and scope and so adopts different Receiver initiated mechanism. Similarly, in macro scale, the design guidelines require directional antennas and therefore demands different solutions. However, the main theme of receiver-initiated MAC protocols in both types of networks is the same, which is to save energy and reduce excess message overhead. Different existing solutions for both types of networks are discussed below.

1) Nano scale networks: In nanoscale networks, which are prone to energy utilization, the excess of transmissions or message exchange means more utilization of energy. In nanonetworks, the amount of energy stored is just enough to transmit one packet [252]. The transmission remains unsuccessful when the receiver receives the request from the sender but does not acquire enough energy to send an ACK or data packet. Therefore, in receiver initiated protocols, the receiver takes initiative and announce its status of energy first to all senders by sending a Request-to-Receive (RTR) packet. Then only a sender can send a message or data packet.

The receiver initiated communication is used both in centralized as well as distributed networks [132], [151], [156], [158]. In centralized nanonetworks, a nanocontroller [151] is mainly responsible for performing major processing and decision making, as they are energy enrich devices. Since the receivers are usually assumed to generate their own energy resource, they harvest just enough energy to transmit a packet. Therefore, in solutions like [132], [156], [158], the receiver starts the communication by informing the senders, when it is ready to receive a packet and can exchange the information like coding schemes, error rates, and scheduling. This is possible only when the receiver has already stored enough energy through harvesting. Therefore, the limited energy resources are one of the main reason, receiver-initiated communications are preferred in centralized networks. The problems occur when the receiver remains busy energy harvesting phase, and senders start sending the packets, which can result in the loss of a packet. Therefore, scheduling becomes an essential part of such kind of schemes. In [158], a receiver-initiated communication model is presented for centralized topology, in which a receiver announces an RTR packet to nearby nano nodes and then the nano nodes send a DATA packet or ACK in response in a random access manner with probability p to establish a handshake between the nodes.

Due to energy limitation, the traditional channel access schemes cannot be directly applicable, as they increase the message overhead due to frequent request/clear-to-send message exchange. To overcome the traditional MAC approaches, scheduling is used to avoid the collision among different nodes. A distributed scheme is presented in [132] in which scheduling and harvesting mechanism are proposed to work together to enhance the energy utilization of nanonetworks. The proposed scheme uses the receiver-initiated approach to achieve the handshake and schedule by exchanging messages.

The problem occurs due to delay in exchanging the packets between two nodes when they are busy in harvesting energy which can also result in a hidden node problem. Therefore, new schemes are required to avoid the hidden node problem in a distributed environment using a receiver-initiated approach. A MAC protocol is discussed in [156] in which optimal energy consumption and allocation problem are presented which aims to maximize the data rate. It is also shown that the amount of energy harvested is not enough for transmitting one packet and therefore it can take multiple timeslots to transmit a single packet when the harvesting rate is lower than the energy consumption rate.

2) Macro scale networks: Unlike, the nanonetworks in macro scale networks directional antennas are used to extend further the transmission distance of more than 1 meter. In these networks, high path/propagation/absorption loss and low transmission power at Terahertz frequencies affect the achievable distance between the Terahertz devices. It also requires tight synchronization between a transmitter and receiver to overcome the deafness problem [159], [244]. A receiver initiated MAC protocol using directional antennas is discussed in [159] which uses a sliding window flow control mechanism with a one-way handshake that increases the channel utilization. High speed turning directional antennas are used to periodically sweep the space. The main objective is to prevent unnecessary transmission when the receiver is not available due to facing the problem. In this scheme, a node with sufficient resources broadcasts its current status by using a CTS message by using a dynamically turning narrow beam while sweeping its entire surrounding space. The CTS frame contains the information of receivers sliding window size. On the other side, the transmitter checks for a CTS frame from the intended receiver and then points its direction for the required period towards the receiver. The initial neighbor discovery of the neighbor nodes is not considered in [159]. Further, due to the bit error rate and path losses, there is no guarantee that the packet is successfully received by the receiver or transmitter. Therefore, it is required to utilize proper error control mechanisms to prevent this situation while reducing the delays and achieving the handshake efficiency. It is also possible that multiple receivers might point out at same receiver at the same time, which can result in possible collisions. Therefore, the collision avoidance techniques should also be part of future efficient Terahertz MAC protocols, while considering the physical layer parameters.

A MAC protocol focused on cross-layer analysis for relaying strategies is discussed in [174] with distance dependant throughput maximization analysis while considering the antenna, physical, link, and network layer effects. In particular, the receiver initiated communication is shown to be better than the transmitter-initiated communication in [159].

In general, the receiver initiated communication is mostly used in nanonetworks due to its limited resources. However, it is also been proposed in Macroscale networks to reduce the message overhead and to solve an antenna facing the problem. Typically, in centralized networks, they offer benefits like efficient energy utilization while considering the energy harvesting and consumption rate and reduced message overhead. However, in distributed environments, where the devices are assigned with pre-assigned roles as a sender or receiver, can increase the delay in terms of achieving coordination and increases the hidden node problem. Although, it reduces the message overhead the complexity increases with assigning extra responsibilities for a receiver.

C. Summary and discussion

The MAC protocols are mainly used to establish communication among the nodes. Depending upon the scenario and the network, different Terahertz MAC protocols are proposed. The nanonetworks are considered as networks with limited energy and resources in which mainly the schemes are preferred in which energy consumption can be minimized. This kind of networks mostly uses their energy harvesting mechanism to store energy which can then be utilized for the communication. Other than the traditional way, some receiver initiated mechanism is proposed in the literature, in which a receiver initiates the communication establishment by announcing its status for the sufficient energy resources to receive a packet. Whereas, in transmitter initiated communication, the node which have information to send can initiate to establish the communication. At nanoscale networks, mostly the networks are centralized and therefore nano controllers are used mostly to manage the control and data transmissions and so form a centralized network. In this kind of networks, scheduling the transmission is the main requirement as they use the pulse based communication instead of carrier sensing based communication. Although, the bandwidth is high and the probability of collision is low. But, that can be true only when the network density is low. For higher network density, the collisions cannot be ignored and so require an efficient mechanism to avoid the collisions and minimize the packet loss.

The nanonetworks are the networks in which the transmission range is less than 1 meter and uses the omnidirectional antennas. For distances beyond one meter for the macro scale networks, directional antennas are mainly used to extend the coverage using beamforming and MIMO techniques. Although, distance is increased it introduces the antenna facing a problem, which increases the delay in establishing communication between the number of devices. The receiver initiated communication is used also in the macro scale networks. Although it minimizes the control messages overhead, it increases the complexity and is not preferable in the distributed scenarios. In a distributed environment, where two nearby nodes performing the same operation such as energy harvesting can increase the delay and can cause a hidden node problem. Therefore, efficient synchronization and scheduling mechanism are required for these scenarios.

The Terahertz band in itself are sensitive to atmospheric molecules and so the path loss is high and it increases more with an increase in the distance. Efficient mechanisms are required to achieve the reliability of transmissions, which could distinguish between packet error, collisions and packet loss due to other reasons including medium uncertainty. So far, single channel mechanism is preferred in the Terahertz communication network. However, flexible MAC mechanism is also required which can work in multiple channels scenario as well as shared access in both single and multiple channels. For efficient MAC layer mechanisms, it is also required to consider the unique properties of Terahertz band which can severely affect the network performance, which is molecular absorption, interference, and noise due to other Terahertz devices.

Currently, the devices and antenna technology only allow using the directional antennas for distances beyond 1 meter. The future Terahertz MAC protocols can be in a form to use the omnidirectional antennas. Therefore, the flexible MAC protocols should be focused to work in both current and future situations, including the mobility and highly dynamic scenarios.

VIII. Challenges and Future Research Directions

Designing an efficient Terahertz MAC protocol needs to address different challenges. In this section, these challenges are presented with future research directions.

A. Terahertz communication network topologies

The design and performance of Terahertz MAC protocol highly depends upon the geometry of the network, arrangement of the nodes and the requirements of application scenario. Each different application introduces separate challenges, which are discussed below based on nano and macro scale network scenarios.

1) Macro scale network: The indoor communication scenarios like TWANs and TPANs are typical centralized networks with limited mobility which requires high data rate and efficient channel access mechanisms. Due to directional antenna requirements, MAC protocols should consider narrow focused beam management with tracking and steering, fast handovers and link establishment. These are the unique challenges in Terahertz band protocols which cannot be seen at lower frequency band protocols. Although, the communicaion range achieved so far with high data rate is still limited to few meters [20]. Extending this range to reach to 10 m for an indoor scenario using low power transmission devices and efficient communication protocols is an active field of research for B5G networks. As a future topic, the Terahertz wireless and fiber connectivity for backhaul and fronthaul high data rate communication is also gaining attention (cf. Sect.III-A1,III-A2,III-A2, and III-A2). In these centralized scenarios, the controller or Access point is mainly responsible for assigning schedules, link establishments, parameter negotiations, antenna alignment, and collision-free channel access. Efficient channel access mechanisms are required which could support a maximum number of users without causing interference. NLOS communication can be used to avoid antenna alignment and beam management problem. However, due to high path loss and molecular absorption, the range can be shorter. Therefore, directional antennas based MAC solutions are encouraged but needs to incorporate MIMO techniques and beam management for link establishment and high data rate transfer with minimum delay. Limiting transmit power also requires attention to further improve energy consumption while using the directional antennas. The antenna arrays can be used to reduce the chances of blocking, however, with directional antennas, beam management becomes critical which needs to be addressed while designing an efficient MAC protocol.

In Terahertz centralized networks, a single node works as a controller which is responsible for assigning transmission schedules. Although, scheduled access in centralised networks reduces the collision probability. The message overhead reduction techniques needs attention for random access. Due to shorter transmission range using Terahertz badn, the networks with higher mobility like indoor femtocell requires to address frequent handover management and user association. The mobility causes the need for frequent and re-establishment of communication links. Further, to support the mobility of a user from one access point to another SDN like controller can be used to support handovers (cf. Sect.III-A1). As a future work, with point to point, point to multipoint schemes also needs attention.

The Terahertz outdoor networks like backhaul networks involves the point to point and multipoint connection between the base stations. The point to point incurs less management, however, the point to multipoint requires beam steering and scheduling mechanism for efficient data transmission with minimum delays. The THz signal is highly sensitive to the outdoor environment, for example, weather fluctuation, and the presence of blockers between two nodes can affect the communication link. MAC layer for such a system should include fast link re-establishment mechanism and alignment operation in case of sudden miss-alignment between the two nodes by giving alternative paths for transmission. After being free from alignment problem, the focus should be on improving the QoS parameters.

Using a centralized and clustered scheme reduce MAC complexity, although more energy is wasted to achieve this objective [151]. For Terahertz distributed network, forward and backward messages between nodes are required to identify active neighbors and prepare for link establishment. For Terahertz network, a reference time should be adopted to guarantee the alignment procedure between nodes and to exchange information messages for future transmission, due to the fact that high attenuation and low beam width are available in Terahertz communication. Message overhead and pre-establishment time should be minimized to increase the spectral and energy efficiency of the network.

Although the antenna directionality and pencil beams can reduce the interference chances in distributed networks. The interference can occur which can result in collision among the users close to each other. For THz channel, interference mitigation, the power control and frequency selection techniques can be used in a cooperative fashion at MAC layer to mitigate the interference effect. The power attenuation is a limiting factor for low power devices. Therefore, transmitting with few mW, then, deploying phased array with beamforming and beam steering deemed essential to increase link budget and meet network requirements.

The indoor distributed scenarios like Data Centres is gaining much attention nowadays, due to the possibility of replacing existing wired links with ultra-high bandwidth wireless links. New mechanisms are required to establish inter and intra rack communication. In data centres, nodes are relatively close to each other, however a blockage between two distant nodes may exist. Therefore, to increase the reachability among nodes, operations such as relaying and path selection using reflectors placed at walls or ceiling can be used to mitigate the blockage [235]. The Terahertz band can be used with fibre to manage the traffic resources and as a backup link in a Data Centre.

