Terahertz Band Communication Systems: Challenges, Novelties and Standardization Efforts

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Abstract

Wireless data rates are expected to be around 10Gbps or even more within the upcoming decade. The realization of such high data rates is unlikely with the currently licensed bands in the spectrum. Therefore, it is clear that such high rates could only be achieved by employing more bandwidth with the state–of–the–art technology. Considering the fact that bands in the range of 275GHz–3000GHz, which are known as Terahertz (THz) bands, are not yet allocated for specific active services around the globe, there can be a true potential to achieve the desired data rates at THz bands. However, due to the characteristics of these bands, there are many open issues in terms of THz radio communication system design. In this study, open issues and the state–of–the–art solutions to theses issues for THz communication system design are discussed. Moreover, standardization efforts up to date are elaborated. This study concludes that the actual implementation of fully operational THz communication systems obliges to carry out a multi–disciplinary effort including statistical propagation and channel characterizations, adaptive transceiver designs (including both baseband and radio frequency (RF) front–end portions), reconfigurable platforms, advanced signal processing algorithms and techniques along with upper layer protocols equipped with various security and privacy levels.

Keywords: Terahertz, beyond 5G wireless communication, nanonetworks, terahertz hardware, graphene

1. Introduction

The value of information is increasing day by day and accordingly, extensive work is carried out on generation, transmission, and storage of information. For instance, rapid expansion of sensor networks and high definition video streaming devices in daily life motivate researchers to investigate new ways to find data transmission. Moreover, video surveillance with ultra-high definition cameras and wireless backhauls that demand high data rates are increasing exponentially. According to the report published by Cisco [1], in 2021, the annual total IP traffic will reach 2.3 zetta–bytes and 63 percent of this traffic will belong to wireless mobile devices. Besides, it is pointed out that virtual reality (VR) and augmented reality (AR) traffic will increase 20–fold between 2016 and 2021 globally. According to Edholm's Law of Bandwidth, as explained in [2], it is expected that the wireless data rates will reach 100Gbps by the year 2020. As a result, it is required that the transmission bandwidth becomes wider. mmWave technology cannot fulfill the demand alone for such a high data rate since there is only 9GHz bandwidth for available data transmission [3]. It can be seen from the frequency allocation chart [4] that there is no single chunk of available bandwidth larger than 10GHz below 100GHz. Although free space optical (FSO) communication systems can be thought as a solution, low transmission power constraint owing to eye safety, and necessity of alignment between transmitter and re-

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ceiver in a strict manner make FSO unpractical for mobile and personal network [5]. On the other hand, in contrary to FSO, signals transmitted at terahertz (THz) frequencies are reflected from the minimal objects; thus, the data can be transmitted over non–line–of–sight (NLOS) links [6]. THz bands which are least studied frequency region, look promising to achieve data rates demanded by the users. As a result of the progress in the electronic components, it has opened the way for the THz band to be utilized in scenarios[7, 8].

Wireless communications at THz bands are expected to cause emergence of many applications in the near future. Some technologies which were not possible to be realized due to their high data rate demands could be implemented by available extensive bandwidth resources in the THz region. Any kind of short range - very high data rate application becomes a possibility with THz communications. On the other hand, nano devices will also be able to operate at THz frequencies since these frequencies have much shorter wavelengths when compared to millimeter wave bands and nano devices with miniature antennas will be able communicate under these conditions. Such wirelessly communicating nano devices will lead to many different applications. Moreover, THz wireless communications will be likely utilized in applications such as AR and VR. Considering that 5G wireless networks will operate at Tbps data rates [9], THz bands can be used for 5G and beyond wireless backhauling. In addition, it can be expected that chip–to–chip and on–chip communications, security–oriented communications, and body area networks (BANs) to utilize THz bands.

In spite of promising available bands in THz spectrum, there are many challenges to be overcome. As a result of high frequency characteristics, high absorption loss is one problem, spreading loss is another. Classical physical layer and medium access control layer methods should be revised to combat such problems and new systems should be designed to operate in these bands. THz channel characteristics must be investigated, analyzed and modeled for reliable and dependable wireless communications. When the studies in this context are investigated, it is seen in literature that some features are proposed for the physical layer of THz links in terms of modulation and channel coding. The upper layers must be revised for the usage of THz frequencies due to the difficulties in the processing of data at terabits level. On the other hand, it is necessary to design hardware (i.e. transceivers, antennas, amplifiers) in order to produce and detect high–frequency signals. With the progress in Graphene technology, it is thought that these difficulties, which are very difficult to overcome until recently, can be solved [10, 11].

It is known that wireless communication systems operating in licensed bands are brought to a standard with various regulations. Consequently, THz bands must have a standard for reliable communications. For this purpose, IEEE 802.15 wireless personal area network (WPAN) Task Group 3–D 100 Gbit/s Wireless (TG 3d 100 G) [12] is activated and has begun to take the first steps for standardization. This paper addresses the current open issues in the design of THz wireless communication system in terms of hardware, physical channel and network. Furthermore, the solutions for open issues are discussed in the light of the works recently proposed in this field.

The remainder of this paper is organized as follows: Section 2 details the usage scenarios of THz wireless communication. In Section 3, we define the challenges specific to THz bands and give novel approaches to deal with these challenges from literature. The achieved data rates with the transmission at THz frequencies are given in Section 4. The standardization efforts to date are presented in Section 5. Finally, Section 6 concludes the paper.

2. Application Scenarios

As THz bands provide ultra–wide bandwidth, there are several applications areas which require high data rates above tens of Gbps that can be provided in these bands, including nano-scale and macro-scale communications utilization. THz band communications can play the role in bridging the dream to reality for many applications. The increasing amount of data and the frequent use of communication systems indicate that THz band communications will contribute to emergence of a vast number of use cases in the near future. Some example applications which will possibly employ THz networks are depicted in Figure 1. In this section, we will provide possible utilization of THz band communications in several important applications.

2.1. Fronthaul and Backhaul Links

The wireless backhaul will need to satisfy high data rates demanded by users applications in the

