A review on intelligent reflecting surface-based terahertz communication

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ABSTRACT

Terahertz (THz)-band communications can be considered as the new frontline for future-generation wireless communication systems as it has a wider bandwidth in comparison to microwave and mmwave communications. It also promises to integrate the wide range of diverse applications. Because of high path loss and narrow spreading of THz waves, the transmission is extremely sensitive and signal coverage is a critical problem. To overcome this, an intelligent reflecting surface (IRS), has received great interest which steers the beams of THz waves by regulating the phase shifts to alleviate blockage and improve the coverage capability. In this paper, the role of IRS in conjunction with the THz communication has been discussed. Further, challenges and research directions of IRS for terahertz communication are also discussed.

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1. INTRODUCTION

Sixth generation (6G) wireless communication networks have attracted more attention to support the numerous applications in the near future. Figure 1 presents an 6G system overview along with some enabling technologies and use cases. In the case of the telecommunication sector, the race is towards improving the data rate to fulfill different applications like virtual reality (VR), wireless data center, on-chip communication [1], [2]. This never ending quest of high data rate and the growth of wireless usage sets the target for the research community to discover suitable regions in the radio spectrum to satisfy the growing needs of individuals. Following this trend, wireless terahertz (THz) band are getting noticeable attention within the global community that can resolve the spectrum shortage problem and can enhance the capacity of wireless system [3]. The THz band is the band that spans from 0.1 to 10 THz. There are several reasons that motivates the use of THz band like seamless data transfer, unlimited bandwidth, low latency and high download rate.

A new horizon in the field of communications deployed for 5G technology by many funding agenesis who supports the THz projects. The list of the latest terahertz projects [4]. THz waves are alluring for remote interchanges since they can offer tremendous transfer speed and large bandwidth, which is fundamental for expanding data capacity. Nonetheless, there is an undeniable disadvantage: large signal loss. The attenuation in the atmosphere at frequencies over 100 GHz is a lot bigger than that in the microwave recurrence band and the huge loss not just limits the service yet additionally corrupts the signal to noise (SNR) of the system, which impacts data capacity as well.

Several studies reviewed and discribed the limitations and potential benefits of the THz band. The first survey was on THz applications,sources and sensors for frequencies above 500 GHz. After that an article have been published for terahertz sources, detector and modulators for various applications [5]. Federici and Moeller [6], Channel modeling for THz communication with some investigation results are presented. In 2010, a review on basic channel modeling, implementation and detection issues for THz bands are preseted [7]. A study on THz modulators, channel modeling and research directions for future wireless communication systems is studied [8]. Huang and Wang [9], shed light on THz communication for short range network as substitute for high data rate communication Systems. Nagatsuma [10], an overview of current advances in THz generation with phonetics is presented,which can achieve data rate up to 100 Gbps on real time or offline. Akyildiz *et al.* [2], the challenges and applications in generation of the THz band has discussed. Kürner and Priebe [11], have demonstrated some research projects and spectrum regulations. Hirata and Yaita [12], the challenges and opportunities in THz communications for vehicular networks is presented. Sengupta *et al.* [13], review of research, development and implementation test beds in generating THz signals for communication, sensing and imaging applications is discussed. The process in wave propagation and channel modeling for wireless on chip communication from mm wave to THz and optics are presented [14], [15]. Han *et al.* [3], provides a brief review on applications for THz band and research directions of 6G Heterogeneous network. THz channel feature and current advancement in device technologies are reviewed [1]. Comprehensive comparison amongst the THz communication and its other contenders of THz communication are reviewed with its potential use cases of THz band [16]. Recently a survey on comparison of the type and materials for THz antennas and the issues, challenges and opportunities are presented [17]. Rahaman *et al.* [18], attributes and issues of THz range with some test-case scenario are presented. An overview of recent progresses in signal processing techniques for THz communications is presented [19]. Finally, Sarieddeen *et al.* [20], applications of imaging, sensing, and localization at the THz band with proof f-concept simulations are presented. The aforementioned review articles are itemized in Table 1 focus on review for related technologies for THz Band.