2) Nano scale network: By using sophisticated devices endowed with additional capabilities such as isotropic antenna, energy harvesting functionalities, the nano-network can persist and deliver acceptable quality of services. However, frame collision and overall interference are the most important challenges for distributed network at the nanoscale. For centralized network, it is possible to reduce interference but central node should have more functionalities and capabilities to process more networking operations such as node synchronization and scheduling. In different applications, like agricultural or in-body health monitoring, the nodes scalability is required (cf.Sect.III-B). Managing node discovery and link stability are still challenges while dealing with limited energy resources at nanoscale. The limited energy and computational processing required addresses with reasonable size as well. Models to quantify the resources like time, storage and amount of communications are required to reduce the computational complexity in centralised as well as distributed networks. Managing scalability in distributed networks is also a challenge.

Nano devices are small devices with limited computational capacity and power management and so require simple communication protocols. More functionalities can be provided by adding additional technologies and optimizing the nano devices behavior. Therefore, to manage the nano devices and processing the complex computations externally, hierarchical architecture is required with required decisions to be taken to devices with higher computational capacity and powerful communication layers [253]. Gathering the data in a distributed network architecture to perform complex operation is a challenge task. Compared to centralized topology, the distributed topology suffer from high synchronization overhead. Therefore, new mechanisms are required for synchronization and coordination for distributed network. Further, the nanonetworks can also be combined with current network technologies like software defined networks, IoTs and virtual networks to solve the complex problems at those technologies and higher layers [16].

The nanonetwork topology can be dynamic at times, due to dynamic channel conditions which can affect the reliable transmissions. In response, the nano devices in a network might not share the same topology information. Further, the limited memory, storage and computational processing capabilities. The nano device also face difficulty in storing the routing tables and heavy algorithms. To solve this, a controller with software defined functionality can be utilised to do the extra computations, which can also change and reconfigure the behavior of nanonetwork. The individual devices can only perform simple tasks which adds the gap between the nano devices and the user applications. Therefore, the current service architecture cannot deal with large variety of nano network services [16]. New and novel architectures together with nanonetworks are required to provide different services for different nano applications.

The efficient utilization of harvested energy in a distributed environment is still a challenge for dense network deployment, considering thousands and millions of nano devices data is being processed by one gateway node. This can also increase the overall latency and processing delay. The future research directions include the use of fog computing with Internet of things to handle the local computations efficiently [16].

B. Terahertz channel access mechanisms

1) Macro scale network: For macro-scale networks the transmission is time and frequency multiplexed, which increases network synchronization and reduces the risk of collisions. The challenge is how to design techniques meeting fairness, data throughput, and delay requirement by assuming time and frequency multiplexing. Precisely, when using particular antenna architecture with directional beams, then how to map between access time, frequency and beam direction. Fast beam scanning and steering mechanisms are required to obtain channel state information to improve the channel usage decisions at macro scale networks. The random channel access can solve the problem of antenna alignment, however, the range becomes short due to high path loss. Efficient TDMA based scheduling mechanism is required for both centralized and distributed networks to avoid multi-user interference.

New waveforms, and modulation and coding schemes for Terahertz system are also required to improve the data rate and quality of service for beyond 5G communications [254]. The use of OOK mapped with ultra-short pulses at one hand can reduce the transceiver complexity, however, it also introduces challenges for antenna arrays for ultra-broadband design. Further, adaptive usage of distance variant Terahertz transmission windows also required further research to improve the transmission range and to mitigate the interference.

2) Nano scale network: The limited available bandwidth in traditional networks, forces the nodes to contend for the channel or follow time scheduling schemes. However, in nanonetworks, the Terahertz band provide huge bandwidth, which can result in very high data rate, short transmission time with low collision probability [16]. Due to low transmission power of nano transceivers, high path loss at Terahertz band and energy limited nano machines. The MAC protocol role is very important in regulating the link behavior, arranging the channel access and coordinating the transmission in a distributed environment.

Terahertz nano scale networks require more attention for energy saving and interferences management at MAC layer. Random access to the channel should be optimized for Terahertz nanonetwork with high density nodes per surface or volume unit under energy constraint, a deep study of interference in nanoscale communication can be found in [85].

Although the actual Terahertz nanoscale network are characterized by a basic MAC layer, it is possible to implement efficient error control protocols to reduce packet retransmissions and packet waiting time. Optimized mechanisms are required overall to run communication tasks at nanoscale, due to energy limitations and to support a large number of nanodevices. Efficient scheduling mechanisms for nanonetworks are required overall to balance the energy harvesting and channel access for data transmissions. Terahertz pulse-based communication is generally adopted for nanonetworks due to its simplicity and low power consumption. They need to be further optimized, to enable fast communication among a larger number of nanodevices. Further, additional functionalities such as scheduling transmissions are required between inter-cluster and TDMA based intracluster communication to avoid collisions and increase throughput [255].

C. Terahertz Receiver and Transmitter initiated communication

1) Macro scale network: At macro scale communication is linked with directional antennas. To initiate a communication, one end of the transmission link should have enhanced MAC functionalities such as simultaneous measurement and beam steering capabilities to track channel and node position jointly. Additional technology can assist in transmission initiation, such as RADAR and LIDAR for mobile nodes, and lower band technologies such as WiFi and LTE.

The radar-based sensing is gaining attention to solve the deafness problem in the vehicle to vehicle communication to efficiently align the antenna direction and communication establishment [90]. A preamble injection is shown useful in low SNR scenarios to avoid deafness problem in [89].

Further research is required on device and channel characterization to enhance the range and data rate for NLOS antenna and communication. This can also benefit the distributed environment in reducing the message overhead for link establishment and antenna alignment. Although, energy is not a high constraint like in nanonetworks, fast link establishment techniques, especially for distributed Terahertz networks and networks with high mobility requires novel solutions, for example, small cells and vehicular communications.

2) Nano scale network: For nanoscale networks, nodes with higher energy harvesting capabilities can take the responsibility of link establishment and transmission initiation, however designing sophisticated algorithms for rapid link initiation still remains an issue. Research is required for distributed MAC protocols for Nanosensor networks to reduce messaage overhead with energy control mechanism. Receiver initiated transmission suits the low power nano devices link establishment process due to reduced message overhead, it should consider energy as well as data size to be transferred. A combination of distributed communication in presence of a controller can help in managing the transmission schedules among nano devices [256].

D. General challenges and future research directions

The Terahertz technology is capable of delivering high data rate traffic with acceptable quality of services such as low delay, and minimized energy consumption. However, many challenges still exist and require further research and attention. Some of them are discussed below related to Terahertz MAC protocols in general.

1) Interference management: Although, interference can be reduced by using highly directional antenna, it is not considered by many research works [33]. It can be considered for large network requiring high data rate connection per node, such as top of the rack data center network, where nodes should transmit all the time with high data rate and low delay. Interference for dense indoor scenarios should be deeply studied and interference model needs to be established. The MAC layer, should be aware of interference in the channel to elaborate further the rapid scheduling and fast channel access and switching based on channel interference information. New and dynamic channel selection mechanism are also required while considering the Terahertz band unique characteristics and band specific interference and achievable distance.

The interference management module can track channel status and decides on the transmission time slot as well as the carrier to be used and physical parameters to be set, such as modulation and coding scheme and annulating side lobes in some directions. Additional procedure can be also implemented such as adoption, at the design stage, of a specific frequency plan for network and setting sub-band spacing strategy for each application. At operational mode, each node can use a fixed frequency pattern at the deployment stage or adopts the frequency hopping strategy to keep an acceptable SINR and to overcome the molecular absorption of the propagation medium [157], as the noise generated by molecule depends on frequency. Using frequency hopping scheme is promising as it tracks the channel switching, however, the designing of the frequency hopping algorithm is a challenge. The second challenge is to explore the number of frequencies the MAC layer can manage because of more the number of frequencies more the throughput.

2) Antenna design: The link quality depends on the physical layer and channel, for Terahertz communication antenna technology improvement is considered as a key factor for link budget enhancement, to reach this objective antenna should be highly directional. The MAC layer should monitor antenna by fast switching beams to serve all users in a fair way, to increase throughput and reduce the interference. MAC can also select antenna carrier frequency and polarization. To monitor efficiently a Terahertz communication, MAC layer should interface with the antenna system, for example controlling the steering angles, beam width and switching time. Because, a good command of antenna system can increase data throughput and reduce delays due to misalignment errors. Antennas properties should be optimized, the MAC layer can monitor Terahertz antenna via frequency switching, beamforming, and diversity in order to meet network requirements including:

Polarization capabilities: Using two polarizations (horizontal and vertical) with sophisticated algorithms of cross polarization cancellation is promising to boost the Terahertz system performance toward higher throughput and lower total system signal to interference ratio [257]. The main challenges with the dual polarization approach from MAC point of view are to balance the traffic between the two polarizations and to mitigate errors. Moreover, channel impulse response and then received power depends on polarization [258], one challenge is how to exploit efficiently Terahertz wave polarization to increase data throughput by balancing the data flow simultaneously between horizontal and vertical polarization.

Wideband and multi-band antenna: The design of multi wideband antennas are required to increase MAC efficiency and meet system requirements in term of high throughput, as more bandwidth will be available to transmit more data rate [259]. Using multiband antenna can also reduce system latency by deploying separate bands for data transmission and control message exchange.

High antenna gain: To mitigate channel impairment and extend the communication range, antenna gain should be maximized, Horn, logarithmic antenna and phased array are promising for designing high antenna gain Terahertz communication. For high antenna gain it is possible to increase node reachability, but more care should be addressed to antenna side lobes as they can generate more interferences.

Spatial diversity: To mitigate channel impairment and increase channel capacity, multiple antennas along with phased array, exploiting Terahertz propagation diversity, can be deployed for Terahertz links, such as MIMO and ultra massive MIMO. Using MIMO increase spectral and energy efficiency for the link, however, it requires efficient signal processing performance to encode and decode MIMO signals and exploit diversity. From MAC point of view, deployment of ultra massive MIMO will affect resource allocation techniques [216].

Fast switching capability: In a network scenario where nodes are distributed spatially in a given region, each node should establish a communication link to its neighbors. To increase data throughput and reduce latency per link, the beam switching time should be minimized. Switching can occur at pulse, symbol or frame level.

Adaptive beamforming: Directional antenna is considered an alternative solution to mitigate channel impairment and increase link budget, nevertheless, antenna pattern can take different shapes, and it should be optimized for a network use case, by using adaptive weighting of antenna elements monitored at the the physical layer and MAC, it is possible to reduce effect of interference by annulling lobes in some direction to avoid interferences, a MAC module can be implemented to control antenna beamforming and adapt the antenna technology to the network topology. In [260], a log-periodic toothed antenna is optimized for beamforming and beam steering for the Terahertz band. A concept of intelligent communication by using ultra massive MIMO is proposed in [261], to increase the communication distance and data rates at Terahertz band frequencies.

3) Synchronization: Synchronization adds accuracy to network operations and coordination and reduces frame collisions among nodes, as a result, it contributes to QoS enhancement. Moreover, it is responsible for more computation complexity and requires additional time slots before data transmission starts. Nodes memory and time for link establishment are the main cost to pay, in order to deploy the synchronous network. At MAC level, the challenge is to design algorithms for nodes and frame synchronization, for nodes to be aware of the transmission time. Another challenge is to efficiently allocate the radio resources for synchronization procedures such as frequency, time and power, which can increase the delay. To reduce the delay transceivers with more capabilities such as memory and processing can be used.

4) Transceiver design: With sophisticated antenna Terahertz design and efficient physical layer functionalities, a challenge related to transceiver performances should be considered.

MAC layer aims at adapting high data rate traffics to the physical layer. An efficient transceiver is required to deal with different MAC functionalities ranging from framing, synchronization, error control, scheduling and buffering. Authors in [170], demonstrate that it is possible to optimize transceiver architecture to bear high data rate reaching $100Gbps$ using parallelism and optimized memory usage along with frame length and error controlling techniques. Using efficient processing technique at the transceiver and sufficient memory size, it is possible to implement MAC protocols dealing with fast channel access, efficient scheduling technique and multi traffic communication

5) Link establishment, neighbor discovery and deafness problem: Before any communication starts, an establishment phase should be initiated. Link establishment is the duty of the MAC layer when a node needs to transmit to another node. This phase starts with setting up all the required parameters such as physical layer parameters, timers, synchronization procedure, then after receiving the acknowledgment from the receiver, a new transmission can begin. The challenge is how fast we can establish any Terahertz connection, and how to increase the success probability of link establishment phase.