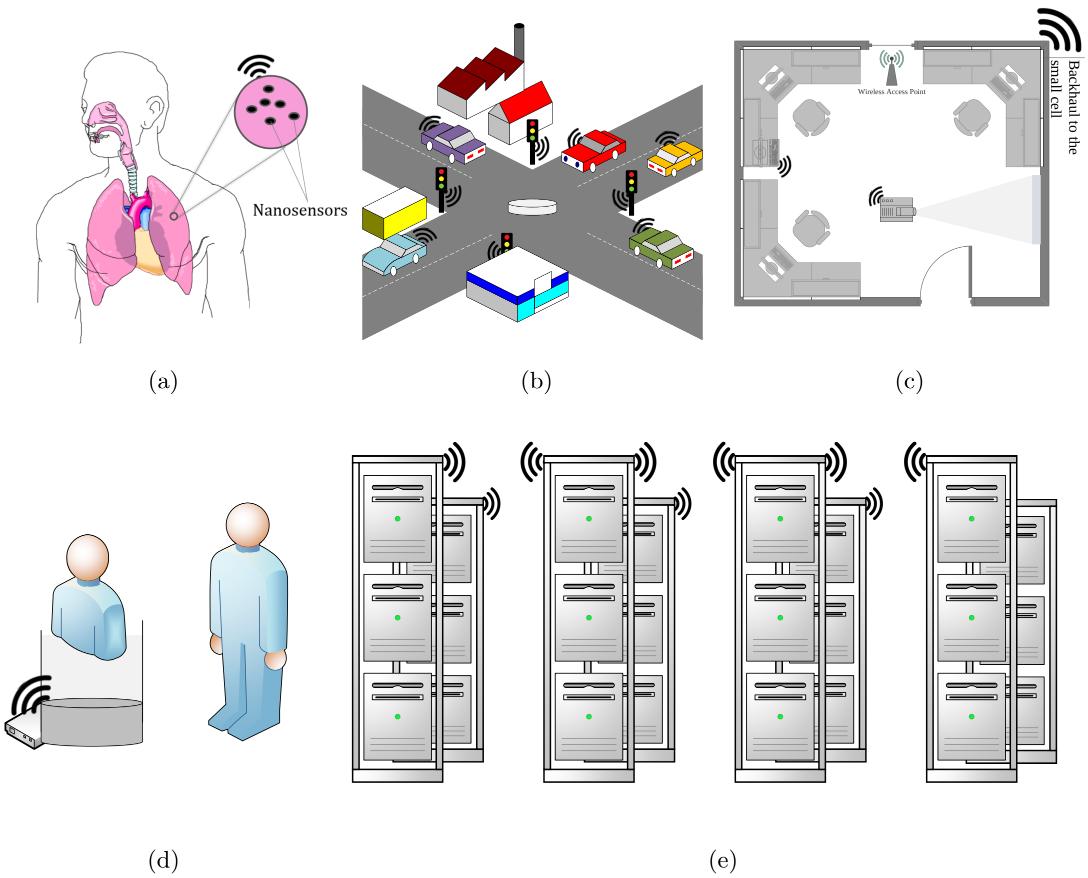


Figure 1: Some of the major terahertz communication application areas such as (a) nano sensors for monitoring lung cells, (b) vehicular THz network, (c) small cell, (d) high–definition holographic video conferencing, (e) inside data center communication

following decade. For example, 5G and beyond wireless networks are planned to reach Tbps data rates [9]. The new bands around 60GHz can provide increase up to only 6Gbps in terms data rates [3]. Since the installation of end-to-end fiber–optic communications is very costly and takes much time to build, THz links can be employed as wireless extension of optical fiber systems [13] to reduce cost and installation periods. This architecture is illustrated in Figure 2. Furthermore, the requirement of increasing overall throughput of cellular base stations leads also to high data rate demand for their wireless backhaul, especially as mmWave communications comes into the picture. Hence, fronthaul and backhaul links must promise high data rates for reliable data transmission from end users or applications connecting to a mmWave small cell. In [14], it is shown that THz bands can realize several tens of Gbps of wireless links for distances up to 850m. ThoR project which is supported in Horizon 2020 program investigates backhauling and fronthauling by utilizing transceivers operating at 300GHz [15]. Recently, the project analyzed the interference due to Earth exploration–satellite service (EESS) and provide possible bands to be used without harmful interference to EESS. A THz wireless communications system is worked outdoors, it needs highly directive antennas or antenna arrays. The nano antennas such as Yagi–Uda nano antenna recently proposed in [16] and they can be employed to set highly directional links in order to solve the distance problems in THz band propagation channels.

2.2. Nano Devices

The developments in electronic technologies enable to reduce size of devices by use of nano materials. The nano devices and nano sensors can be employed in the vast applications from health monitoring (e.g. monitoring of lung cells [17, 18]) to defence [19].

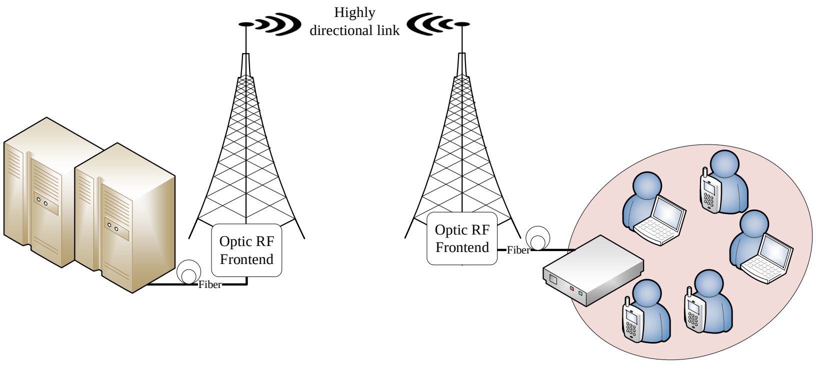


Figure 2: Fiberoptic communication architecture with THz backhaul

THz bands encourage nano-scale device communications since antenna size constraints are drastically changing in these frequencies. Due to the size of nano devices, emission frequency range of antennas becomes very wide since nano-scale antennas such as graphene nano ribbon (GNR) and carbon nano tube (CNT) can radiate efficiently starting from THz frequency ranges [10]. Although nano devices can emit electromagnetic wave at MHz frequency levels with electromechanical nano transceivers, the energy efficiency of mechanically electromagnetic wave generation is lower when compared to THz bands [19]. Moreover, nano devices are considered to have a constraints on the power consumption; therefore from power perspective it seems more appropriate to operate in these bands for them too. Some examples for implementation of wireless nano devices at THz frequencies are detailed below.

2.2.1. Health

One of the biomedical applications of stand alone or networked nano-devices is visual imaging for diagnosis by using capsule endoscopes [20–24] which allows painless imaging of bowel of patients with recurrent gastrointestinal bleeding. Furthermore, health monitoring [25–32] can be conducted by biosensors which enable to track the prognostics in cancer and DNA mutations. Another biomedical application of nano devices is drug delivery [33–42]. For instance, the nano devices can be employed in the drug delivery for treatment of metastatic cancer since many drugs are not able to reach the sites of metastases [43], thereby mostly taking failure in the cancer cure. Besides all these, nanorobots can be employed in the tissues in order to detect and fight against malicious microorganisms and cancer cells with non–operative and real–time treatment [44]. In–vivo applications [45–49] are required to be carefully analyzed in the aspects of channel and noise modeling since biological tissues have different amount of water which causes peaks in the absorption–frequency relation [50].

2.2.2. Military

Besides the health applications, nano devices that are communicating in THz bands can be employed in military defense field such as detection of chemical, biological and nuclear agents in the battlefield and brain–machine interface for the safety of the troops [51, 52]. The BioFluids program of DARPA envisions the applications of nano devices in military defense [53]. Furthermore, the equipment of a soldier and nano sensor network deployed on the body of a soldier can be thought of as a BAN application. Furthermore, the nano devices can have a potential application in the industry to control the product quality [51] and make work sites such as production lines to be more intelligent [54]. Nano sensor or nano device network can communicate with each other and also with other networks over the THz frequency band. The lower latency requirement for the production line can be provided with the use of THz networks.

2.2.3. Environmental Pollution Monitoring

As THz communications equipped nano sensors can sense the chemical compounds present in the environment with one part per billion density [55], they can be employed to track the toxic element density in the environment or in the potable water reservoirs of cities and report the results immediately. In this way, the life quality of people can be raised up to levels that are planned to be achieved with smart city applications. Also, air pollution can be monitored with wireless nano sensor networks utilizing THz bands. Another aspect of air pollution tracking can be thought as nano sensors and global positioning system (GPS) deployed on a vehicle and joined together to collect data in cities while driving. THz receiver systems that can be built on the roadsides or mounted on the traffic lights can be utilized to download these data collected by vehicles.