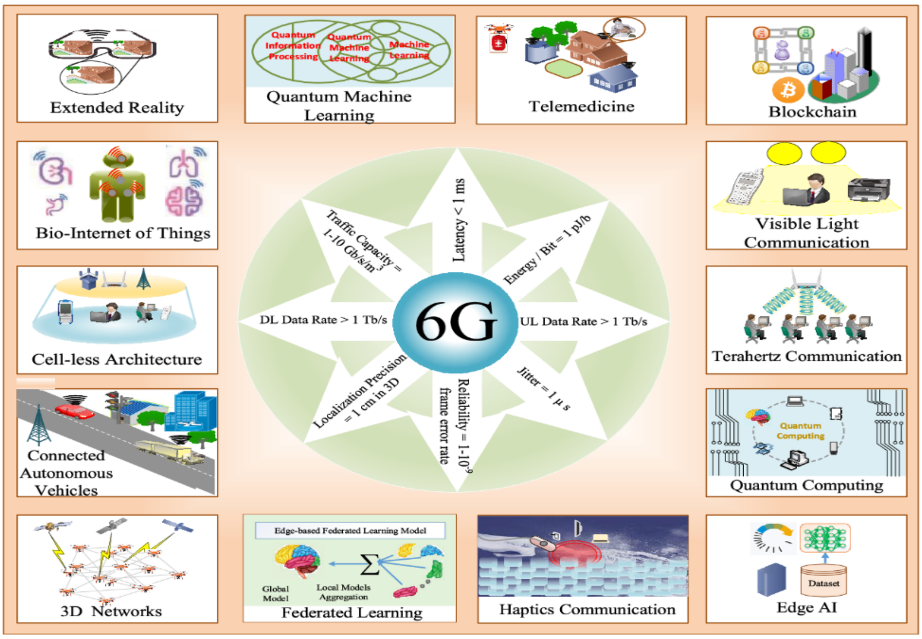

Figure 1. 6G system overview [21]

At present, there is still a demand to have a complete vision on the existing development and new improvements in the field of THz communication which can help scientists to draw revolutionary footsteps for several communication systems. By contrast, this is the first reveiw on intelligent reflecting surface (IRS) added THz communication systems which also presents the open research challenges and future research directions. Further, the paper is organized as follows: in section 2, introduction to IRS and terahertz communication is presented. Section 3 categorize the recent studies of intelligent reflecting surfaces for THz. In section 4, some directions for forthcoming research of the porposed work have presented and finally, section 5 concludes the paper.

Table 1. Brief review on THz communication

Year	Focus	Ref
2002	This paper is the first survey on sources, sensors and application for terahertz with frequency higher than 500 GHz -10	[22]
2004	A review on terahertz sources, detector and modulators for various applications	[5]
2009	Investigation results for channel modeling in terahertz communication are presented	[6]
2010	Basic channel modeling techniques, generation methods, detection methods and antennas for THz communication is presented with some link measurements.	[7]
2011	A review on THz technologies, channel modeling with research directions for future wireless communication systems is presented	[8]
2011	This paper surveys short range network for THz communication as a substitute for high data rate as forthcoming wireless communication systems	[23]
2011	The development in THz technology with its applications are reviewed	[9]
2013	A paper presents survey on current developments in THz technology using phonetics to achieve data rate upto 100 Gbps	[10]
2014	This paper presents review on THz applications, challenges and channel modeling with some experimental and simulation testbeds.	[2]
2014	A survey on research projects, regulations and standardization for THz communications is presented	[11]
2015	A review on research for THz communication along with its development and implementation is presented	[12]
2016	A review on wave propagation and channel modeling for wireless in chip scale wireless communication from mm wave to THz and optics	[24]
2017	Review on terahertz band opportunities and challenges for vehicular networks is presented	[14]
2018	A brief review on progress of THz integrated electronic and electronic–photonic systems is presented	[13]
2019	This article provides a brief review on THz frequency assisted wireless systems, applications of utilizing THz bands and the research directions of an ultra-fast beyond 5g heterogeneous network	[3]
2019	A review on the progress to THz communications with few key enabling technologies for THz systems are presented	[1]
2019	The article provides THz frequency generation and channel models along with future research direction	[16]
2020	This article discusses and compares various parameters like type and materials for THz antennas and with the issues, challenges and for the THz antennas	[17]
2020	This paper provides the technology roadmap for THz communication	[18]
2020	An overview of recent progresses in signal processing techniques for THz communications	[19]
2020	Reviewed the applications of imaging, sensing, and localization at the THz band with proof-of-concept simulations	[20]