Deafness can complicates the neighbor discovery due to transceiver misalignment and prevents the control messages to be exchanged in a timely manner (cf. Sect.IV-B2). To avoid the antenna miss alignment and link establishment, the mmWave standard IEEE 802.15.3c and IEEE 802.11ad uses beam training, in which one node operates in a directional mode and other node search space in a sequential directional mode. After a complete search sector level training occurs to perfectly align the beams. For neighbor discovery the challenges are to discover all the nodes with minimum delay, and techniques to search the space for beam alignment in a short time when two nodes are not initially aware of their beam directions.

The existing wireless technologies like WiFi and LTE can also be used to exchange the control messages and then can be switched to Terahertz mode for data transfer. Control messages can also be used for beam alignment between two users by exchanging information like angel of arrival, location, and beam pairing. Since directional antennas again complicates the discovery process, omni-directional and directional antennas together with pairing of existing wireless and Terahertz technology can be used in combination to exchange the control messages in short time to start data transfer. However, it increases the hardware complexity to support multi band antennas. Antenna pattern should also be considered while designing a MAC protocol because high gain antennas can enhance the link quality like throughput, coverage and errors. In response, the low gain side lobes from other sides can occur and cause interference which should be annealed to keep the signal to interference ratio above an acceptable level.

Neighbor discovery is a first and important phased of a network establishment and management, in which nodes identify and discover the neighbor nodes with link establishment. Particularly, for Terahertz communication the neighbor discovery is challenging due to unique band characteristics and antenna directionality, and for nano scale networks due to limited energy resources. Therefore, new and novel discovery mechanisms are required for Terahertz communication to reduce the link establishment delay in distributed networks with directional antenna, and for nanoscale, mechanisms with trade-off between transmission and energy harvesting are required. Neighbor discovery is required to synchronise nodes within a network and rapidly consider new nodes in the network. As a future research direction, optimization of discovery time by correctly choosing reference time for antenna alignment is an important challenge with timely information exchange. The discovery can be enhanced by using multibeam with fast switching and coordination among distributed nodes [262].

6) LOS blockage: Blockage is the situation when an object cross the main link between two nodes transmitting to each others, it can also generated from frequency shifting and reflected signal from surrounding objects. Due to high data rate, a small or temporary blockage can results in very high data loss. Therefore, it is important to propose novel anti-blockage mechanisms to avoid blockage situations and to achieve seamless coverage. At MAC layer, it is important to identify blocked channel to avoid false detection and correction, and to distinguish between the deafness and un-blocked error. In Terahertz band, due to small wavelength (0.3 mm) the directional links can be easily attenuated by LOS obstacles. In mobility scenarios, these obstacles can occur more frequently, and therefore can degrade the Terahertz link performance. Only increasing the transmission power cannot penetrate the obstacles, therefore an alternative unblocked channel is required to steer around. Reflectors can be used to avoid permanent blockage, but new mechanisms are required with beam steering and management functionalities to avoid link blockage. Modelling the blockage phenomena for each use case is required, and MAC layer should be aware of it. The main challenge is to detect blockage and tackle this issue at MAC layer. One alternative is to differ its transmission till the link is cleared or to select an alternative path with new parameters to avoid transmission interruption.

7) Design of relaying protocols: The short range communication like indoor and Data Centre scenarios, require new and efficient relaying techniques to increase the reachability of nodes. Nodes relaying or forwarding capability can be implemented at the MAC layer. It is activated when the signal from one transmitter needs to be regenerated by intermediary nodes to reach its final destination. However, to activate this, each node must have a complete view of the neighbors which can be exchanged among the nodes as a neighbor table. Due to antenna directionality and tight beam requirement of Terahertz communication, beam switching techniques can be used where antenna can take 0.1 ns to switch antenna beam direction [218], which can increase the overall delay in forwarding the packets. The relaying protocol using directional antenna must be designed to reduce this delay and to overcome channel impairment problem.

The Terahertz band can be easily affected due to environment losses and scattering and reflection effects both in indoor and outdoor environments. Only short transmission range is achievable until now. Due to which the signal needs to regenerated by an intermediate node to reach to the destination. Designing strategies with relaying capabilities by considering the unique band features and environment is a challenging requirement. Work on node relying on Terahertz band were performed at nanoscale communication [263], where two modes were considered: amplify and forward, and decode and forward, to strengthen the direct path by maximum ratio combining.

The relay node can be selected from the existing neighbors or can be placed especially in a network. Each mechanism needs to address different challenges including link quality, location and number of relays. In a distributed environment, where nodes communication range is shorter, multi-hop communication should be enable. Die to shorter range and directional antennas, multihop protocol design can be challenging when high throughput and low latency are the requirements. Therefore, new multihop strategies are required to fulfil Terahertz communication requirements by considering limited capabilities and behavior of communication layers in case of nano scale networks. For macro scale networks, the path loss, molecular noise and antenna directionality should be considered. Reflectors can also be used for communicating and reaching to nodes with LOS bloackage.

8) Coordination: The outdoor Terahertz applications include high and reliable data rate and delivery when transmission can be affected by weather conditions and Doppler effect. Designing efficient MAC protocols for vehicular and satellite communication with relaying and coordination among the nodes seems to be open challenges for MAC design. The node should decide the next relay node before the final destination and to strengthen the communication among different nodes using coordination mechanisms. The nodes should be capable of deciding to which node it should coordinate.

9) Cross layer design: The performance of Terahertz MAC protocols is dependant on the behavior and input from the other communication layers. Therefore, it is importance to consider these parameters from other layers to optimize the working of MAC protocols and enhance the network performance. For example, interference statistics can be gathered from the Physical layer to decide on the usage of a Terahertz band.

Terahertz cross-layer design for service requirements can be performed using physical and networking layer aware algorithms at the MAC layer. MAC layer should adapt between traffic flows coming from the upper layer and the channel fluctuations along with the physical layer procedures, for instance, selection of frame size per transmission period should be adaptively chosen based on packet arrival from networking layer as well as considering measurements from the physical layer. Scheduling transmissions can be optimized based on measurements gathered from the physical layer. MAC decisions such as band selection and path switching, in case of blockage are also affected by the physical layer and channel status. The transceiver memory should be optimized to support traffics with different QoS profiles.

10) Scheduling: In Terahertz network, scheduling algorithms can enhance the overall quality of service by using radio resources for a given policy such as maximizing throughput, minimizing the total interference in the network or reducing system delay. Scheduling module will be interfaced with the medium access module as well as physical layer, knowledge about the channel conditions and traffic requirements will govern scheduler decisions. Exchanging information related to buffer, channel quality and requirement of each traffic flow should be considered by the scheduler and also schedules of other nodes.

11) Framing and Error handling: Selection of frame size, frames and multi-frame structure and error control strategies, such as CRC insertion and frame retransmission, can enhance Terahertz link in term of frame error rate as well as leads to an increase of throughput.

Adaptive frame size and control overhead are fundamental to maintain a communication link and reduce errors among transmitted frames. Due to larger available bandwidth, the chances for collisions are less, however increasing the packet size can cause higher number of channel errors which requires more robust error detection and correction schemes. The longer packets can also introduce the buffering problems. Therefore, the optimal packet size and analysis of the trade-off between the size and performance, and flow control policies to avoid congestions and buffer overflow, requires further research.

12) Mobility management: Mobility can easily affect the quality of the established links die to narrow beams. Therefore, frequent re-establishment of links is required to maintain the links and communication over it. Two mobility models are mentioned in [264], linear and circular motion. In different Terahertz scenarios, different mobility models needs to be studied like in V2X scenarios and small cells, where LOS blockage can also occur frequently. It is important to track the best beam in case of frequent link damaging and beam alignment requirement.

In V2X networks nodes change their position with variable speed. To keep the connectivity with the network, a management module should be implemented at the MAC layer monitoring node location and tracking its speed. For such application, a mobility model needs to be proposed for each scenario, and how MAC layer should keep tracking nodes position as well as its neighbors then how to select and reselect nodes to which it should transmit while taking into consideration also the receiver mobility. Mobility management module will decide on the handover and how to make the link robust all the time till the end of the transmission without interruption, it is possible to decide to change a new node as receiver or to transmit by relaying. An update mechanism should be set to sort all neighbor nodes based on their availability. One more challenge is how to sample channel condition and how fast the MAC can decide for the handover.

13) Message overhead, parameter aware and hybrid MAC protocols: Mainly, the transmission of control messages in excess can cause the message overhead problem which can easily occur in directional Terahertz communication. Efficient techniques are required to reduce the message overhead. The control packets are normally of a small size which results in poor channel utilization in case of Terahertz band [265]. Different windows or bands can be used to utilize the channel resource efficiently. The overhead can also be reduced by adopting the memory, which has been demonstrated to enhance the throughput and latency performances in [169]. The memory of neighbor table, beamforming table to reduce training space and alignment overhead with relay selection can be used to enhance the operational performance of Terahertz network. The memory can be stored in a static network to get benefits, however in dynamic networks it is important to know when to update the memory status.

The distance aware transmission can be used as well in a system with single transmitter and multiple receivers, where each receiver remains at different distance from the transmitter. Communicating each receiver using a different transmission window with different path loss and gain can benefit in efficient resource management. A distance aware THz approach is presented in [266], [267] for multi user network. New mechanisms are required with analysis for optimal channel usage for different transmission windows with optimal window, bandwidth size, and rate adaptation.

In Terahertz communication networks, directional antennas are usually required for enhanced coverage. In future, hybrid protocols which can take benefits from both contention based and contention free channel access mechanisms, are a way to move forward. The contention based mechanism are good in throughput and latency performance, whereas contention free a are good in collision avoidance.

14) Challenges for nanonetworks: The nanonetworks mostly share the same challenges due to the usage of the Terahertz band. There are some specific challenges for nanonetworks because of their small size, capacity, architecture and high node density. Some of the challenges are mentioned below.

- *System scalability:* Due to the small size of the nodes, the number of nodes can increase significantly, in nanoscale networks. When the system is able to support a large number of nodes and the addition of new nodes with enhanced performance. That system can be considered as a scalable system. Further, the investigation is required for the system scalability.
- *Energy harvesting and consumption trade-off:* The nanodevices are small devices with small energy storage capacity, which is mostly just enough for few transmissions. These devices have to generate their energy source by them self. To support more transmissions, the nano nodes must be able to utilize their energy resource efficiently while generating the energy. Further, research is required to optimize the trade-off between the energy consumption and harvesting rate.

Research work on MAC layer of Terahertz communication system will boost efforts to standardize and deploy such technology in realistic scenarios. Advances in electronic, photonic and plasmonic Terahertz devices, a new finding in Terahertz propagation properties and channel modeling indicate that the era of Terahertz communication will obviously mark the near future. Investigation on designing efficient MAC layer for Terahertz networks will also be promising. It will include algorithm design for channel access, dynamic resources sharing, dealing with advanced physical layer techniques such as multicarrier and multi-antenna communication to boost data rate to tens of Tbps. Optimizing frame length and implementation of advanced MAC techniques for error control and flow control are also worth considering. The dynamic behavior of MAC, can increase awareness of the upper and lower layers and also optimize the global power usage without degradations in the quality of service.

IX. Conclusion

In this paper, a comprehensive survey is presented for Terahertz MAC protocols. The Terahertz band have a great potential to support the future ultra-high bandwidth and low latency requirement for beyond 5G networks. Especially, the existing unused frequency operating at disruptive bandwidths of 70 GHz can be a key enabler for beyond 5G networks. In this regard, the key features, design issues for Terahertz MAC and decisions which should be taken at MAC layer to enhance the performance of the network, are highlighted and discussed. Different Terahertz applications for macro and nano scale are also discussed with their scenario specific challenges. The survey has identified numerous gaps and limitations of existing Terahertz MAC protocols for enhancing further research in this domain. To highlight the limitations, the existing literature on Terahertz MAC protocols is also classified based on topology, scale, channel access mechanism and transmitter/initiated communication. To push further the research in this domain, challenges and future research directions are also presented with a cross layer approach.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 761579 (TERAPOD).

References

[1] C. Systems., "Cisco visual networking index: Global mobile data traffic forecast update, 2016âĂŞ2021 white paper," Tech. Rep., 2018. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[2] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Physical Communication*, vol. 12, pp. 16 – 32, 2014.

[3] A. S. Hamza, J. S. Deogun, and D. R. Alexander, "Wireless communication in data centers: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 1572–1595, thirdquarter 2016.