2.3. Entertainment Technologies and Augmented Reality

Advanced developments in visual technologies such as 3D movies, Blu–ray, ultra–high definition movies, and gaming platforms require huge data rates. Apart from this, new emerging technologies such as AR, VR, high–definition holographic video conferencing, haptic communications, and tactile internet also demand high data rates. To satisfy such demand ultra–wide THz bands can be employed. By using a THz band, the files with high data size can be downloaded from kiosks deployed in shopping malls, airports, and so on [56, 57]. They enable users with hand-held devices to achieve data rates of 100Gbps. At 90cm distance from the kiosk data rates can reach up to 108Gbps [56]. In kiosk applications, the cavity–like channel is observed due to high directional beam in line–of–sight (LOS) condition. However, it is not a vexed issue and channel response is easily estimated and the cavity can be eliminated [57]. The kiosk–like application can be accomplished for airplane entertainment systems too. The THz band can be used instead of transmitting data over wired network to the passengers. Thus, cable cost can reduced and, more importantly, aircraft weight can also be reduced and implementation turns into efficiency in fuel consumption.

The applications requiring high data rates such as high–definition holographic video conferencing AR and VR can utilize THz communications because it can enable seamless connection between ultra–high speed wired networks and wireless devices [13]. When eye and ear are not synchronized, cybersickness appears while using AR and VR systems. Synchronization has to be below 10ms to avoid cybersickness [58]. This synchronization constraint can be satisfied with THz networks. The audiovisual communication supporting by haptic modality provides touching or manipulating objects. This phenomenon is called as haptic communications [59–62]. Haptic modality enhances the sense of togetherness and study performance [62] but it needs small delay compared to audio and video communications [63]. Since distributed haptic–based virtual environments use transmission control protocol (TCP) at the transport layer [64], congestion can occur at the time when transmission exceeds available throughput and delay in the network may occur. To deal with the congestion problem in a haptic communications system, THz networks can be a good candidate for the infrastructure. It is expected that the tactile internet which is a special form of haptic communications, will operate at low latency values[65–70]. It will also require fast network congestion detection and avoidance schemes. For these reasons, it is envisioned that THz networks will be a catalyst in the emergence of the tactile internet. THz networks seem to be candidate systems enabling ultra–low latency. For example, TERRANOVA [71] which is the project funded by Horizon 2020 program, focuses on the network design that provides almost zero–latency with extremely high data rates.

2.4. Directional Communication Links

THz band communication suffers from short distance propagation characteristics due to high molecular absorption loss, this disadvantage can enable to secure communication because of short distance, narrow beam, and short pulse duration that cannot be eavesdropped. Furthermore, spread spectrum techniques can be employed in THz band to avoid and cope up with serious jamming attacks [72].

Another possible usage of a THz band is on–chip and chip–to–chip communication. The cores need to communicate with each other, share data among themselves, and make synchronization to realize data parallelism. Since the number of nodes increases, the solutions originally proposed for the problems in the network are reused to deal with the same problems arising in on–chip communications [73]. Although the network concept is used for chip communication, the communication must satisfy extremely high data rates. Therefore, THz network can be a candidate to operate in chip communication. Besides fast communication, another reason for using the wireless communication is that the wired connectors and microstrip lines on printed circuit boards (PCBs) are a bottleneck of inter–chip communications [74]. The wireless connections in data centers are investigated for mmWave band in [75–77]. These connection techniques can be upgraded to THz links which have adaptive beamforming and steering. As a result, the possibility of transmitting data at high speed on the order of Tbps levels within the data center occurs. For this purpose, TERAPOD project [78] is conducted by the supports of Horizon 2020. In the project, end–to–end demonstration of THz wireless communication system in a data center is targeted.

2.5. Satellite Communications

Another use of THz bands is for satellite communications. For instance, Atacama Large Millimeter/sub–millimeter Array (ALMA) in Chile is planned to operate at ten bands between 0.031 and 0.95THz [79]. Even though there is a concern about the short propagation distance due to spreading and molecular losses, THz propagation distance can be extended by using massive-antenna array techniques, high output power, and high gain amplifiers. It is more appropriate to use the THz bands in dry regions because molecular absorption is mostly caused by water vapor. By using airborne platforms which can fly above over 99% of all atmospheric water vapor, the molecular absorption loss can be eliminated mostly [80]. The use of airborne platforms makes eavesdropping more and more difficult because of low–earth absorption loss. In [81], link budget analysis and signal–to–noise ratio (SNR) performance are evaluated. This study shows that using the THz band to establish high–speed data links is not a pie in the sky.

Furthermore, there are many application scenarios cases such as wearable devices operating at THz frequencies in BAN [82, 83], railway technology [84–87], energy harvesting in nano sensor networks [88–90], vehicular networks [91–93]. We see a high possibility of being used in adaptive energy–efficient computing box [94] for inter–device and intra–device communication. In addition, each usage area can lead to new application domain. For this reason, there is no doubt that the area of use will be expanded.

2.6. Heterogeneous Networks

The size of THz cells is expected to be only a few meters; hence, new architectural designs are required. However, as stated in [95], THz cells cannot provide seamless connection on their own. To exploit THz bands efficiently, THz wireless communication system might be employed in heterogeneous networks. The standalone and non–standalone modes defined in Release 15 [96] can be an example for the heterogeneous network concept for THz networks. A similar system can be employed in between THz and mmWave networks for beyond 5G. Obviously, improving THz wireless communication in different layers of heterogeneous networks is inspirational for future research.

3. Challenges and Solutions

There are several challenges for wireless THz communications system design, which need to be investigated and tackled in order to be able to create practical systems. In this section, the challenges and the novel approaches to solve these problems are discussed.

3.1. Transceivers Design in Terahertz Band

The design of transceivers that should operate with a wide bandwidth in the THz bands is an important challenge. The difficulty in the signal generation at THz frequencies arises from the fact known as the THz gap which means the frequency band is too high for conventional oscillators and too low for optical photon emitters. The signal generation at THz level is achieved by two methods: top–down and bottom–up. The bottom–up method is performed by multiplexer while the top–down approach uses a photonics system such that laser stimulation of the semiconductors produces continuous or pulsed THz radiation, and the non–linear crystals or lasers are operated directly on the THz frequencies [97]. As shown in Figure 3, the bottom–up method may include more than one multiplexer. In this case, it is expected that the number of inter–modulation products and their total power will increase in the generated signal; therefore, modulated signals are highly distorted when multiple mixers are employed. A large number of multiplexers should be avoided in order to keep spurious effects and inter–modulation distortion as low as possible in the bottom–up method. Because transceivers have to deal with high path loss due to high absorption and molecular loss in the THz bands, one should consider the problems of high power, high sensitivity and low noise figure

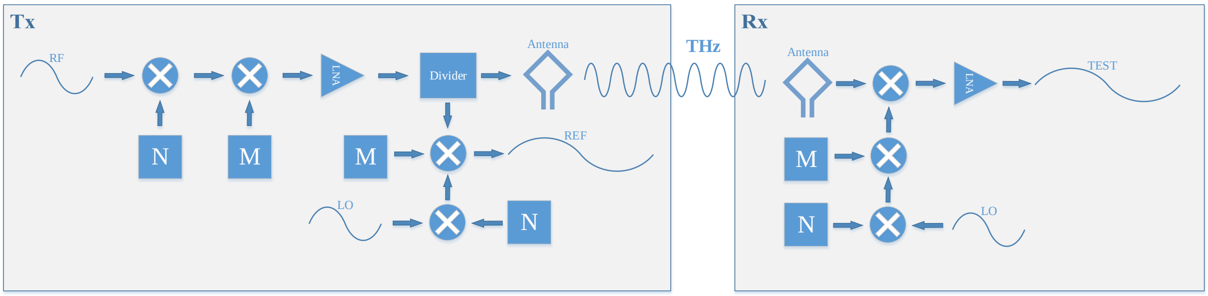


Figure 3: Block diagram for bottom–up approach in THz signal generation and reception

in the design. The materials such as Silicon Germanium (SiGe), Gallium Nitride (GaN), Indium Phosphide (InP), and Graphene are used in design to realize transceiver targets [98, 99].