2. INTELLIGENT REFLECTING SURFACES AND THZ COMMUNICATION

2.1. THz communication

The explosion of wireless device and services have raised the demand to satisfy the requirement for high data rate transmission. The technology like millimeter wave (mm wave-30-300 GHz), massive multiple-input multiple-output (MIMO), beamforming has already considered as enablers of fifth-generation (5G) of wireless mobile communications. While due to trend of super high data rate and low latency requirements, it is difficult to handle the quality of service in mm wave systems for 5G. To remove these barriers in networks beyond 5G, one need to explore the resource s and technologies to validate. THz technology is one of those technologies which are expected to become main trend and shall play important role in beyond 5G (i.e., 6G) communication systems. THz band is the last unexplored piece of the spectrum and it is sandwich between microwave and optical band. Hence one can explore the technologies from both sides to support THz communications. Being a neighbor to mm wave spectrum, THz band (0.1 to 10 THz) has potential to fulfill the future demands of 6G wireless communication systems. The user in remote areas is difficult to access and needs a high data rate up to 10 Gbits/s per user. THz transmission will be an important block to face this challenge and can give high speed internet access everywhere.

2.2. Intelligent reflecting surfaces (IRS)

The 6G network needs more strict requirements than 5G, like higher data rate, global coverage and connectivity and low latency. These cannot be fulfilled with existing technology for 5G services, which need to deploy more base stations and antennas to achieve enhance network coverage and capacity. Also, it requires to migrate to mm wave and even terahertz frequency to use large bandwidth to compensate for prorogation loss. By looking at above issues, it is necessary to develop new and innovative technologies to have more supportable capacity with low cost and complexity for future wireless networks. IRS, is a recently new paradigm for wireless communication systems. An IRS is a planar surface with an array of passive reflecting elements. These elements can independently impose the required phase shift on the incoming signal [25], [26]. The developments in metamaterials [27] can lead to the recofiguration of reflection coefficient in the real time to adapt the fulatuating wireless enviornment. IRS is also very benificial for practical implementation. It has a very low-cost hardware due to low cost printed dipole which can reflect without any radio frequency (RF) chains. Also, it is free form antenna noise and interference and can be easily mounted on object as it is having a light weight. Due to all this advantages, IRS is applicable in wireless network at terahertz frequency to enhance its spectral efficiency with low cost. In summary we can argue that, to compensate for high propagation loss at terahertz frequency, IRS is a good choice. Though, there is a limited paper to incorporate Intellignet surfaces into THz communication. The next section discusses the classification of IRS for THz.

3. PROPOSED STUDIES OF INTELLIGENT REFLECTING SURFACES USE IN THZ BAND

In this section the recent research work on IRS in THz communication have been classified. For IRS based communications systems, meta-materials and metasurface based design, power/spectral optimizations, channel estimation and sum rate analysis for IRS assisted THz. We also review use of IRSs in security-based communication systems, and other novel applications.

3.1. Channel estimation in IRS based communications

A novel method of estimating the average channel capacity per user of a spread spectrum MIMO multiple-user system is discussed [28], [29]. Since IRS has no capacity to transmitting and receiving the signals, the channel state information (CSI) of IRS-based system is isolated through old channel estimation methods. So, to obtain the complete CSI for IRS driven systems is the main problem. To overcome this challenge, numerous works have proposed so as to look into novel channel estimation methods for the IRS-assisted THz communications.