[4] I. F. Akyildiz, J. M. Jornet, and C. Han, "Teranets: Ultra-broadband communication networks in the Terahertz band," *IEEE Wireless Communications*, vol. 21, no. 4, pp. 130–135, August 2014.

[5] H. Elayan, O. Amin, R. M. Shubair, and M. S. Alouini, "Terahertz communication: The opportunities of wireless technology beyond 5G," in *International Conference on Advanced Communication Technologies and Networking (CommNet)*, April 2018, pp. 1–5.

[6] T. Yilmaz and Ö. B. Akan, "On the 5G wireless communications at the low Terahertz band," *CoRR*, vol. abs/1605.02606, 2016.

[7] T. Kurner and S. Priebe, "Towards Terahertz communications status in research, standardization and regulation," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 35, no. 1, pp. 53–62, January 2014.

[8] I. F. Akyildiz, J. M. Jornet, and M. Pierobon, "Nanonetworks: A new frontier in communications," *Communications of the ACM*, vol. 54, no. 11, pp. 84–89, 2011.

[9] ——, "Propagation models for nanocommunication networks," in *Proceedings of the Fourth European Conference on Antennas and Propagation*, April 2010, pp. 1–5.

[10] F. Dressler and F. Kargl, "Towards security in nano-communication: Challenges and opportunities," *Nano Communication Networks*, vol. 3, no. 3, pp. 151 – 160, 2012.

[11] J. M. Jornet and I. F. Akyildiz, "The internet of multimedia nano-things," *Nano Communication Networks*, vol. 3, no. 4, pp. 242 – 251, 2012.

[12] I. F. Akyildiz and J. M. Jornet, "The internet of nano-things," *IEEE Wireless Communications*, vol. 17, no. 6, pp. 58–63, December 2010.

[13] K. Darchini and A. S. Alfa, "Molecular communication via microtubules and physical contact in nanonetworks: A survey," *Nano Communication Networks*, vol. 4, no. 2, pp. 73 – 85, 2013.

[14] D. Malak and O. B. Akan, "Molecular communication nanonetworks inside human body," *Nano Communication Networks*, vol. 3, no. 1, pp. 19 – 35, 2012.

[15] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks*, vol. 1, no. 1, pp. 3 – 19, 2010.

[16] Q. H. Abbasi, K. Yang, N. Chopra, J. M. Jornet, N. A. Abuali, K. A. Qaraqe, and A. Alomainy, "Nano-communication for biomedical applications: A review on the state-of-the-art from physical layers to novel networking concepts," *IEEE Access*, vol. 4, pp. 3920–3935, 2016.

[17] F. Dressler and S. Fischer, "Connecting in-body nano communication with body area networks: Challenges and opportunities of the internet of nano things," *Nano Communication Networks*, vol. 6, no. 2, pp. 29 – 38, 2015.

[18] S. A. Busari, S. Mumtaz, S. Al-Rubaye, and J. Rodriguez, "5G millimeter-wave mobile broadband: performance and challenges," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 137–143, June 2018.

[19] S. Mumtaz, J. M. Jornet, J. Aulin, W. H. Gerstacker, X. Dong, and B. Ai, "Terahertz communication for vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 5617–5625, July 2017.

[20] V. Petrov, J. Kokkoniemi, D. Moltchanov, J. Lehtomaki, Y. Koucheryavy, and M. Juntti, "Last meter indoor Terahertz wireless access: Performance insights and implementation roadmap," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 158–165, June 2018.

[21] K. c. Huang and Z. Wang, "Terahertz terabit wireless communication," *IEEE Microwave Magazine*, vol. 12, no. 4, pp. 108–116, June 2011.

[22] C. Han and Y. Chen, "Propagation modeling for wireless communications in the Terahertz band," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 96–101, June 2018.

[23] A. A. A. Boulogeorgos, A. Alexiou, T. Merkle, C. Schubert, R. Elschner, A. Katsiotis, P. Stavrianos, D. Kritharidis, P. K. Chartsias, J. Kokkoniemi, M. Juntti, J. Lehtomaki, A. Teixeira, and F. Rodrigues, “Terahertz technologies to deliver optical network quality of experience in wireless systems beyond 5G,” *IEEE Communications Magazine*, vol. 56, no. 6, pp. 144–151, June 2018.

[24] P. T. Dat, A. Kanno, T. Umezawa, N. Yamamoto, and T. Kawanishi, “Millimeter and Terahertzwave radio-over-fiber for 5G and beyond,” in *IEEE Photonics Society Summer Topical Meeting Series (SUM)*, July 2017, pp. 165–166.

[25] V. Petrov, A. Pyattaev, D. Moltchanov, and Y. Koucheryavy, “Terahertz band communications: Applications, research challenges, and standardization activities,” in *8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, October 2016, pp. 183–190.

[26] I. F. Akyildiz and J. M. Jornet, “Realizing ultra-massive MIMO (1024ÃŮ1024) communication in the (0.06âĂŞ10) Terahertz band,” *Nano Communication Networks*, vol. 8, pp. 46 – 54, 2016.

[27] H. J. Song and T. Nagatsuma, “Present and future of Terahertz communications,” *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 256–263, September 2011.

[28] I. Hosako, N. Sekine, M. Patrashin, S. Saito, K. Fukunaga, Y. Kasai, P. Baron, T. Seta, J. Mendrok, S. Ochiai, and H. Yasuda, “At the dawn of a new era in Terahertz technology,” *Proceedings of the IEEE*, vol. 95, no. 8, pp. 1611–1623, August 2007.

[29] M. Hasan, S. Arezoomandan, H. Condori, and B. Sensale-Rodriguez, “Graphene Terahertz devices for communications applications,” *Nano Communication Networks*, vol. 10, pp. 68 – 78, 2016.

[30] J. F. Federici, J. Ma, and L. Moeller, “Review of weather impact on outdoor Terahertz wireless communication links,” *Nano Communication Networks*, vol. 10, pp. 13 – 26, 2016.

[31] K. Wu, Y. J. Cheng, T. Djerafi, and W. Hong, “Substrate-integrated millimeter-wave and Terahertz antenna technology,” *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2219–2232, July 2012.

[32] K. M. S. Huq, J. M. Jornet, W. H. Gerstacker, A. Al-Dulaimi, Z. Zhou, and J. Aulin, “Thz communications for mobile heterogeneous networks,” *IEEE Communications Magazine*, vol. 56, no. 6, pp. 94–95, June 2018.

[33] C. Han, X. Zhang, and X. Wang, “On medium access control schemes for wireless networks in the millimeter-wave and terahertz bands,” *Nano Communication Networks*, vol. 19, pp. 67 – 80, 2019.

[34] M. Fitch and R. Osiander, “Terahertz waves for communications and sensing,” *Johns Hopkins APL Technical Digest*, vol. 25, no. 4, pp. 348–355, October 2004.

[35] T. Kurner, “Towards future Terahertz communications systems,” *Terahertz Science and Technology*, vol. 5, pp. 11–17, 01 2012.

[36] C. M. Armstrong, “The truth about Terahertz,” *IEEE Spectrum*, vol. 49, no. 9, pp. 36–41, September 2012.

[37] S. Balasubramaniam, S. Ben-Yehuda, S. Pautot, A. Jesorka, P. LioâĂŹ, and Y. Koucheryavy, “A review of experimental opportunities for molecular communication,” *Nano Communication Networks*, vol. 4, no. 2, pp. 43 – 52, 2013.

[38] A. Hirata and M. Yaita, “Ultrafast Terahertz wireless communications technologies,” *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 6, pp. 1128–1132, November 2015.

[39] N. Khalid, T. Yilmaz, and O. B. Akan, “Energy-efficient modulation and physical layer design for low Terahertz band communication channel in 5G femtocell internet of things,” *Ad Hoc Networks*, vol. 79, pp. 63 – 71, 2018.

[40] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, W. Chen, L. Li, and S. Li, “A survey on terahertz communications,” *China Communications*, vol. 16, no. 2, pp. 1–35, February 2019.

[41] I. F. Akyildiz, F. Brunetti, and C. BlÃązquez, “Nanonetworks: A new communication paradigm,” *Computer Networks*, vol. 52, no. 12, pp. 2260 – 2279, 2008.

[42] I. F. Akyildiz and J. M. Jornet, “Electromagnetic wireless nanosensor networks,” *Nano Communication Networks*, vol. 1, no. 1, pp. 3 – 19, 2010.

[43] J. M. Jornet and I. F. Akyildiz, “The internet of multimedia nanothings in the terahertz band,” in *18th European Wireless Conference*, April 2012, pp. 1–8.

[44] S. V. Sivapriya and D. Sridharan, “A comprehensive review on MAC protocol of wireless nanosensor networks for intrabody application,” *International Journal for Innovative Research in Science and Technology*, vol. 4, no. 2, pp. 83–89, July 2017.

[45] M. Fujishima, S. Amakawa, K. Takano, K. Katayama, and T. Yoshida, “Tehrahertz CMOS design for low-power and high-speed wireless communication,” *IEICE Transactions*, vol. 98-C, pp. 1091–1104, 2015.

[46] I. Kallfass, I. Dan, S. Rey, P. Harati, J. Antes, A. Tessmann, S. Wagner, M. Kuri, R. Weber, H. Massler, A. Leuther, T. Merkle, and T. Kürner, “Towards MMIC-based 300ghz indoor wireless communication systems,” *IEICE Transactions*, vol. 98-C, pp. 1081–1090, 2015.

[47] X. Yu, S. Jia, H. Hu, P. Guan, M. Galili, T. Morioka, P. U. Jepsen, and L. K. OxenlÃÿwe, “Terahertz photonics-wireless transmission of 160 Gbit/s bitrate,” in *21st OptoElectronics and Communications Conference (OECC) held jointly with International Conference on Photonics in Switching (PS)*, July 2016, pp. 1–3.

[48] X. Pang, S. Jia, O. Ozolins, X. Yu, H. Hu, L. Marcon, P. Guan, F. D. Ros, S. Popov, G. Jacobsen, M. Galili, T. Morioka, D. Zibar, and L. K. Oxenkwe, “260 gbits photonic-wireless link in the Terahertz band,” in *IEEE Photonics Conference (IPC)*, Oct 2016, pp. 1–2.

[49] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, “Visible light communication, networking, and sensing: A survey, potential and challenges,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2047–2077, Fourthquarter 2015.

[50] S. Rajagopal, R. D. Roberts, and S. Lim, “IEEE 802.15.7 visible light communication: modulation schemes and dimming support,” *IEEE Communications Magazine*, vol. 50, no. 3, pp. 72–82, March 2012.

[51] S. Sur, X. Zhang, P. Ramanathan, and R. Chandra, “BeamSpy: Enabling robust 60 ghz links under blockage,” in *Proceedings of the 13th Usenix Conference on Networked Systems Design and Implementation*, ser. NSDI’16. Berkeley, CA, USA: USENIX Association, 2016, pp. 193–206.

[52] S. Singh, F. Ziliotto, U. Madhow, E. Belding, and M. Rodwell, “Blockage and directivity in 60 GHz wireless personal area networks: from cross-layer model to multihop MAC design,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1400–1413, October 2009.

[53] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, “Millimeter wave communication: A comprehensive survey,” *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 1616–1653, thirdquarter 2018.

[54] I. F. Akyildiz, D. M. Gutierrez-Estevez, R. Balakrishnan, and E. Chavarria-Reyes, “LTE-Advanced and the evolution to Beyond 4G (B4G) systems,” *Physical Communication*, vol. 10, pp. 31 – 60, 2014.

[55] B. Glushko, D. Kin, and A. Shar, “Gigabit optical wireless communication system for personal area networking,” *Optical Memory and Neural Networks*, vol. 22, no. 2, pp. 73–80, April 2013.

[56] X. Li, J. Vucic, V. Jungnickel, and J. Armstrong, “On the capacity of intensity-modulated direct-detection systems and the information rate of ACO-OFDM for indoor optical wireless applications,” *IEEE Transactions on Communications*, vol. 60, no. 3, pp. 799–809, March 2012.

[57] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D’Errico, V. Guarino, and M. Matsumoto, “1.28 terabit/s (32x40 gbit/s) WDM transmission system for free space optical communications,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, pp. 1639–1645, December 2009.