SiGe heterojunction bipolar transistors (HBTs) provide good linearity, high gain, low noise, and silicone compatibility at THz frequencies [100]. There are several studies on the mixer–based receivers with SiGe HBTs which have the maximum frequency of 380GHz [101], 435GHz [102], 450GHz [103, 104], and 500GHz [105]. SiGe–based transistors are proposed to allow maximum oscillation frequency and cut–off frequency to reach up to 798GHz and 479GHz, respectively [106]. Silicon technologies can only present limited improvement to 1THz because of its intrinsic characteristics [5]. Moreover, SiGe HBT's limited power gain and inadequate transistor breakdown voltage prevent its use in high power applications at frequencies above 500GHz [72].

Since high gain power amplifiers are required owing to very high path loss, GaN–based transistors stand out in order to compensate for high power necessity. Thanks to high voltage characteristics around 3.3MV/cm and high electron velocity around 2.5×10^7cm/s, GaN high electron mobility transistor (HEMT) is a profound research area for high voltage and high power mmWave and THz applications. Recently, a GaN–based HEMT with the maximum oscillation frequency of 444GHz, the cut–off frequency of 454GHz, and the breakdown voltage of 10V is designed [107]. GaN–based metal–semiconductor–metal two–dimensional electron gas (2DEG) varactor [108] has cut–off frequency of 1.54THz and figure of merit of 4.06THz. Furthermore, another GaN–based HEMT [109] has features such as cut–off frequency at 2.24THz but with very low breakdown voltage. The authors have shown by incorporating ohmic and 2DEG/metal Schottky contacts to make possible to reach up to the cut–off frequency of 2.02THz while maintaining the breakdown voltage above 18V.

Semiconductor technologies such as InP HBT implies good performance in output power, noise figure, and efficiency at sub–THz band [110]. InP HBTs achieves much wider bandwidths in similar scalable generation while delivering twice as much breakdown voltage as SiGe–based transistors [111]. For instance, it is reported in [112–115] that InP–based HEMTs indicate cut–off frequency/maximum oscillation frequency of 600GHz/1.2THz. Besides these transistors, InP–based HEMT THz monolithic integrated circuits (TMICs) enable to reach up to 850GHz [116, 117]. It is demonstrated in [118] that InP HEMT can provide amplification at 1THz.

Fujitsu recently introduced a compact 300GHz receiver capable of 20Gbps data stream [119]. The mentioned systems up to here, use multipliers to upconvert multi–GHz into THz frequencies. Therefore, the harmonics can be generated, then they degrade the energy efficiency of the transceiver [120].

The most recent material employed for transceiver design is graphene since it has high electrical and thermal conductivity properties and shows plasmonic effects. Graphene is two–dimensional material which allows signals to propagate at THz frequency [121]. Another virtue of graphene is supporting the propagation of THz surface plasmon polariton (SPP) waves [122]. The nano transceiver based on HEMT built with III–V semiconductor and enhanced with graphene is detailed in [123]. Applying voltage between drain and source of HEMT causes electrons to accelerate in the channel so that this electron movement forms SPP wave on the graphene gate. This process reciprocally occurs in reception. The wideband modulators are necessary for utilization from the large bandwidth advantage of THz. For this purpose, graphene–based THz SPP modulators are designed in [11, 124, 125]. The modulator is based on graphene–based constant length plasmonic wave-guide and modifies the difference between the energies of highest and lowest occupied states, which is known as the Fermi energy of the graphene layer, to increase the probability of adjusting the propagation velocity of SPP waves on the graphene. Its working principle is based on the capability of dynamic control over graphene conductivity. As a consequence of that, the amplitude modulation can be realized.

Top–down approaches use the quantum cascade lasers (QCLs) or bolometric detectors as a local oscillator in the heterodyne transceiver. Combining QCLs and III–V semiconductors (i.e GaN, InP) provides the device to operate at THz frequencies [72]. The QCLs are stated that they are able to perform within the frequency range from 1.2THz to 5.4THz with power about 1W [126, 127]. Even though QCLs are able to provide high power signal [128], the transceiver based on photonic approaches are not practically usable since they require a laser and operate at cryogenic temperatures. So far, according to our knowledge, the highest operating temperature is 199.5 K [129] which indicates why the cryogenic cooler is necessary. The use of Peltier thermoelectric cooler is offered as a solution for QCL operation at around 230 K [130].

The materials and devices are listed in Table 1 based on their characteristic advantages and disadvantages.

3.1.1. Antennas

Broadband antenna are needed to be designed to take the advantage of ultra–wideband transmission at the THz bands. Another design criterion for mitigate the transmission distance problem due to high path loss is antenna directivity. Graphene–based antennas and large antenna arrays are frequently suggested to meet these two requirements. Graphene supports propagation of SPP waves at THz frequencies. Compared to copper and CNT, graphene shows better performance to create antennas with small size implementation [131] and high directivity [132, 133]. Plasmonic graphene antennas [134–140] can be sized at nanoscale which means that these antennas can be used for nano devices.

The plasmonic graphene antennas enable propagation of SPP waves at THz frequencies for nano devices. The speed of SPP waves in the graphene is almost twice as fast as the velocity in the vacuum [10, 136]. Therefore, the SPP wave propagates at the frequencies as low as THz band. Furthermore, the frequency can be tuned by material dopping because the conductivity of graphene is dependent on chemical doping, Fermi energy, and electron mobility [141]. For example, the doping is expressed as an intentional introduction of impurities into an intrinsic semiconductor in order to modulate, electrical, optical and structural properties; hence, the performance of graphene can be increased by chemical doping [142]. In [143], the performance of graphene–based plasmonic nano antenna arrays in THz frequencies is investigated by taking into account the effect of reciprocal coupling. It shows that near–field coupling can be ignored when the distance between antennas is less than free space wavelength. Nafari and Jornet developed a mathematical framework [144] and analyzed plasmonic nano antenna performance based on it. In [145, 146], waveguide–fed graphene–based antennas operating at 2.7THz and 2THz are given. These antennas have operating bandwidth up to 170GHz. A plasmonic patch antenna based on graphene is designed to operate at 700GHz is proposed in [139]. As mentioned in [147], an antenna can be tuned by applying electrostatic bias. Besides SPP wave propagation, graphene allows designing reconfigurable directional antennas.

The beamforming and beam scanning is two crucial design criteria for multi–input multi–output (MIMO) systems. In [148, 149], antenna designs capable of beam scanning are proposed. Use of this antenna design is not that easy for nano device since different bias voltages, as much as 45V, are used to tune radiation pattern. Also, [150] provides insight for the recent studies in beam control. A reconfigurable graphene–based Yagi–Uda MIMO antenna design is given in [151] which is designed for the first time by using a graphene patch array.