A hybrid beam forming architectures for channel estimation along with transmission solutions for IRS assisted system with massive MIMO in THz communication is presented [30]. They invoked beam training method for channel measurement. The analysis of beam pattern and quantization error are also assessed. A search code book design is proposed toreduce the complecity in channel estinamtion. Then, precoder/combiner and IRS designs and cooperative channel estimation method is also proposed which achieves a good spectral efficiency compared to non-IRS assisted approach. Chen *et al.* [31] have used the graphene-based IRS and developed a low complexity channel estimation scheme by utilizing the sparsity characteristics of THz channel. Wang *et al.* [32] addresses channel estimation problem using deep learning perspective for enabled MIMO system in THz. They have used sparse nature of THz channel and developed low complexity channel estimation scheme. Channel estimation issue is tackled with cooperative beam training scheme without searching exact path for departure/arrival [33]. They have concluded that only fewer angel differences need to search with fewer code words. The authors have first designed ternary-tree search at base station (BS) with the use of two novel training codebooks which balance between noise and complexity. Then hybrid beamforming methods are proposed to maximize the achievable rate. Chen *et al.* [34], the channel estimation and data rate maximization for IRS-aided THz MIMO system for 6G indoor applications is discussed further. Table 2 focus on review on channel estimation in THz band using IRS.

Table 2. Using IRS for channel estimation in THz

Ref	Scheme	Design methodology	Application scenario	Justification
[30]	Massive MIMO	Cooperative channel measurement via beam training and codebook	THz communications	Improved spectral efficiency
[31]	MIMO	Compressed sensing channel estimation with graphene IRS	6G indoor application	Consistent channel recovery performance with extreme complexity reduction
[32]	MIMO	Channel estimation using deep learning with the use of sparse channel configuration	THz communications	Better recovery performance with reduced computational complexity
[33]	Massive MIMO	Cooperative channel estimation via joint beam training and hybrid beam forming	THz communications	Improvement in the achievable data rate under the estimated CSI
[34]	MIMO	Joint channel estimation and data rate maximization	Indoor 6G application	Improved communication rate with reduced computational complexity

3.2. IRS for Secure communications in THz band

Intelligent reflecting surface has gained much attention in secure transmission to reduce the path loss in THz band. IRS wisely adjusts the phase shifts so as to reduce the information leakage and signal power is navigated to desired user. We now see that how IRS can be used in THz band for secure transmission. Qiao and Alouini [35] have focused on secure transmission via IRS for mm wave and terahertz system. The security rate of this system is optimized by the jointinty optimizing the beam forming at base station and discrete phase shift at IRS. Ning *et al.* [36] uses active beam former and passive phase shifter at the base station and at IRS respectively for maximizing the secrecy rate. To tackle the non convex problem, a joint design is proposed to optimize the phase shifter and beam former. Chen *et al.* [37], security rate of the IRS based multi-inputs single-output (MISO) system is exploited with the use of discrete phase-shifts method. An overview of secure transmission in tera herts band using IRS is discussed in Table 3.

Table 3. Using IRS for secure transmission in THz

Ref	Scheme	Design methodology	Application scenario	Justification
[35]	IRS-based THz system	Joint optimization of transmit beam forming and reflecting matrix	Mm wave and THz communications	Optimum secrecy rate
[36]	MISO	Active beamforming and the passive reflecting phase shifters	THz communications	Improvement in secrecy rate with low complexity
[37]	MISO	Discrete phase-shift and precoder	THz communications	Improved secrecy rate