[58] L. V. Titova, A. K. Ayesheshim, A. Golubov, D. Fogen, R. Rodriguez-Juarez, F. A. Hegmann, and O. Kovalchuk, “Intense Terahertz pulses cause h2ax phosphorylation and activate dna damage response in human skin tissue,” *Biomed. Opt. Express*, vol. 4, no. 4, pp. 559–568, April 2013.

[59] iBROW, http://ibrow-project.eu/, accessed: 01-04-2019.

[60] TERRANOVA, https://ict-terranova.eu/, accessed: 01-04-2019.

[61] TERAPOD, https://terapod-project.eu/, accessed: 01-04-2019.

[62] ULTRAWAVE, https://ultrawave2020.eu/, accessed: 01-04-2019.

[63] EPIC, https://epic-h2020.eu, accessed: 01-04-2019.

[64] DREAM, https://www.h2020-dream.eu/, accessed: 01-04-2019.

[65] WORTECS, https://wortecs.eurestools.eu/, accessed: 01-04-2019.

[66] THOR, https://thorproject.eu/, accessed: 01-04-2019.

[67] NTT, http://www.ntt.co.jp/news2016/1605e/160526a.html, accessed: 09-01-2019.

[68] “IEEE standard for high data rate wireless multi-media networks– amendment 2: 100 gb/s wireless switched point-to-point physical layer,” *IEEE Std 802.15.3d-2017 (Amendment to IEEE Std 802.15.3-2016 as amended by IEEE Std 802.15.3e-2017)*, pp. 1–55, Oct 2017.

[69] IEEE, “IEEE 802.15.3d: Application requirement document,” Tech. Rep., 2015.

[70] ——, “IEEE 802.15.3d: Technical requirement document,” techreport, 2015. [Online]. Available: https://mentor.ieee.org/802.15/dcn/14/15-14-0309-20-003d-technical-requirements-document.docx

[71] ——, "IEEE 802.15.3d: Channel modelling requirement document," Tech. Rep., 2015. [Online]. Available: https://mentor.ieee.org/802.15/dcn/14/15-14-0310-02-003d-channel-modeling-document.docx
[72] ——, "IEEE 802.15.3d: Evolution criteria requirements document," Tech. Rep., 2015. [Online]. Available: https://mentor.ieee.org/802.15/dcn/14/15-14-0309-18-003d-technical-requirements-document.docx
[73] A. Kasamatsu, I. Hosako, and H. Ogawa, "Recent standardization activities in the terahertz communication field," Tech. Rep., 2015. [Online]. Available: https://www.ituaj.jp/wp-content/uploads/2015/01/nb27-1_web-11_tt2.pdf
[74] ITU, "Recommendation Report ITU-R SM.2352-0: Technology trends of active services in the frequency range 275-3 000 ghz," Tech. Rep., 2015, accessed: 01-04-2019. [Online]. Available: https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SM.2352-2015-PDF-E.pdf
[75] ——, "Recommendation ITU-R P.676-10: Attenuation by atmospheric gases," Tech. Rep., 2013, accessed: 01-04-2019. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.676-10-201309-S!!PDF-E.pdf
[76] ——, "Recommendation ITU-R P.676-11: Attenuation by atmospheric gases," Tech. Rep., 2017, accessed: 01-04-2019. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.676-11-201609-I!!PDF-E.pdf
[77] ——, "Recommendation ITU-R P.372-13: Radio noise," Tech. Rep., 2016, accessed: 01-04-2019. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.372-13-201609-I!!PDF-E.pdf
[78] C. Wang, B. Lu, C. Lin, Q. Chen, L. Miao, X. Deng, and J. Zhang, "0.34-thz wireless link based on high-order modulation for future wireless local area network applications," *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 1, pp. 75–85, January 2014.
[79] H. Song, H. Hamada, and M. Yaita, "Prototype of KIOSK data downloading system at 300 ghz: Design, technical feasibility, and results," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 130–136, June 2018.
[80] T. Yilmaz and O. B. Akan, "Utilizing terahertz band for local and personal area wireless communication systems," in *IEEE 19th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, December 2014, pp. 330–334.
[81] L. You, Z. Ren, C. Chen, and Y.-H. Lv, "An improved high throughput and low delay access protocol for Terahertz wireless personal area networks," *Journal of Computers*, vol. 28, no. 3, pp. 147–158, June 2017.
[82] V. Petrov, D. Moltchanov, and Y. Koucheryavy, "Applicability assessment of terahertz information showers for next-generation wireless networks," in *IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–7.
[83] P. T. Dat, A. Kanno, N. Yamamoto, and T. Kawanishi, "Radio-over-fiber-based seamless fiber-wireless convergence for small cell and linear cell networks," in *2018 Optical Fiber Communications Conference and Exposition (OFC)*, March 2018, pp. 1–3.
[84] M. T. Barros, R. Mullins, and S. Balasubramaniam, "Integrated terahertz communication with reflectors for 5g small-cell networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 5647–5657, July 2017.
[85] V. Petrov, D. Moltchanov, and Y. Koucheryavy, "Interference and sinr in dense Terahertz networks," in *IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, September 2015, pp. 1–5.
[86] A. S. Cacciapuoti, S. Ramanathan, K. R. Chowdhury, and M. Caleffi, "Software-defined network controlled switching between millimeter wave and Terahertz small cells," *CoRR*, vol. abs/1702.02775, 2017.
[87] K. Guan, G. Li, T. KÃijrner, A. F. Molisch, B. Peng, R. He, B. Hui, J. Kim, and Z. Zhong, "On millimeter wave and THz mobile radio channel for smart rail mobility," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 7, pp. 5658–5674, July 2017.
[88] C. Zhang, K. Ota, J. Jia, and M. Dong, "Breaking the blockage for big data transmission: Gigabit road communication in autonomous vehicles," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 152–157, June 2018.
[89] P. Kumari, J. Choi, N. GonzÃąlez-Prelcic, and R. W. Heath, "Ieee 802.11ad-based radar: An approach to joint vehicular communication-radar system," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 3012–3027, April 2018.
[90] V. Petrov, G. Fodor, J. Kokkoniemi, D. Moltchanov, J. Lehtomäki, S. Andreev, Y. Koucheryavy, M. J. Juntti, and M. Valkama, "On unified vehicular communications and radar sensing in millimeter-wave and low terahertz bands," *CoRR*, vol. abs/1901.06980, 2019. [Online]. Available: http://arxiv.org/abs/1901.06980
[91] D. L. Woolard, J. O. Jensen, R. J. Hwu, and M. S. Shur, *Terahertz Science and Technology for Military and Security Applications*. WORLD SCIENTIFIC, 2007.
[92] S. Sonmez and S. Ergun, "Terahertz technology for military applications," *Journal of Management and Information Science*, vol. 3, no. 1, pp. 13 – 16, 2015.
[93] K. Iwaszczuk, P. Jepsen, and H. Heiselberg, "Terahertz technology for defense and security-related applications," Ph.D. dissertation, 2012.
[94] S. U. Hwu, K. B. deSilva, and C. T. Jih, "Terahertz wireless systems for space applications," in *IEEE Sensors Applications Symposium Proceedings*, February 2013, pp. 171–175.
[95] T. M. Narytnyk, "Possibilities of using Terahertz band radio communication channels for super high rate backhaul," *Telecommunications and Radio Engineering*, vol. 73, no. 15, pp. 1361–1371, 2014.
[96] L. Felicetti, M. Femminella, G. Reali, and P. LiÃš, "Applications of molecular communications to medicine: A survey," *Nano Communication Networks*, vol. 7, pp. 27 – 45, 2016.
[97] E. Zarepour, M. Hassan, C. T. Chou, A. A. Adesina, and M. E. Warkiani, "Reliability analysis of time-varying wireless nanoscale sensor networks," in *2015 IEEE 15th International Conference on Nanotechnology (IEEE-NANO)*, July 2015, pp. 63–68.
[98] Z. L. Wang, "Towards self-powered nanosystems: From nanogenerators to nanopiezotronics," *Advanced Functional Materials*, vol. 18, no. 22, pp. 3553–3567.
[99] S. Mathanker, "Terahertz applications in food and agriculture: A review," *Transactions of the ASABE (American Society of Agricultural and Biological Engineers)*, vol. 56, pp. 1213–1226, April 2013.
[100] A. Zahid, K. Yang, H. Heidari, C. Li, M. A. Imran, A. Alomainy, and Q. H. Abbasi, "Terahertz characterisation of living plant leaves for quality of life assessment applications," in *2018 Baltic URSI Symposium (URSI)*, May 2018, pp. 117–120.
[101] A. Afsharinejad, A. Davy, and B. Jennings, "Dynamic channel allocation in electromagnetic nanonetworks for high resolution monitoring of plants," *Nano Communication Networks*, vol. 7, pp. 2 – 16, 2016.
[102] N. Khalid, N. A. Abbasi, and O. B. Akan, "300 ghz broadband transceiver design for low-thz band wireless communications in indoor internet of things," in *2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*, June 2017, pp. 770–775.
[103] V. Petrov, D. Moltchanov, M. Komar, A. Antonov, P. Kustarev, S. Rakheja, and Y. Koucheryavy, "Terahertz band intra-chip communications: Can wireless links scale modern x86 cpus?" *IEEE Access*, vol. 5, pp. 6095–6109, 2017.
[104] O. Yalgashev, "Towards nanoscale interconnect for system-on-chip," Ph.D. dissertation, UniversitÃľ de Technologie de Belfort-Montbeliard, 2018.
[105] S. Kim and A. ZajiÄĞ, "Characterization of 300-ghz wireless channel on a computer motherboard," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 12, pp. 5411–5423, Dec 2016.
[106] Y. Katayama, K. Takano, Y. Kohda, N. Ohba, and D. Nakano, "Wireless data center networking with steered-beam mmwave links," in *IEEE Wireless Communications and Networking Conference*, March 2011, pp. 2179–2184.
[107] J. Zhang, F. R. Yu, S. Wang, T. Huang, Z. Liu, and Y. Liu, "Load balancing in data center networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 2324–2352, thirdquarter 2018.
[108] S. Mollahasani and E. Onur, "Evaluation of Terahertz channel in data centers," in *IEEE/IFIP Network Operations and Management Symposium (NOMS)*, April 2016, pp. 727–730.
[109] K. Wu, J. Xiao, and L. M. Ni, "Rethinking the architecture design of data center networks," *Frontiers of Computer Science*, vol. 6, no. 5, pp. 596–603, October 2012.
[110] E. Baccour, S. Foufou, R. Hamila, and M. Hamdi, "A survey of wireless data center networks," in *2015 49th Annual Conference on Information Sciences and Systems (CISS)*, March 2015, pp. 1–6.
[111] J. Shin, E. G. Sirer, H. Weatherspoon, and D. Kirovski, "On the feasibility of completely wireless datacenters," in *2012 ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS)*, October 2012, pp. 3–14.
[112] H. Vardhan, N. Thomas, S. Ryu, B. Banerjee, and R. Prakash, "Wireless data center with millimeter wave network," in *IEEE Global Telecommunications Conference GLOBECOM*, December 2010, pp. 1–6.
[113] T. Yilmaz and O. B. Akan, "On the use of low Terahertz band for 5G indoor mobile networks," *Computers and Electrical Engineering*, vol. 48, pp. 164 – 173, 2015.

[114] A. D. Angelica, *GoogleâĂŹs self-driving car gathers nearly 1 GBps*, 2013. [Online]. Available: http://www.kurzweilai.net/googles-self-driving-car-gathers-nearly-1-gbsec.

[115] SAS, *Are you ready for your smart car?* [Online]. Available: http://www.sas.com/enus/insights/articles/big-data/the-internet-of-things-and-connected-cars.html

[116] Toyota, *Toyota to display new map generation system at CES 2016.* [Online]. Available: http://newsroom.toyota.co.jp/en/detail/10765074/

[117] A. S. Cacciapuoti, K. Sankhe, M. Caleffi, and K. R. Chowdhury, "Beyond 5G: Terahertz-based Medium Access Protocol for mobile heterogeneous networks," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 110–115, June 2018.

[118] A. Kanno, "Fiber-wireless signal transport by Terahertz waves," in *International Conference on Advanced Technologies for Communications (ATC 2014)*, Oct 2014, pp. 766–769.