Another antenna type is horn antenna [152, 153] which can operate in THz bands. While the horn antennas have the capability of propagation at 300GHz with the bandwidth of 100GHz and 18dBi gain, the dimension of the antenna does not allow the utilization for on–chip design [151]. The planar antennas can be candidate antenna design for employment in THz applications due to their easy fabrication and integration to other planar anten-

Table 1: Advantages and disadvantages of materials used in transceiver design

Material/Device	Advantages	Disadvantages	References
SiGe	• good linearity • high gain • low noise • silicone compatibility	• limited improvement up to 1THz • limited power gain • insufficient breakdown voltage	[101–106]
GaN	• high voltage characteristics • high electron mobility • high gain	• low breakdown voltage in some applications	[107–109]
InP	• high breakdown voltage • low noise figure	• frequency up to 1.2THz	[110–118]
Graphene	• high electrical conductivity • support SPP waves	• more research is required	[11, 123–125]
QCL	• very high operating frequency • high power	• very low operating temperature • large size	[126–130]

nas [154]. Planar antennas, however, are deprived of high gain and directivity, providing long–distance transmission. The pros and cons of the antennas are summarized in Table 2.

3.1.2. Amplifiers

As radiation power and received power are low, THz signals should be amplified to propagate through long distances. However, an amplifier must support a wide frequency regime to operate in the THz bands. When multiple signals are amplified at the same time, the intermodulation products are generated by amplifiers owing to nonlinear characteristics. Intermodulation products are not desired since they are decreasing the energy efficiency. Besides intermodulation products, it is expected that the designed amplifier shows low noise figure. The amplifiers can be designed based on solid–state electronics [155–159] for the low THz frequency region. Nevertheless, the present trend takes an interest in the frequencies above 300GHz. In addition, graphene–based amplifier design given in [160] has maximum gain of 31dB, on the other hand, it operates at the temperatures as low as 40 K. So that this amplifier cannot make full amplification of the signal at the room temperature. The recent developments in amplifier design which can efficiently operate above 300GHz are summarized in Table 3 for the readers.

3.2. Channel and Noise Modeling

As a result of very small wavelengths in the THz regime, the propagation characteristics become different compared to the bands are used currently. Channel and noise should be firstly modeled to make high performance and reliable THz communications real. In this section, noise and channel characteristics at THz bands are discussed.

3.2.1. Channel

In studies related to channel modeling, various methods are introduced for frequency, time, and spatial domains. Also, application specific scenarios are encountered in the literature. Some application–specific studies (e.g. channel measurement on a desktop) indicates the channels at 300GHz [175–177].

There are two main methods for propagation analysis in a given environment; first is the deterministic approach based on ray–tracing or ray–launching. When ray–tracing is employed to model

Table 2: Advantages and disadvantages of antennas used in THz bands

Antenna Type	Advantages	Disadvantages	Reference(s)
Graphene	• propagation of SPP waves • small size implementation • high directivity	• need more studies on it	[10], [136], [141], [143], [145–147]
Horn	• wide bandwidth • propagation at 300GHz • high gain	• large size • non-compatible with nano devices	[151–153]
Planar	• easy fabrication • easy integration	• low gain • low directivity	[154]

Table 3: Amplifiers in THz bands

Frequency (GHz)	Gain (dB)	Material	Reference
324	4.8	InP DHBT	[161]
340	15	InP HEMT	[162]
340	16	InP HEMT	[163]
390	7	InP HEMT	[164]
460	16.1	GaAs HEMT	[165]
460	16.1	metamorphic-HEMT	[166]
480	11.7	InP HEMT	[167]
492	9	InAs HEMT	[168]
500	13.5	InGaAs HEMT	[169]
550	10	InP HEMT	[170]
576	15.4	metamorphic-HEMT	[171]
610	20.3	metamorphic-HEMT	[114]
650	10	InP HEMT	[113]
670	30	InP HEMT	[172]
670	24	InP DHBT	[115]
850	6	InP HEMT	[116]
1000	10	InP BDT	[173]
1000	12	TWA	[174]

a channel, the environment in which the electromagnetic waves propagate is completely defined with sizes, shapes, and materials of objects. It is a fact that this method hampers to get a result if any change in the scenario is conducted. Moreover, the complexity increases exponentially when the size of the environment becomes larger. However, it gives accurate information about the channel [178] under given conditions. Ray–tracing based approach is recently utilized in [179, 180] to analyze channels in a data center and indoor communications in terms of temporal and spatial channel characteristics. In [56], the channel parameters in time, frequency, and spatial domains are modeled for each type of ray in order to analyze the channel characteristics for kiosk applications.

The stochastic methods get the average of the environmental effects instead of a specific environment model is contrary to the deterministic model. Some models are recently proposed in [181–183]. The path loss and noise diverse rapidly for in–vivo applications because human tissues include materials with different molecular characteristics. In such cases, the path loss is dependent on not only frequency and distance but also the dielectric loss of tissue. Moreover, the scatterers such as particles and cells cause the loss in signal energy. Recently, the studies [184–186] are published which focus on the nano device communications in the human body.

The measurements are needed to define strategies for wideband signal processing in unitTHz bands. For instance, the spectrum between 260GHz and 400GHz is swept with bandwidth of 19GHz by [187] and such "divide–and–conquer" approach is not safe and it can create artifacts due to the post-processing of the smaller chunks of bandwidth. Most of the studies make an assumption such that derived impulse response is linear phased. The assumption results in the presupposition of that impulse response is symmetric with respect to LOS propagation delay yet it is not possible in the real physical environment owing to the fact that the causality is contravened. In [188], the phase function is derived for impulse response of the channel without violating causality.

Spatial diversity is investigated by the use of MIMO measurement systems as well. The channel characteristics for 2×2 MIMO system are presented in [151, 189]. Apart from MIMO, the channel for ultra–massive MIMO systems is studied in [143, 190, 191]. The peculiarities of three–dimensional THz channels are investigated in terms of path gain and array steering vector. The signals in THz band scatter from thin objects due to their short wavelength. As a result of scattering, the received signal power decreases; thus, the phenomena must be investigated in the sense that it affects the NLOS propagation. [192–194] explain the impacts of scattering on THz channels through the employment of ray–tracing algorithms. Compared to LOS and NLOS reflected rays, the diffraction and scattering show less influence on the power of a received signal [191].

THz channel characteristics are strongly dependent on the characteristics of materials in the environment and on the density of these materials, thus it is not easy to establish a common channel model. Further investigations are needed on the channel models dealt with in the context, and the validity of these models must be confirmed and verified. Similar to [195], channel estimation methods for the THz band can be developed using various approximate message passing algorithms. We foresee that the THz channels can be modeled as mixture models (e.g. Gamma or Gaussian) by using expectation maximization.

3.2.2. Molecular Absorption Noise and Loss

There are several noise sources in THz bands; however, the main contribution to the total noise is created by the transmission process as absorption of molecules. The noise is called molecular absorption noise which is originated from shifting the molecules in the medium to higher energy states by electromagnetic waves. The absorption noise is self–induced because transmissions of users in the medium cause the noise to be induced [50]. The energy absorbed by the molecules is re–emitted in random directions according to radiative transfer theory [196] and then, it adds extra noise except additive white Gaussian noise (AWGN) to the system [197]. Moreover, the absorption noise does not have flat power spectral density due to the peaks arising from vibrational and rotational spectrum of molecules. Hence, it is not white but colored noise. With respect to the Beer–Lambert Law, the absorption loss is exponential in distance. For longer distances in the lower frequencies, free space path loss (FSPL) attenuates signal power dominantly, while, in the THz bands, the molecular absorption is more effective on the loss due to its exponentially increasing impact as a function of distance [13]. In [55], power spectral density of molecular absorption noise for the atmosphere is derived by using high–resolution transmission (HITRAN) [198] molecular absorption database. They also evaluate the molecular absorption noise power for a given bandwidth. From Beer–Lambert Law, the transmissivity of the medium is defined as the ratio of radiated power to incident power. The transmissivity is calculated as