3.3. Data rate aided IRS for THz communication

An IRS is a collection of passive reflecting elements, which individually execute the required phase shift on the received signal. The sum rate for IRS based THz communication is exploited by improving the phase shift at IRS. The data rate of IRS based THz MIMO system is improved [34] by using joint approach of data rate and channel estimation method. Here, the channel estimation is performed by iterative atom pruning based subspace pursuit scheme and with the help of this estimated CSI, various data rate maximization techniques are suggested for the hunt of phase shifts of IRS elements. Amongst them, deep neural network-based method gives optimum data rate performance by lower computational complexity. Shen *et al.* [38], two methods have been proposed to maximize the data rate performance by choosing best phase shift of IRS. A recent work by [39] examines that to improve the data rate of THz transmission using IRS, it is imperious to optimize the reflecting phase shift and sub-band allocation simuntaneously. Graphene-based IRS technique to increase coverage performance in indoor THz communication is proposed [40]. Here the, coverage problem is first converted into discrete phase shift problem and then, a novel suboptimal phase shift search technique is suggested which greatly reduce the complexity of exhaustive search method and also improve the coverage performance. The trajectory of unmanned aerial vehicle (UAV), phase shift of IRS with THz sub bands and power control is examined by [41] to achieve the higher data rate. Hao *et al.* [42], the joint analysis of hybrid beam forming and reflection matrix is examined to increase the data rate at BS and IRS respectively. Authors have considered imperfect CSI from IRS to users and jointly optimized the algorithm again and proved that channel estimation is playing important role on system data rate. Analytical physical model to enhance communication distance and data-rate for ultra-massive multiple-input multiple-output (UM-MIMO) at mm and THz band frequencies is proposed [43]. In their approach they have used plasmonic antenna arrays for transmission, reception and waveguiding. Table 4 shows various schemes of sum rate maximization in IRS for THz communication as mentined above.

Table 4. Sum rate maximization in IRS aided THz communication

Ref	Scheme	Design methodology	Application scenario	Justification
[29]	MIMO	Joint approach of channel estimation sum rate maximization	Indoor THz communications	Improved communication rate with reduced computational complexity
[38]	MIMO	Optimization of phase shift of reflecting surface	THz communications	Improved the sum-rate
[39]		Location of IRS, phase shift, sub-band allocation, and power control for UE need to optimize jointly	Indoor THz communications	Improved the sum-rate
[40]	MISO	Suboptimal search scheme with graphene IRS and ray tracing technique	Indoor THz communications	Improved the sum-rate with reduced complexity
[41]	MIMO	Optimization of UAV's path, IRS phase shift, sub bands of THz with power control	UAV-supported THz communications	Improved the sum-rate
[42]	MIMO-OFDM	Hybrid beamforming and reflection matrix are joint optimized	THz communications	Impact of channel estimation error on data rate with imperfect CSI and maximized sum rate with perfect CSI
[43]	Ultra-Massive MIMO	Deployment of plasmonic arrays	Mm wave and THz communications	Significant improvements in communication distance and data rate

3.4. Spectral efficiency optimization in IRS communication at THz

In this section, we review recent study on spectral efficiency optimization in IRS based THz communications. The spectral efficiency is maximized by using plasmonic antenna array and jointly optimized the beam forming beam at transceivers in UM-MIMO and achieved a desired power level [44]. Chen *et al.* [45] has studied the application of the IRS for improving the spectral efficiency in THz communication system. Authors have utilized the discrete phase-shifts at IRS and precoder at base station for THz MIMO communication system. The non-convex optimization issue is resolved by invoking cross entropy algorithm for optimal phase shift matrix and water filing solution to enhance the precoder at BS. A descent method for MIMO is proposed recently [46] to enhance spectral efficiency with negligible complexity compared to Cross entropy-based method. Also the work presented [30] for channel estimation method also achieves a good spectral efficiency for THz massive MIMO IRS-assisted system. Table 5 focus on review on recent study on spectral efficienty using IRS in terahertz band.

Table 5. Spectral efficiency via IRS in THz

Ref	Scheme	Design methodology	Application scenario	Justification
[44]	Ultra-Massive MIMO	Joint beamforming with plasmonic antenna arrays enabled by graphene meta surface	Mm Wave and THz communications	Improved spectral efficiency
[45]	MIMO	Phase-shifts matrix and the precoder matrix of IRS	THz communications	Improved spectral efficiency
[41]	MIMO	Taylor expansion aided gradient descent (TE-GD) scheme	THz communications	Improved spectral efficiency with low computational complexity

3.5. Meta Material's and metasurface based design for IRS Aided THz Communication

Apart from THz communication system, numerous material properties support THz-band IRS systems. Dash *et al.* [27], a graphene meta surface at low THz frequencies with a simple structure has been developed. Authors have analyzed the performance under normal and oblique incidences in TE and TM mode polarization. The modeling and design of 3D curvilinear metasurface-based structures for cloaking application and for THz communication is developed [47]. Yang *et al.* [47] reviewed the terahertz beam steering method from conventional to reconfigurable metasurface routes based on various materials. The use of beam steering in terahertz plasmonic antennas with digital metasurface based on graphene is proposed [48]. Table 6 shows review on metamaterial and metasurface based design for tera herts communication.