[119] A. Greenberg, J. Hamilton, D. A. Maltz, and P. Patel, "The cost of a cloud: Research problems in data center networks," *SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 1, pp. 68–73, December 2008.

[120] Y. Chen, S. Jain, V. K. Adhikari, Z. Zhang, and K. Xu, "A first look at inter-data center traffic characteristics via Yahoo datasets," in *Proceedings IEEE INFOCOM*, April 2011, pp. 1620–1628.

[121] J. Ma, R. Shrestha, J. Adelberg, C.-Y. Yeh, Z. Hossain, E. W. Knightly, J. M. Jornet, and D. M. Mittleman, "Security and eavesdropping in terahertz wireless links," *Nature*, vol. 563, pp. 89–93, November 2018.

[122] Y.-M. Ding, S. Gao, X. Shi, and H. Wu, "Analysis of inter-satellite terahertz communication link," in *3rd International Conference on Wireless Communication and Sensor Networks (WCSN)*. Atlantis Press, 2016.

[123] S. Dong, Z. Zhu, and Y. Wang, "Advances of terahertz research and Terahertz satellite communications," in *International Conference on Electronics, Communications and Control (ICECC)*, September 2011, pp. 4122–4125.

[124] W. Dou, L. Zhang, H. Meng, and Z. Wang, "Tracking antennas for inter-satellite communications at sub-millimeter wavelengths," in *Proceedings of 3rd Asia-Pacific Conference on Antennas and Propagation*, July 2014, pp. 1149–1152.

[125] T. Nagatsuma and A. Kasamatsu, "Terahertz communications for space applications," in *Asia-Pacific Microwave Conference (APMC)*, November 2018, pp. 73–75.

[126] N. Llombart, O. Yurduseven, A. Neto, I. E. Lager, and J. Baselmans, "Dual polarised antenna for thz space applications: Design and optimization," in *44th European Microwave Conference*, October 2014, pp. 100–103.

[127] H. Han, J. Yuan, and J. Tong, "Design of Terahertzspace application system," *Journal of Computer and Communications*, vol. 3, no. 3, pp. 61–65, 2015.

[128] A. Amro, M. Ilchenko, V. Kalinin, and O. Turabi, "Sub-terahertz low power uwb communication link for wpan," in *IISTE Network and Complex Systems*, 2012.

[129] S. Koenig, D. Lopez-Diaz, J. Antes, F. Boes, R. Henneberger, A. Leuther, A. Tessmann, R. Schmogrow, D. Hillerkuss, R. Palmer, T. Zwick, C. Koos, W. Freude, O. Ambacher, J. Leuthold, and I. Kallfass, "Wireless sub-thz communication system with high data rate," *Nature Photonics*, vol. 7, pp. 977–981, October 2013.

[130] V. Petrov, M. Komarov, D. Moltchanov, J. M. Jornet, and Y. Koucheryavy, "Interference and SINR in millimeter wave and Terahertz communication systems with blocking and directional antennas," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1791–1808, March 2017.

[131] A. A. Boulogeorgos, A. Alexiou, D. Kritharidis, A. Katsiotis, G. D. Ntouni, J. Kokkoniemi, J. Lethtomaki, M. J. Juntti, D. Yankova, A. Mokhtar, J. Point, J. Machado, R. Elschner, C. Schubert, T. Merkle, R. Ferreira, F. Rodrigues, and J. Lima, "Wireless terahertz system architectures for networks beyond 5g," *CoRR*, vol. abs/1810.12260, 2018. [Online]. Available: http://arxiv.org/abs/1810.12260

[132] S. Mohrehkesh, M. C. Weigle, and S. K. Das, "DRIH-MAC: A distributed receiver-initiated harvesting-aware MAC for nanonetworks," *IEEE Transactions on Molecular, Biological and Multi-Scale Communications*, vol. 1, no. 1, pp. 97–110, March 2015.

[133] G. K. Walia, D. K. K. Randhawa, and K. S. Malhi, "A brief survey on molecular communications in nanonetworks," in *International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT)*, March 2016, pp. 343–348.

[134] J. M. Dubach, D. I. Harjes, and H. A. Clark, "Fluorescent ion-selective nanosensors for intracellular analysis with improved lifetime and size," *Nano Letters*, vol. 7, no. 6, pp. 1827–1831, 2007.

[135] J. Li, T. Peng, and Y. Peng, "A cholesterol biosensor based on entrapment of cholesterol oxidase in a silicic sol-gel matrix at a prussian blue modified electrode," *Electroanalysis*, vol. 15, no. 12, pp. 1031–1037.

[136] I. E. Tothill, "Biosensors for cancer markers diagnosis," *Seminars in Cell and Developmental Biology*, vol. 20, no. 1, pp. 55 – 62, 2009.

[137] P. Tallury, A. Malhotra, L. M. Byrne, and S. Santra, "Nanobioimaging and sensing of infectious diseases," *Advanced Drug Delivery Reviews*, vol. 62, no. 4, pp. 424 – 437, 2010.

[138] M. J.l, M. JornetJ, and M. Pierobon, "Nanonetworks in biomedical applications." *Current drug targets*, 2019.

[139] T. Qiu, T.-C. Lee, A. G. Mark, K. I. Morozov, R. Münster, O. Mierka, S. Turek, A. M. Leshansky, and P. Fischer, "Swimming by reciprocal motion at low reynolds number," in *Nature communications*, 2014.

[140] C. Cvetkovic, R. Raman, V. Chan, B. J. Williams, M. Tolish, P. Bajaj, M. S. Sakar, H. H. Asada, M. T. A. Saif, and R. Bashir, "Three-dimensionally printed biological machines powered by skeletal muscle," *Proceedings of the National Academy of Sciences*, vol. 111, no. 28, pp. 10 125–10 130, 2014.

[141] S. Yim and M. Sitti, "Design and rolling locomotion of a magnetically actuated soft capsule endoscope," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 183–194, February 2012.

[142] F. Qiu, S. Fujita, R. Mhanna, L. Zhang, B. R. Simona, and B. J. Nelson, "Magnetic helical microswimmers functionalized with lipoplexes for targeted gene delivery," *Advanced Functional Materials*, vol. 25, no. 11, pp. 1666–1671, 2015.

[143] S. Abadal, E. AlarcÃşn, A. Cabellos-Aparicio, M. C. Lemme, and M. Nemirovsky, "Graphene-enabled wireless communication for massive multicore architectures," *IEEE Communications Magazine*, vol. 51, no. 11, pp. 137–143, November 2013.

[144] C. Liaskos, A. Tsioliaridou, A. Pitsillides, N. Kantartzis, A. Lalas, X. A. Dimitropoulos, S. Ioannidis, M. Kafesaki, and C. M. Soukoulis, "Building software defined materials with nanonetworks," 2014.

[145] INTERNATIONAL ATOMIC ENERGY AGENCY, *Characterization and Testing of Materials for Nuclear Reactors*. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2007, iAEA-TECDOC-CD-1545. [Online]. Available: http://www-pub.iaea.org/books/IAEABooks/7760/Characterization-and-Testing-of-Materials-for-Nuclear-Reactors

[146] A. Tsioliaridou, C. Liaskos, S. Ioannidis, and A. Pitsillides, "Lightweight, self-tuning data dissemination for dense nanonetworks," *Nano Communication Networks*, vol. 8, pp. 2 – 15, 2016.

[147] M. Gagliano, M. Renton, N. Duvdevani, M. Timmins, and S. Mancuso, "Acoustic and magnetic communication in plants," *Plant Signaling and Behavior*, vol. 7, no. 10, pp. 1346–1348, 2012, pMID: 22902698.

[148] D. Arifler, "Link layer modeling of bio-inspired communication in nanonetworks," *Nano Communication Networks*, vol. 2, no. 4, pp. 223 – 229, 2011.

[149] J. M. Jornet, J. C. Pujol, and J. S. Pareta, "PHLAME: A physical layer aware MAC protocol for electromagnetic nanonetworks in the Terahertz band," *Nano Communication Networks*, vol. 3, no. 1, pp. 74 – 81, 2012.

[150] V. Srikanth, S. Chaluvadi, Sandeep, Vani, and Venkatesh, "Energy efficient, scalable and reliable MAC protocol for electromagnetic communication among nano devices," *International Journal of Distributed and Parallel Systems (IJDPS)*, vol. 03, no. 1, pp. 249–256, January 2012.

[151] P. Wang, J. M. Jornet, M. A. Malik, N. Akkari, and I. F. Akyildiz, "Energy and spectrum-aware MAC protocol for perpetual wireless nanosensor networks in the Terahertz band," *Ad Hoc Networks*, vol. 11, no. 8, pp. 2541 – 2555, 2013.

[152] Z. Ren, Y. N. Cao, S. Peng, and H. J. Lei, "A MAC protocol for Terahertz ultra-high data-rate wireless networks," in *Mechanical Engineering, Industrial Electronics and Information Technology Applications in Industry*, ser. Applied Mechanics and Materials, vol. 427. Trans Tech Publications, 12 2013, pp. 2864–2869.

[153] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "Nano-sim: Simulating electromagnetic-based nanonetworks in the network simulator 3," in *Proceedings of the 6th International ICST Conference on Simulation Tools and Techniques*, ser. SimuTools '13. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2013, pp. 203–210.

[154] Z. Ren, Y.-N. Cao, X. Zhou, Y. Zheng, and Q. bin Chen, "Novel MAC protocol for Terahertz ultra-high data-rate wireless networks," *The Journal of China Universities of Posts and Telecommunications*, vol. 20, no. 6, pp. 69 – 76, 2013.

[155] J. Lin and M. A. Weitnauer, "Pulse-level beam-switching MAC with energy control in picocell Terahertz networks," in *IEEE Global Com-*

munications Conference (GLOBECOM), December 2014, pp. 4460–4465.

[156] S. Mohrehkesh and M. C. Weigle, "Optimizing energy consumption in Terahertz band nanonetworks," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 12, pp. 2432–2441, December 2014.

[157] E. Zarepour, M. Hassan, C. T. Chou, and A. A. Adesina, "Frequency hopping strategies for improving Terahertz sensor network performance over composition varying channels," in *Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014*, June 2014, pp. 1–9.

[158] S. Mohrehkesh and M. C. Weigle, "RIH-MAC: Receiver-initiated harvesting-aware MAC for nanonetworks," in *Proceedings of ACM The First Annual International Conference on Nanoscale Computing and Communication*, ser. NANOCOM' 14. New York, NY, USA: ACM, 2014, pp. 1–6.

[159] Q. Xia, Z. Hossain, M. Medley, and J. M. Jornet, "A link-layer synchronization and Medium Access Control protocol for Terahertz band communication networks," in *IEEE Global Communications Conference (GLOBECOM)*, December 2015, pp. 1–7.

[160] S. DâĂŹOro, L. Galluccio, G. Morabito, and S. Palazzo, "A timing channel-based MAC protocol for energy-efficient nanonetworks," *Nano Communication Networks*, vol. 6, no. 2, pp. 39 – 50, 2015.

[161] N. Akkari, J. M. Jornet, P. Wang, E. Fadel, L. Elrefaei, M. G. Malik, S. Almasri, and I. F. Akyildiz, "Joint physical and link layer error control analysis for nanonetworks in the Terahertz band," *Wirel. Netw.*, vol. 22, no. 4, pp. 1221–1233, May 2016.

[162] S. J. Lee, C. A. Jung, K. Choi, and S. Kim, "Design of wireless nanosensor networks for intrabody application," *International Journal of Distributed Sensor Networks*, vol. 11, no. 7, pp. 1–12, 2015.

[163] N. Akkari, P. Wang, J. M. Jornet, E. Fadel, L. Elrefaei, M. G. A. Malik, S. Almasri, and I. F. Akyildiz, "Distributed timely throughput optimal scheduling for the internet of nano-things," *IEEE Internet of Things Journal*, vol. 3, no. 6, pp. 1202–1212, December 2016.

[164] X.-W. Yao and J. M. Jornet, "TAB-MAC: Assisted beamforming MAC protocol for Terahertz communication networks," *Nano Communication Networks*, vol. 9, pp. 36 – 42, 2016.

[165] R. Alsheikh, N. Akkari, and E. Fadel, "Grid based energy-aware MAC protocol for wireless nanosensor network," in *8th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, November 2016, pp. 1–5.