$$\tau(f,d) = \frac{P_0}{P_i} = e^{-k(f)d}, \tag{1}$$

where $k(f)$ and d are the absorption coefficient of the medium in terms of frequency and the length of total path, respectively. Then, the emissivity of the medium is given as

$$\epsilon(f,d) = 1 - \tau(f,d). \tag{2}$$

T_0 and k_B denote the reference temperature and Boltzmann constant respectively, then, the molecular absorption noise power for given bandwidth B is evaluated as

$$P_n(f,d) = k_B \int_B T_0 \epsilon(f,d) df. \tag{3}$$

The molecular absorption noise with its power given in (3) is seen around the frequencies in which vibrations of molecules in the medium occur. Thus, water vapor mainly affects the channel. The spreading loss occurs due to expansion of electromagnetic waves through the medium. As well as the molecular absorption loss, the spreading loss is dependent on the carrier frequency and propagation distance between the transmitter and the emitter. With the increasing frequency and the distance, rise in total path loss can be seen in Figure 4a. The peaks in the path loss arise due to the fact that the vibrational and the rotational spectrum of molecules in the transmission environment absorb the energy from transmitted signals. In addition, the relative humidity of the medium has an impact on the path loss as shown in Figure 4b. Various methods are needed to counteract the high power loss caused by the THz band's own characteristics. Some of them can be listed as high–directional antennas, low–density channel codes, energy efficient modulation schemes.

3.3. Physical Layer

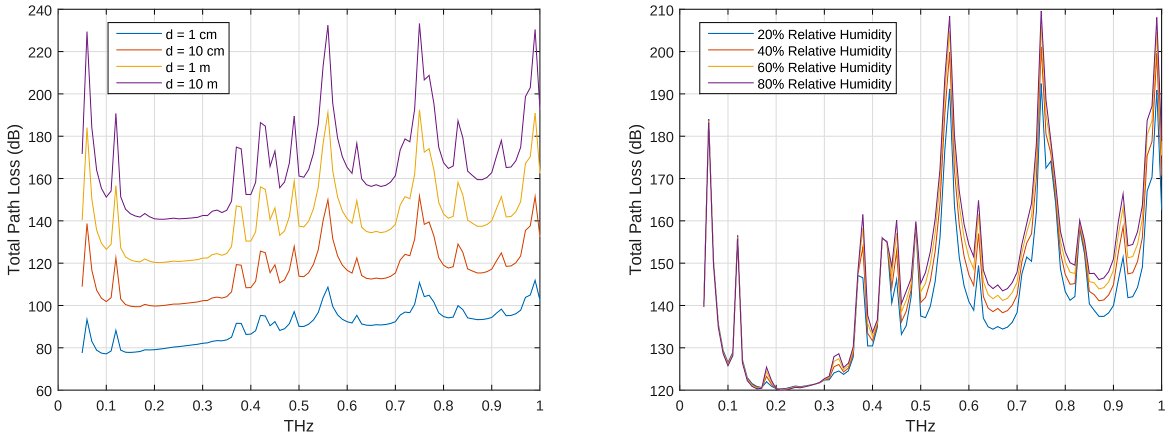
The exact utilization of THz bands requires the design of a complete set of physical layer methods which do not lead efficiency gains in terms of system performance. Therefore, considering the lack of compatibility in between classic physical layer methods currently used and the requirements of the communications in THz bands, physical layer characteristics should be well studied in terms of modulation, coding, relaying, and so on. In this section, the challenges lie in the physical layer design for THz communications and novel approaches for solutions are given.

3.3.1. Modulation Schemes

The modulation schemes used at lower frequencies could be employed for THz bands; however, they are not able to show adequate performance that these bands require [72]. The transmission windows dramatically change due to peaks which their intervals change with respect to transmission distance. Hence, the physical layers of THz systems are in need of novel modulation schemes considering the constraints due to propagation characteristics. On the consequence of short distance dependency, modulation schemes must be distance–aware for macro scale networks. On the other hand, nano networks necessitate low power consumption and compact modulator design.

Two pulse–based modulation schemes are given in [199, 200]. The schemes are designed for the short–range communications in THz bands by taking asynchronous pulses as on–off modulation spread in time. Noting that the molecular absorption is not dominant for the short–range transmissions where the transmission windows are not present. However, the windows differ from distance to distance even if there are minor changes. The modulation scheme is given in [201] enables to share the bandwidth with respect to distances. In this modulation, the transmitter chooses available windows by considering distance, then it divides them into sub–windows. After that, each carrier signal is assigned to sub–windows and modulated by M–ary quadrature amplitude modulation (QAM) where M satisfies desired bit error rate (BER). Although the modulation provides several Tbps data rate, there is a high complexity issue with the control unit. For this problem, the algorithm proposed in [202] can be a solution in order to decrease the complexity. The algorithm firstly determines the available transmission bandwidth. Then, the number and bandwidth of subcarriers are chosen so that the subcarrier bandwidth is smaller than coherence bandwidth (i.e. flat fading).

Another crucial constraint for THz systems especially nano networks is the energy consumption. The limited energy capacity of nano devices confines the transmission power in order to use a battery for a long time. Considering in–vivo applications, it is important to consume the power efficiently. For this aim, a new modulation scheme based on time spread on–off keying (OOK) (TS–OOK) and pulse position modulation (PPM) is proposed in [203]. Whereas TS–OOK sends bits one by one, the modulation transmits bits as a sequence which is defined by silence and very short pulse. From this aspect, it bears resemblance to PPM, but the symbol duration is not constant. While the mean transmission time for each bit increases with order of modulation, the energy per bit remains constant and data rate generally decreases. In this scheme, there is a trade–off between energy and data rate. According to the analysis made in [204], M–QAM is more suitable to use in the femtocell systems than M–ary frequency shift keying (FSK). The authors state that M–QAM shows better performance in energy efficiency for the distances up to 10m. Another comparison is given in [205] indicates that binary phase shift keying (BPSK) shows higher performance and bet-



(a) (b)

Figure 4: Total path losses for (a) different distances between transmitter and receiver at room temperature with 20% relative humidity and 1 atm pressure (b) different relative humidity levels at 1 m distance and room temperature with 1 atm pressure

ter energy efficiency compared to OOK and PPM. However, the hardware complexity is required to employ BPSK.

Furthermore, very short pulse duration results in almost virtual orthogonal channels [206]. In [202], distance and frequency dependent modulation scheme that allows for multicarrier communication is proposed. First, it selects the bandwidth, then sets the subcarrier bandwidth of orthogonal frequency division multiplexing (OFDM) signal because the THz bands are resistant to the frequency selective characteristic. Moreover, the distance–aware bandwidth–adaptive resource allocation scheme is given in [207]. In [208], a novel waveform, which adjusts the ratio and transmission power depending on distance for each sub–window, is given.

3.3.2. Channel Codes

Not only the modulation schemes but also channel coding can aid to the design of energy–efficient THz wireless communications systems. In the systems such as LTE and WLAN which utilize lower frequencies, channel codes aim to maximize data rates for constant energy consumption. The codes to be designed for physical layer operations of THz systems must take decoding power consumption in addition to transmit power into consideration. The coding and decoding processes should be light–weight because of limited computation capacity of nano devices. Noting that THz bands enable tera–bits in a second, decoding times become one of the key parameters for the channel coding. To avoid long decoding times, the codes can purpose prevention from error instead of correction. For instance, the coding schemes proposed in [209–211] operate in the same manner. Actually, any novel channel coding scheme is proposed in these studies. They show that the interference can be mitigated by adjusting the average Hamming weight of a codeword.