Table 6. Meta material's and metasurface based design for IRS Aided THz communication

Ref	Scheme	Design methodology	Application scenario	Justification
[27]	THz Communication	Graphene meta surface	Thz communication	excellent absorption, zero reflection and transmission at 2.5 THz
[47]	THz Communication	3D curvilinear metasurface	Cloaking and THz communication	For immidiate control of amplitude and phase of the wave the link is crated between filed and circuit theory
[47]	THz Communication	Reconfigurable metasurface	THz communication	flexible for producing orbit angular momentum and polarization conversion
[48]	THz Communication	Plasmonic antennas with digital metasurface	THz communication	Beam steering in all practical directions
[43]	Ultra-Massive MIMO	Install plasmonic arrays at the transceivers	Mm wave and THz communications	Major enchancement in communication distance and data rate

4. DISCUSSION ON FUTURE SCOPE

In this section, the challeneghs and results are discussed based on the algorithms applied in order to receive the probable solutions. The techniques used for the intelligent reflecting surfaces assisted THz communication in analyzed in brief and it enhance the communication quality. Also, in this section we highlight a possible research direction in THz communication for future investigation that enables the deployment of THz links and opens the door in the direction of various applications such as mobile heterogeneous networks (HetNtes), machine learing, medium access protocol and artificial intelligence.

4.1. Terahertz communications for mobile HetNets

High path loss and requirements of greatly directional antennas are the main drawback of THz communication systems. By using the femtocell regime these could turn into favorable attributes. Femtocells are able to redue the distance between serving base-station and the user and though maintain a high SNR at the receiver they also enhance the frequency reuse capacity of the THz systems. These femtocells are also known as low-power nodes, and can be used in home service, shopping malls and in various other applications. These have led to a new era of THz communications for mobile heterogeneous networks (HetNets) to improve the data rate at the level of Tbps [49].

4.2. Compressive sensing and machine learning (ML)

To enahce the THz communicaiton, compressive sensing and machine learning techniques are promising. To enhace the femtocell, machine learning could be aso used as articifalc intelligence tool to support the smart radio terminals. ML methods can also address the number of nano-scale biomedical challenges, including once that refer to molecular and nano-scale THz communications.

4.3. Medium access protocol for THz communication

There are many challenges on THz medium access control (MAC) design modeled by the THz communications like, deafness problem, requirement for the coverage of transmission and the demand of deafness avoidance, cell boundary etc. These challenges are addressed in the literature which could be use with physical layer signal processing schemes. MAC protocals technology is supported by the tertrahertz communication with the unique feature of tetrahertz band as scattering, high path loss and reflection pose new challenges and results in short communication [50]. Pure and hybrid plasmonic tetrahertz antennas provide the new degree of freedom to design the graphene-based antennas for tetrahertz band operation [51].

4.4. Artifical intelligence (AI)

The presence of interconnected devices with the accessibility of data has permitted the successful integration of AI in wireless communication. 6G shall appear as an intelligent information system which is driven by the current AI technologies. Also, the shifting of things to connected intelligence with high rate and low latency control requires the usage of THz frequeney band.

5. CONCLUSION

A broad survey on IRS based THz communication system is presented. The use of IRS in wireless communication has set up new shift in the design of wireless system. Firstly, we have presented an overview of the terahertz band and their limitations. Then we have focused on how IRS is useful to overcome these limitations and role of IRS in terahertz. Even though reserch on IRS-based system in THz is still in its early stages, this paper categorizes the role of IRS in various domain of THz like channel modeling, data and spectral efficiency improvement, antenna designing and secrecy rate along with the directions for further investigation. We can say that upcoming years will have more study for the IRS aided THz communication to shape next generation communications.

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