[166] P. Johari and J. M. Jornet, "Packet size optimization for wireless nanosensor networks in the Terahertz band," in *IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–6.

[167] R. Alsheikh, N. Akkari, and E. Fadel, "MAC protocols for wireless nano-sensor networks: Performance analysis and design guidelines," in *Sixth International Conference on Digital Information Processing and Communications (ICDIPC)*, April 2016, pp. 129–134.

[168] C. Jianling, W. Min, C. Cong, and R. Zhi, "High-throughput low-delay MAC protocol for Terahertz ultra-high data-rate wireless networks," *The Journal of China Universities of Posts and Telecommunications*, vol. 23, no. 4, pp. 17 – 24, 2016.

[169] C. Han, W. Tong, and X.-W. Yao, "MA-ADM: A memory-assisted angular-division multiplexing MAC protocol in Terahertz communication networks," *Nano Communication Networks*, vol. 13, pp. 51 – 59, 2017.

[170] L. Lopacinski, M. Brzozowski, and R. Kraemer, "Data link layer considerations for future 100 Gbps Terahertz band transceivers," *Wireless communications and mobile computing*, 2017.

[171] W. Tong and C. Han, "MRA-MAC: A multi-radio assisted medium access control in terahertz communication networks," in *IEEE Global Communications Conference (GLOBECOM)*, December 2017, pp. 1–6.

[172] Q. Li, X.-W. Yao, and C.-C. Wang, "RBMP: A relay-based MAC protocol for nanonetworks in the Terahertz band," in *Proceedings of the 4th ACM International Conference on Nanoscale Computing and Communication*, ser. NanoCom. New York, NY, USA: ACM, 2017, pp. 1–2.

[173] H. Yu, B. Ng, and W. K. G. Seah, "Pulse arrival scheduling for nanonetworks under limited IoT access bandwidth," in *IEEE 42nd Conference on Local Computer Networks (LCN)*, October 2017, pp. 18–26.

[174] Q. Xia and J. M. Jornet, "Cross-layer analysis of optimal relaying strategies for Terahertz band communication networks," in *IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, October 2017, pp. 1–8.

[175] N. Rikhtegar, M. Keshtgari, and Z. Ronaghi, "EEWNSN: Energy efficient wireless nano sensor network MAC protocol for communications in the Terahertz band," *Wireless Personal Communications*, vol. 97, no. 1, pp. 521–537, November 2017.

[176] Z. Li, L. Guan, C. Li, and A. Radwan, "A secure intelligent spectrum control strategy for future Terahertz mobile heterogeneous networks," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 116–123, June 2018.

[177] X. Yao, C. Wang, W. Wang, and J. M. Jornet, "On the achievable throughput of energy-harvesting nanonetworks in the Terahertz band," *IEEE Sensors Journal*, vol. 18, no. 2, pp. 902–912, January 2018.

[178] S.-J. Lee, H. Choi, and S. U. Kim, "Slotted CSMA/CA based energy efficient MAC protocol design in nanonetworks," *CoRR*, vol. abs/1803.00900, 2018.

[179] S. E. Hosseininejad, S. Abadal, M. Neshat, R. Faraji-Dana, M. C. Lemme, C. Suessmeier, P. H. BolÃ■var, E. AlarcÃşn, and A. Cabellos-Aparicio, "MAC-oriented programmable terahertz PHY via graphene-based yagi-uda antennas," in *IEEE Wireless Communications and Networking Conference (WCNC)*, April 2018, pp. 1–6.

[180] S. Salous, *Radio Propagation Measurement and Channel Modelling*, 1st ed. Wiley Publishing, 2013.

[181] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the Terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211–3221, October 2011.

[182] I. Gordon, L. Rothman, C. Hill, R. Kochanov, Y. Tan, P. Bernath, M. Birk, V. Boudon, A. Campargue, K. Chance, B. Drouin, J.-M. Flaud, R. Gamache, J. Hodges, D. Jacquemart, V. Perevalov, A. Perrin, K. Shine, M.-A. Smith, J. Tennyson, G. Toon, H. Tran, V. Tyuterev, A. Barbe, A. CsÃąszÃąr, V. Devi, T. Furtenbacher, J. Harrison, J.-M. Hartmann, A. Jolly, T. Johnson, T. Karman, I. Kleiner, A. Kyuberis, J. Loos, O. Lyulin, S. Massie, S. Mikhailenko, N. Moazzen-Ahmadi, H. MÃijller, O. Naumenko, A. Nikitin, O. Polyansky, M. Rey, M. Rotger, S. Sharpe, K. Sung, E. Starikova, S. Tashkun, J. V. Auwera, G. Wagner, J. Wilzewski, P. WcisÅĆo, S. Yu, and E. Zak, "The HITRAN2016 molecular spectroscopic database," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 203, pp. 3 – 69, 2017, hITRAN2016 Special Issue.

[183] H. Cui, J. Yao, and C. Wan, "The study on Terahertz wave propagation feature in atmosphere," *Journal of Physics: Conference Series*, vol. 276, no. 1, pp. 1–7, 2011.

[184] H. Song, K. Ajito, A. Wakatsuki, Y. Muramoto, N. Kukutsu, Y. Kado, and T. Nagatsuma, "Terahertz wireless communication link at 300 ghz," in *IEEE International Topical Meeting on Microwave Photonics*, October 2010, pp. 42–45.

[185] S. Priebe, C. Jastrow, M. Jacob, T. Kleine-Ostmann, T. Schrader, and T. Kurner, "Channel and propagation measurements at 300 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 5, pp. 1688–1698, May 2011.

[186] S. Priebe and T. Kurner, "Stochastic modeling of Terahertz indoor radio channels," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4445–4455, September 2013.

[187] S. Priebe, M. Kannicht, M. Jacob, and T. KÃijrner, "Ultra broadband indoor channel measurements and calibrated ray tracing propagation modeling at terahertz frequencies," *Journal of Communications and Networks*, vol. 15, no. 6, pp. 547–558, December 2013.

[188] K. Tsujimura, K. Umebayashi, J. Kokkoniemi, J. LehtomÃď'ki, and Y. Suzuki, "A causal channel model for the Terahertz band," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 1, pp. 52–62, January 2018.

[189] A. Afsharinejad, A. Davy, B. Jennings, S. Rasmann, and C. Brennan, "A path-loss model incorporating shadowing for Terahertz band propagation in vegetation," in *IEEE Global Communications Conference (GLOBECOM)*, December 2015, pp. 1–6.

[190] J. Kokkoniemi, J. LehtomÃď'ki, and M. Juntti, "A discussion on molecular absorption noise in the Terahertz band," *Nano Communication Networks*, vol. 8, pp. 35 – 45, 2016.

[191] ITU, "Recommendation ITU-R P.525-3: Calculation of free-space attenuation," Tech. Rep., 2016, accessed: 01-04-2019. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.525-3-201611-I!!PDF-E.pdf

[192] S. Bhardwaj, N. Nahar, and J. L. Volakis, "Link budget analysis for 350 GHz communication link," in *US National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*, January 2013, pp. 1–1.

[193] D. A. B. Miller, *Quantum Mechanics for Scientists and Engineers*. Cambridge University Press, 2008.

[194] S. Paine, "The am atmospheric model," March 2018. [Online]. Available: https://doi.org/10.5281/zenodo.1193771

[195] E. K. Smith, “Centimeter and millimeter wave attenuation and brightness temperature due to atmospheric oxygen and water vapor,” *Radio Science*, vol. 17, no. 6, pp. 1455–1464, 1982.

[196] F. Box, “Utilization of atmospheric transmission losses for interference-resistant communications,” *IEEE Transactions on Communications*, vol. 34, no. 10, pp. 1009–1015, October 1986.

[197] P. Boronin, V. Petrov, D. Moltchanov, Y. Koucheryavy, and J. M. Jornet, “Capacity and throughput analysis of nanoscale machine communication through transparency windows in the terahertz band,” *Nano Communication Networks*, vol. 5, no. 3, pp. 72 – 82, 2014.

[198] H. W. Elayan, C. Stefanini, R. M. Shubair, and J. M. Jornet, “End-to-end noise model for intra-body terahertz nanoscale communication,” *IEEE Transactions on NanoBioscience*, vol. 17, pp. 464–473, 2018.

[199] E. R. Brown, “Fundamentals of terrestrial millimeter-wave and Terahertz remote sensing,” *International Journal of High Speed Electronics and Systems*, vol. 13, no. 04, pp. 995–1097, 2003.

[200] P. Boronin, D. Moltchanov, and Y. Koucheryavy, “A molecular noise model for Terahertz channels,” in *IEEE International Conference on Communications (ICC)*, June 2015, pp. 1286–1291.

[201] B. Carli, “Basics of radiative transfer.” [Online]. Available: https://earth.esa.int/dragon/D2_L2_Carli.pdf

[202] L. Ippolito, R. Kaul, R. Wallace, U. S. N. Aeronautics, S. A. Scientific, T. I. Branch, and O. R. Incorporated, *Propagation Effects Handbook for Satellite Systems Design: A Summary of Propagation Impairments on 10 to 100 GHz Satellite Links with Techniques for System Design*, ser. NASA reference publication. National Aeronautics and Space Administration, Scientific and Technical Information Branch, 1985.

[203] A. Straiton, “The absorption and reradiation of radio waves by oxygen and water vapor in the atmosphere,” *IEEE Transactions on Antennas and Propagation*, vol. 23, no. 4, pp. 595–597, July 1975.

[204] R. B. L. Richard Feynman, Matthew Sands, *The Feynman Lectures on Physics*. Ingram Publisher Services US, 2015, vol. 1.

[205] J. Kokkoniemi, J. LehtomaÂÍki, and M. Juntti, “Frequency domain scattering loss in Terahertz band,” in *Global Symposium on Millimeter-Waves (GSMM)*, May 2015, pp. 1–3.

[206] F. M. Wu, B. F. Wu, X. Y. Zhao, Z. H. Zhang, H. Zhang, T. Y. Zhang, and Y. Fang, “Analysis on scattering and relationship with granular size in Terahertz spectra,” in *40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, August 2015, pp. 1–2.

[207] Y. Wang, F. Zhang, Z. Dong, and H. Sun, “Effects of nonsphericity on attenuation characteristics of terahertz atmospheric propagation,” in *41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, September 2016, pp. 1–2.

[208] S. Kim and A. ZajiÄĞ, “Statistical modeling of Terahertz scatter channels,” in *9th European Conference on Antennas and Propagation (EuCAP)*, April 2015, pp. 1–5.

[209] J. Ma, R. Shrestha, L. Moeller, and D. M. Mittleman, “Invited article: Channel performance for indoor and outdoor terahertz wireless links,” *APL Photonics*, vol. 3, no. 5, p. 051601, 2018.

[210] Z. Xiao, Q. Yang, J. Huang, Z. Huang, W. Zhou, Y. Gao, R. Shu, and Z. He, “Terahertz communication windows and their point-to-point transmission verification,” *Appl. Opt.*, vol. 57, no. 27, pp. 7673–7680, September 2018.

[211] A. Moldovan, M. A. Ruder, I. F. Akyildiz, and W. H. Gerstacker, “Los and nlos channel modeling for Terahertz wireless communication with scattered rays,” *IEEE Globecom Workshops (GC Wkshps)*, pp. 388–392, 2014.

[212] C. Han and I. F. Akyildiz, “Distance-aware multi-carrier (DAMC) modulation in terahertz band communication,” in *2014 IEEE International Conference on Communications (ICC)*, June 2014, pp. 5461–5467.

[213] H. Mabed and J. Bourgeois, “A flexible medium access control protocol for dense terahertz nanonetworks,” in *Proceedings of the 5th ACM International Conference on Nanoscale Computing and Communication*, ser. NANOCOM ’18. New York, NY, USA: ACM, 2018, pp. 1–7.

[214] N. Zhu and R. Ziolkowski, “Photoconductive thz antenna designs with high radiation efficiency, high directivity, and high aperture efficiency,” *IEEE Transactions on Terahertz Science and Technology*, vol. 3, no. 6, pp. 721–730, November 2013.

[215] W. Na, L. Park, and S. Cho, “Deafness-aware MAC protocol for directional antennas in wireless ad hoc networks,” *Ad Hoc Networks*, vol. 24, pp. 121 – 134, 2015.