Similar to the modulation order, a system that can change the coding rate depending on the channel condition (i.e. distance and humidity) is given in [212]. The rate adaptation algorithm is run by taking the humidity level of the transmission environment into account. The access point estimates the channel condition with respect to humidity. For the systems using TS–OOK, it is important to decrease the number of 1s in the transmitted sequence since 0s corresponds to silences, so energy is saved. To this end, the method in [213] focuses on the reduction of the number of 1s by encoding to the codewords with the least number of 1s. The same approach is employed in [214] for the source coding to reduce the number of 1s in the source symbols. In [215], performance of this algorithm for constructing optimal codebook is analyzed considering energy consumption of receiver and transmitter jointly. However, this approach is not appropriate for links between nano devices and a nodes and could battery problem. For the comparison between low–weight codes, we refer to [216]. For the latency–limited applications mentioned in Section 2, one should bear in mind that the pipelined decoders are not suitable since they cause delays in transmission. The Epic project [217] which was funded in the Horizon 2020 call ICT–09–2017 aimed to design novel forward error correction (FEC) codes for the reliable communication in the THz bands.

3.3.3. MIMO Systems

The antenna arrays can be a solution for the distance problem in the transmission environments having high attenuation as they are able to propagate in the narrow beamwidth; however, they are expensive. In [218, 219], array–of–subarrays is proposed to reduce hardware complexity. Also, MIMO systems can enable the THz bands to be utilized more efficiently in terms of increasing data rates at the cost of complexity. The multiple users can be supported by the MIMO systems with grouped antennas. Moreover, the employement of nano antennas in the MIMO systems provides many elements in compact array size. In [220], performance of 1024×1024 ultra–massive MIMO architecture is investigated with numeric and analytic examination. The architecture and link have the capacity to reach data rates up to 8Tbps for the distance about 10m. In order to increase the data rates at longer distances, it is not the best solution that the number of antennas is raised since the windows are getting smaller with the distance. In [190], the authors suggested the use of different windows at the same time for communication. It is experimentally denoted that 2×2 LOS MIMO system reaches data rates about 7Gbps at the low THz frequency region [189]. The basic misstep in literature is to ignore the multiplexing capability for MIMO systems, assuming THz communications is only LOS, yet [197, 221] show the presence of re–emission of absorbed electromagnetic waves from molecules in the environment. Moreover, it is shown that the emitted signals are highly correlated with the main signal. As a consequence, the multiplexing can be investigated for THz communication. A multiplexing technique can provide performance gain in the environments showing characteristics of re–radiation [222]. For the mobile scenarios, the MIMO systems seriously require the beamspace channel in order to select a proper beam. The channel tracking is a compelling task for ultra–massive MIMO communication in THz band because it is not explained with first–order Markov process as in lower frequencies. However, a tracking algorithm without high pilot overhead is proposed in [223].

3.3.4. Relays

The LOS dominant characteristics of THz communications can open the way to the use of the relay. Especially, in the presence of blockage, relays are able to continue to transmission of the LOS link. In addition, the coverage can be expanded by using relays with a few numbers of hops [224]. For example, the reflect–arrays could be employed for this purpose without forgetting that it should be placed at the appropriate points in the environment. Reflect–arrays cannot permit the dynamic changes in the position of receiver or transmitter due to the high complexity problem.

On the other hand, software–defined metasurfaces [225–227] or hypersurfaces [228, 229] are flexible to use in any indoor environment because they have the ability of control and optimization of the channel effects via software.

3.3.5. Medium Access Control

As THz communications provides wide windows and suffers from low power capacity, the new medium access control (MAC) protocols suitable for THz environment are needed to be designed. Moreover, the razor–sharp beamforming and beam–tracking entail strong MAC protocol in order to avoid from deafness even though the collision probability decreases due to short duration signaling and directional links. In contrary to the current beamforming techniques which are based on single side of the communications link –generally transmitter–, the directional beams are required at receiver side of THz links as well [230]. In this case, the computation complexity increases. For an effective communication between the nodes, antennas must be correctly aligned. The MAC protocol given in [230] operates in two phases which are control information sharing and actual data transmission after alignment via 2.4GHz omnidirectional channel and THz bands, respectively. Another protocol [231] runs in the same manner except that it surveys the spatial domain by using an omnidirectional antenna in the THz bands. The protocol is supported by memory to increase the performance of access point in the angular division multiplexing scheme. The unregistered angular slots are thus omitted by the access point. Another problem in nano networks arises in terms of energy consumption. The nano nodes harvest and store energy from multiple sources in order to continue communication; therefore, the MAC layer must be able to become aware that harvested energy for a nano node is sufficient to receive the data bits from the transmitter. Two novel MAC protocols [232, 233] designed for the energy–aware nano networks using THz band enable to communicate by taking into account the amount of energies in nano nodes. Whereas [232] proposes a protocol for centralized and distributed networks based on probabilistic and graph coloring respectively, [233] focuses on ad hoc networks without central scheduling.

Although the collision probability is low due to the short transmission time, the novel error correction and detection schemes are required in THz networks as longer data packets can face with huge channel errors. It is known that the buffering problems can appear as a result of long data packets. Therefore, packet optimization gains importance for THz communication systems. For this purpose, optimal data packet length can be determined by considering the energy harvesting limits and the successful packet transmission time [234].

As mentioned in Section 3.3, the THz wireless communications systems are required to be aware of availability of bandwidth and distance by adjusting modulation and coding schemes for optimal communications. As a result, the rearrangement of used modulation and coding schemes is handled by MAC. Moreover, MAC must be aware of the physical layer in a THz communication system [235]. Because of the nature of THz band, the smaller coverage area suffers from frequent handovers. For this reason, the system should have ability of switching between THz communication system and other systems such as mmWave. The MAC protocols are proposed in [236, 237] enable that the system can switch between THz and mmWave frequencies. The protocols can be employed for vehicular networks for that probability of handover is high.

3.3.6. Synchronization

The THz communication systems are prone to synchronization errors owing to the fact that they employ ultra–short pulses which have the requirement of high–speed analog–to–digital converters (ADCs). The high–speed ADCs cannot be used with most of nodes in THz networks because of size and high energy consumption. Indeed, in terms of ADCs, the Nyquist rate in the THz band is not easy to achieve. In literature, there are synchronization schemes based on cyclostationarity [238], correlation [239], and subspace technique [240]; however, these schemes are more complex and need to know channel information. Therefore, the synchronization schemes for THz band must be more powerful than the schemes used in standardized bands.

In [241], synchronization scheme based on dynamically time–shifting in the signal at the receiver and adjustable observation window of a continuous–time moving–average (CTMA) symbol detector is proposed for a pulse–based THz communication systems. The scheme uses a voltage controlled delay line for dynamic time–shifting. The synchronization takes place as follows that the array of voltage controlled delay lines and CTMA detector are iteratively used for detection of symbol start time and observation window length. In addition, the time corresponding to maximum energy over the long–integral windows can be selected as the synchronization point [242]. Based on aforementioned reasons, the sampling rates of ADCs are not sufficient for Nyquist rate for THz bands, so small errors in timing affect the system performance even if timing errors are in the range of picoseconds. To avoid these errors at low sampling rates, the annihilating filter method and the spectral estimation techniques in the frequency domain can be employed for timing prediction [243].

3.4. Network Architecture

The unique characteristics such as huge bandwidth, data rate about terabits in a second, very directional links, and the low energy signal generation give rise to the fact that existing network architectures are inadequate to reveal the expected performance of THz communications systems. As a result, the novel architectures must be designed for THz band communications.