[216] C. Han, J. M. Jornet, and I. Akyildiz, “Ultra-massive MIMO channel modeling for graphene-enabled Terahertz-band communications,” in *IEEE 87th Vehicular Technology Conference (VTC Spring)*, June 2018, pp. 1–5.

[217] S. Dhillon, M. Vitiello, E. Linfield, A. Davies, M. Hoffmann, J. Booske, C. Paoloni, M. Gensch, P. Weightman, G. Williams, E. Castro-Camus, D. Cumming, F. Simoens, I. Escorcia-Carranza, J. Grant, S. Lucyszyn, M. Kuwata-Gonokami, K. Konishi, M. Koch, C. Schmuttenmaer, T. Cocker, R. Huber, A. Markelz, Z. Taylor, V. Wallace, J. Zeitler, J. Sibik, T. Korter, B. Ellison, S. Rea, P. Goldsmith, K. Cooper, R. Appleby, D. Pardo, P. Huggard, V. Krozer, H. Shams, M. Fice, C. Renaud, A. Seeds, A. Stohr, M. Naftaly, N. Ridler, R. Clarke, J. Cunningham, and M. Johnston, “The 2017 Terahertz science and technology roadmap,” *Journal of Physics D: Applied Physics*, vol. 50, no. 4, January 2017.

[218] J. M. Jornet and A. Cabellos, “On the feeding mechanisms for graphene-based Terahertz plasmonic nano-antennas,” in *IEEE 15th International Conference on Nanotechnology (IEEE-NANO)*, July 2015, pp. 168–171.

[219] M. Esquius-Morote, J. S. GÃşmez-DÄśÂťaz, and J. Perruisseau-Carrier, “Sinusoidally modulated graphene leaky-wave antenna for electronic beamscanning at Terahertz,” *IEEE Transactions on Terahertz Science and Technology*, vol. 4, no. 1, pp. 116–122, January 2014.

[220] J. M. Jornet and I. F. Akyildiz, “Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band,” in *Proceedings of the Fourth European Conference on Antennas and Propagation*, April 2010, pp. 1–5.

[221] H. Elayan, R. M. Shubair, and A. Kiourti, “On graphene-based Terahertz plasmonic nano-antennas,” in *16th Mediterranean Microwave Symposium (MMS)*, November 2016, pp. 1–3.

[222] J. M. Jornet and I. F. Akyildiz, “Fundamentals of electromagnetic nanonetworks in the Terahertz band,” *Found. Trends Netw.*, vol. 7, no. 2-3, pp. 77–233, Dec. 2013.

[223] M. Naftaly, “Device characterization for Terahertz wireless links,” in *9th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, November 2017, pp. 364–369.

[224] B. Zhang, J. M. Jornet, I. F. Akyildiz, and Z. P. Wu, “Mutual coupling reduction for ultra-dense multi-band plasmonic nano-antenna arrays using graphene-based frequency selective surface,” *IEEE Access*, vol. 7, pp. 33 214–33 225, 2019.

[225] H. Visser, *Array and phased array antenna basics*. United States: Wiley, 2005.

[226] J. M. Jornet and I. F. Akyildiz, “Information capacity of pulse-based wireless nanosensor networks,” in *8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, June 2011, pp. 80–88.

[227] ——, “Channel capacity of electromagnetic nanonetworks in the Terahertz band,” in *IEEE International Conference on Communications*, May 2010, pp. 1–6.

[228] P. G. Fytampanis, G. V. Tsoulos, G. E. Athanasiadou, and D. A. Zarbouti, “Wireless channel capacity estimation in the Terahertz band,” in *International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT)*, March 2017, pp. 339–342.

[229] M. A. Akkas, “Terahertz wireless data communication,” *Wireless Networks*, June 2017. [Online]. Available: https://doi.org/10.1007/s11276-017-1548-4

[230] K. Liu, S. Jia, S. Wang, X. Pang, W. Li, S. Zheng, H. Chi, X. Jin, X. Zhang, and X. Yu, “100 gbit/s Terahertz photonic wireless transmission in the 350-ghz band with extended reach,” *IEEE Photonics Technology Letters*, vol. 30, no. 11, pp. 1064–1067, June 2018.

[231] X. Pang, S. Jia, O. Ozolins, X. Yu, H. Hu, L. Marcon, P. Guan, F. D. Ros, S. Popov, G. Jacobsen, M. Galili, T. Morioka, D. Zibar, and L. K. Oxenlwe, “Single channel 106 gbit/s 16QAM wireless transmission in the 0.4 Terahertz band,” in *Optical Fiber Communications Conference and Exhibition (OFC)*, March 2017, pp. 1–3.

[232] K. KrishneGowda, A. Wolf, R. Kraemer, J. C. Scheytt, and I. Kallfass, “Wireless 100 gb/s: PHY layer overview and challenges in the Terahertz freqency band,” in *WAMICON*, June 2014, pp. 1–4.

[233] J. M. Jornet and I. F. Akyildiz, “Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks,” *IEEE Transactions on Communications*, vol. 62, no. 5, pp. 1742–1754, May 2014.

[234] A. K. Vavouris, F. D. Dervisi, V. K. Papanikolaou, and G. K. Karagiannidis, “An energy efficient modulation scheme for body-centric nano-communications in the Terahertz band,” in *7th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, May 2018, pp. 1–4.

[235] B. Peng and T. KÃijrner, “A stochastic channel model for future wireless Terahertz data centers,” in *International Symposium on Wireless Communication Systems (ISWCS)*, August 2015, pp. 741–745.

[236] S. Kim and A. ZajiÄĞ, "Statistical modeling and simulation of short-range device-to-device communication channels at sub-thz frequencies," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6423–6433, September 2016.

[237] K. Yang, Q. H. Abbasi, K. Qaraqe, A. Alomainy, and Y. Hao, "Body-centric nano-networks: EM channel characterisation in water at the Terahertz band," in *Asia-Pacific Microwave Conference*, November 2014, pp. 531–533.

[238] J. Ma, R. Shrestha, L. Moeller, and D. M. Mittleman, "Channel characteristics for Terahertz wireless communications," in *43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, September 2018, pp. 1–2.

[239] S. Nie and I. F. Akyildiz, "Three-dimensional dynamic channel modeling and tracking for terahertz band indoor communications," in *IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, October 2017, pp. 1–5.

[240] S. G. Muttlak, O. S. Abdulwahid, J. Sexton, M. J. Kelly, and M. Missous, "Ingaas/alas resonant tunneling diodes for Terahertz applications: An experimental investigation," *IEEE Journal of the Electron Devices Society*, vol. 6, pp. 254–262, 2018.

[241] R. R. Choudhury and N. H. Vaidya, "Deafness: a mac problem in ad hoc networks when using directional antennas," in *Proceedings of the 12th IEEE International Conference on Network Protocols*, October 2004, pp. 283–292.

[242] K. Guan, D. He, A. Hrovat, B. Ai, Z. Zhong, and T. KÃijrner, "Challenges and chances for smart rail mobility at mmwave and thz bands from the channels viewpoint," in *2017 15th International Conference on ITS Telecommunications (ITST)*, May 2017, pp. 1–5.

[243] J. M. Jornet and E. Einarsson, "Link and network layers design for ultra-high- speed terahertz-band communications networks state university of new york (suny) at buffalo," 2016.

[244] S. Singh, R. Mudumbai, and U. Madhow, "Interference analysis for highly directional 60-GHz mesh networks: The case for rethinking Medium Access Control," *IEEE/ACM Transactions on Networking*, vol. 19, no. 5, pp. 1513–1527, October 2011.

[245] J. M. Jornet, "Low-weight error-prevention codes for electromagnetic nanonetworks in the terahertz band," *Nano Communication Networks*, vol. 5, no. 1, pp. 35 – 44, 2014.

[246] A. Moldovan, P. Karunakaran, I. F. Akyildiz, and W. H. Gerstacker, "Coverage and achievable rate analysis for indoor terahertz wireless networks," in *IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–7.

[247] C. N. Barati, S. A. Hosseini, S. Rangan, P. Liu, T. Korakis, S. S. Panwar, and T. S. Rappaport, "Directional cell discovery in millimeter wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 6664–6678, December 2015.

[248] Z. Hossain, Q. Xia, and J. M. Jornet, "Terasim: An ns-3 extension to simulate Terahertz band communication networks," *Nano Communication Networks*, vol. 17, pp. 36 – 44, 2018.

[249] M. Pierobon, J. M. Jornet, N. Akkari, S. Almasri, and I. F. Akyildiz, "A routing framework for energy harvesting wireless nanosensor networks in the Terahertz band," *Wireless Networks*, vol. 20, no. 5, pp. 1169–1183, July 2014.

[250] J. M. Jornet and I. F. Akyildiz, "Low-weight channel coding for interference mitigation in electromagnetic nanonetworks in the Terahertz band," in *IEEE International Conference on Communications (ICC)*, June 2011, pp. 1–6.

[251] "IEEE standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, pp. 1–709, April 2016.

[252] J. M. Jornet and I. F. Akyildiz, "Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band," *IEEE Transactions on Nanotechnology*, vol. 11, no. 3, pp. 570–580, May 2012.

[253] A. Galal and X. Hesselbach, "Nano-networks communication architecture: Modeling and functions," *Nano Communication Networks*, vol. 17, pp. 45 – 62, 2018.

[254] C. Han, A. O. Bicen, and I. F. Akyildiz, "Multi-wideband waveform design for distance-adaptive wireless communications in the terahertz band," *IEEE Transactions on Signal Processing*, vol. 64, no. 4, pp. 910–922, Feb 2016.

[255] M. S. I. Mahfuz and S. Saha, "Channel sharing based medium access control protocol for wireless nano sensing network," *Global Journal of Computer Science and Technology*, vol. 15, no. 8, 2015.

[256] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 115–121, April 2006.

[257] M. Kolano, O. Boidol, S. Weber, D. Molter, and G. V. Freymann, "Single-laser polarization-controlled optical sampling system for Terahertz - TDS," in *43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, September 2018, pp. 1–3.

[258] S. Priebe, M. Jacob, and T. KÃijrner, "Polarization investigation of rough surface scattering for thz propagation modeling," in *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, April 2011, pp. 24–28.

[259] M. S. Rabbani and H. Ghafouri-Shiraz, "Improvement of microstrip antenna's gain, bandwidth and fabrication tolerance at Terahertz frequency bands," in *Wideband and Multi-Band Antennas and Arrays for Civil, Security Military Applications*, December 2015, pp. 1–3.

[260] P. Lu, V. Rymanov, S. DÃijlme, B. Sievert, A. Rennings, and A. StÃűhr, "Terahertz beam forming and beam switching using lens-assisted quasi-optical thz transmitter," in *International Topical Meeting on Microwave Photonics (MWP)*, October 2017, pp. 1–4.

[261] S. Nie, J. M. Jornet, and I. F. Akyildiz, "Intelligent environments based on ultra-massive mimo platforms for wireless communication in millimeter wave and terahertz bands," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, May 2019, pp. 7849–7853.

[262] Y. Zhao, B. Ai, D. Fei, Y. Liu, and N. Li, "Adaptive beamforming based on subband structure in smart antennas," in *32nd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, August 2017, pp. 1–2.

[263] Z. Rong, M. S. Leeson, and M. D. Higgins, "Relay-assisted nanoscale communication in the Terahertz band," *Micro Nano Letters*, vol. 12, no. 6, pp. 373–376, 2017.

[264] M. Park and H. K. Pan, "Effect of device mobility and phased array antennas on 60 ghz wireless networks," in *Proceedings of the 2010 ACM International Workshop on mmWave Communications: From Circuits to Networks*, ser. mmCom '10. New York, NY, USA: ACM, 2010, pp. 51–56.

[265] H. Shokri-Ghadikolaei, C. Fischione, P. Popovski, and M. Zorzi, "Design aspects of short-range millimeter-wave networks: A mac layer perspective," *IEEE Network*, vol. 30, no. 3, pp. 88–96, May 2016.

[266] C. Han and I. F. Akyildiz, "Distance-aware bandwidth-adaptive resource allocation for wireless systems in the Terahertz band," *IEEE Transactions on Terahertz Science and Technology*, vol. 6, no. 4, pp. 541–553, July 2016.

[267] I. F. Akyildiz, C. Han, and S. Nie, "Combating the distance problem in the millimeter wave and terahertz frequency bands," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 102–108, June 2018.