In the realization of THz band wireless communications, there are several challenges such as handover, synchronization, MAC, beamforming, and beam–tracking management and so on. To observe the performance of network architectures in the THz band, there are recently developed open source simulation environments as *ns–3* extension: Nano–Sim [244] and TeraSim [245]. Whereas Nano–Sim is suitable for only nano scale scenarios in THz band communication without considering frequency selective channel and energy harvesting for nano nodes, TeraSim has the capability of simulation for frequency selective channels and nano nodes harvesting energy.

4. Current State of the Art: Achieved Data Rates

In this section, the actual data rates reached at the THz bands until recently are discussed. For example, amplitude shift keying (ASK) scheme is used in the frequency range from 0.125THz to 0.54THz with data rate up to 30Gbps. Besides ASK, OOK scheme is utilized and it enables to reach up to 25Gbps for the distance of 50cm [246]. In [247], 25Gbps is reached by multiplier reinforced transmitter and receiver using 0.24THz carrier frequency and OOK modulation over 60cm. Moreover, higher–order modulation schemes are employed for the data transfer in THz band. For instance, [248–250] show that it is possible to reach tens of Gbps around 0.4THz by using 16–QAM. Furthermore, 8–phase shift keying (PSK) modulation is employed in [251], then 30Gbps is realized at 240GHz with 40cm. Surprisingly, [252] demonstrates that the wireless equipment supported with InGaAs/InP HEMT–based mmWave amplifier to increase transmission distance can be able to have 10Gbps data rate without FEC over the distance of 5.8km.

THz wireless communication systems can be considered as power–limited systems, so transmission power should be kept as low as possible. On the other hand, due to high path loss, the path taken by THz signals in the environment is very short. For all these reasons, it is clear that high–level modulation schemes for the same BER and transmission power will allow communication over much shorter distances. THz wireless communication systems are expected to use lower level modulation schemes instead of high–level modulation schemes. Thus, with relatively low transmission power, it will provide acceptable BER at longer distances. To increase data rate, the system must have high output power and use high level modulation scheme. The data rates reached by experimental platforms are summarized in Table 4. For comprehensive information on the data links and transceivers, we refer the readers to the references given in Table 4.

5. Standardization Efforts

The standardization process for the future wireless communications systems in THz bands was initiated by Interest Group on THz communication under the IEEE 802.15 umbrella in early 2008. By the year 2013, IEEE 802.15 WPAN Task Group 3–D 100 Gbit/s Wireless (TG 3d 100 G) [12] was set up to establish the standard for 100Gbps wireless communication between 275 – 325GHz. As a result of efforts of the group, the world's first wireless communication standard, IEEE 802.15.3d–2017, operating on the 300GHz frequency range, was approved on September 28, 2017 and published on October 12, 2018 [268]. The standard targets use of THz communication systems in the applications of Kiosk downloading, intra–device communication, wireless backhauling and fronthauling, and wireless links in data centers. Applications Requirements Document [269] defines use cases and performance and functional requirements of the system in application–based approach. The standard includes key imagery such as new physical layer based on IEEE 802.15.3–2016, MAC mainly based on IEEE 802.15.3e–2017, 8 different channels with a bandwidth of multiples of 2.16GHz up to 69.12GHz. Furthermore, it allows using seven modulation (BPSK, quadrature phase shift keying (QPSK), 8–PSK, 8–PSK, 16–QAM, 64–QAM, and OOK) and three coding (RS(240,224), 14/15–LDPC, and 11/14–LDPC) schemes. The standard also supports single carrier mode and OOK mode in the physical layer. In addition, Channel Modeling Document [270] summarizes channel propagation characteristics for the target scenarios and propounds application–based channel models specifically.

The future steps for the standard should investigate the interference with the bands identified by ITU for usage by the applications such as radio astronomy, Earth exploration–satellite, and space research services which are given in [271].

It is known that the power loss in propagation is mainly caused owing to absorption by water vapor. Therefore, it is important to make analysis taking into account the regional propagation properties in the next actions.

6. Conclusion

The ultra–wide bandwidth provided by the THz bands enables high–speed data transmissions. For this reason, it is planned that future communication systems will benefit from this frequency region. THz wireless communication systems will help to implement various applications as well as many use cases are expected to provide opportunities for the development of THz wireless communication systems.

Table 4: Summary of achieved data rates in THz bands

Frequency (GHz)	Data Rate (Gbps)	Modulation	Distance (m)	Reference
120	20	QPSK	1700	[253]
125	10	ASK	200	[254]
200	1	ASK	2.6	[255]
200	10	ASK	5800	[252]
220	25	OOK	0.5	[246]
220	30	ASK	20	[256]
237	100	16–QAM	20	[257]
240	16	QPSK	0.01	[258]
240	25	OOK	60	[247]
240	30	8–PSK	40	[251]
250	8	ASK	0.5	[259]
260	10	OOK	0.04	[260]
297	10	OOK	0.3	[261]
300	24	ASK	0.3	[262]
300	24	ASK	0.5	[263]
300	48	OOK	1	[264]
340	3	16–QAM	0.3	[265]
350	100	16–QAM	2	[266]
385	32	16–QAM	25	[248]
400	80	16–QAM	0.5	[249]
400	106	16–QAM	N/A	[250]
542	2	ASK	0.01	[267]

Signal generation, transmission, and sensing are the main problems in the THz bands, recent studies on graphene have brought new horizons in the signal generation since graphene allows SPP waves to propagate. Furthermore, the development of graphene–based antennas that are likely to be used in nanonetworks is another promising advance. Besides graphene, SiGe, InP, and InGaAs are populously investigated materials in transceiver design. As QCLs require a cryogenic cooler, it seems to be impractical for THz transceiver design. The high attenuation lies in the nature of THz bands; therefore, the design of amplifiers and antennas is another crucial matter to accomplish high gain and directivity.

The channel and noise characteristics of THz links, which differ greatly when compared to the bands that are already in use, are investigated and modeled in many studies. These studies with the emphasis on channel behavior, and noise characteristics in THz bands are explained in this paper. In order to create a proper communication system in THz bands, physical layer requirements as well as the attributes that the upper layers need to carry are explained. New modulation and channel code schemes that take into account the physical layer parameters such as energy efficiency, distance, and bandwidth are required. When FECs are designed, the number of iterations, flexibility of code rate, and flexibility in block lengths must be taken into consideration in the aspect of reliable physical layer design of THz wireless communications systems. MAC and synchronization should be investigated in more detail. Since the studies have mostly focused on the physical layer, the MAC and upper layers have to be studied carefully in the next steps. The network must be designed to work seamlessly with huge bandwidths, high data rates and a large number of nodes.

Since the size of THz cells will be tiny, the system architecture needs to be designed carefully. THz wireless communications systems can collaborate with other networks heterogeneously. The heterogeneous system can be employed in between THz and mmWave networks for beyond 5G communications. In order to design efficient heterogeneous networks, studies on THz wireless communication in different layers of heterogeneous networks must be carried out by future research.

The THz bands seem to allow data transmission at high speeds up to 100Gbps for short–range communications. Different issues such as channel modeling, transceiver design, antenna design, signal processing, upper layer protocols, and security should be researched jointly in order to increase the data rates that can be reached and realized by THz wireless communications systems.

Clearly, the development and dissemination of THz radio communications systems are not an evolutionary process. On the contrary, hardware, physical channel, and network require revolutionary development to communicate at THz bands for beyond 5G wireless communication systems.

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