Ultra Wide Band THz IRS Communications: Applications, Challenges, Key Techniques, and Research Opportunities

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Abstract—Terahertz (THz) communication is a promising technology for future wireless networks due to its ultra-wide bandwidth. However, THz signals suffer from severe attenuation and poor diffraction capability, making it vulnerable to blocking obstacles. To compensate for these two shortcomings and improve the system performance, an intelligent reflecting surface (IRS) can be exploited to change the propagation direction and enhance the signal strength. In this article, we investigate this promising ultra wide band (UWB) THz IRS communication paradigm. We start by motivating our research and describing several potential application scenarios. Then, we identify major challenges faced by UWB THz IRS communications. To overcome these challenges, several effective key techniques are developed, i.e., the time delayer-based sparse radio frequency antenna structure, delay hybrid precoding and IRS deployment. Simulation results are also presented to compare the system performance for these proposed techniques, thus demonstrating their effectiveness. Finally, we highlight several open issues and research opportunities for UWB THz IRS communications.

Index Terms—Terahertz, intelligent reflecting surface, ultra wide band, beam split.

I. INTRODUCTION

High transmission speed and low power consumption are two key performance metrics for future wireless communications. For example, more than 1 Tbps peak data rate should be supported in the ultra-high-definition video transmissions and more than 10 fold increase in energy efficiency should be obtained for the internet of things (IoTs) [1]. To satisfy the above requirements, terahertz (THz, 0.1–10 THz) and intelligent reflecting surface (IRS) are two promising candidate technologies. THz communication can provide ultra-wide bandwidth to realize the extremely-high transmission rate [2]. However, the coverage of THz signals is limited due to the low frequency or narrow band system, the beam directions at different subcarriers may vary for the UWB THz system, which is called beam split [3]. Due to the frequency independent characteristic of the PSs for the sparse RF chain antenna structure, there exists severe loss in beam gain when the conventional hybrid precoding schemes are applied. IRS further leads to two stage beam split for UWB THz IRS communications, namely, the first stage beam split from the BS to the IRS and the second stage beam split from the IRS to the receivers. Such beam split effects are also affected by the actual IRS deployments. As a result, the conventional IRS deployment and BS antenna structures are not suitable for UWB THz IRS communications, calling for novel solutions and structures.

In this article, we investigate the following aspects of UWB THz IRS communications. First, we motivate our research and introduce three potential application scenarios, namely, indoor communications, dense building communications, and unmanned aerial vehicle (UAV) communications. Next, we summarize the state-of-the-art on the UWB THz IRS communications. Then, we analyze the major challenges underlying UWB THz IRS communications. To deal with these challenges, we propose several key techniques, including the time delayer (TD)-based sparse RF antenna structure, delay hybrid precoding, and IRS deployment. Furthermore, we provide simulation results to compare the system performance under different techniques. Finally, we highlight several open problems and potential research opportunities for UWB THz IRS communications, such as artificial intelligence (AI)/machine learning (ML)-empowered techniques, selection of the TDs,
II. Motivations, Applications, and State-of-the-Art

In this section, we first provide the research motivations, and then introduce several potential application scenarios. Finally, we summarize the state-of-the-art for THz IRS communications.

A. Motivations

Recently, THz communication has attracted considerable attention owing to its ability to provide ultra-wide bandwidth. However, due to its extremely high frequency, THz signals usually suffer from severe attenuation and poor diffraction, which limits its transmission distance and applications in mobile communications. Although the multiple-input multiple-output (MIMO) technique can be applied to design high gain directional beamforming to improve the signals strength, THz signals are still vulnerable to blocking obstacles, which seriously degrades the beamforming gain when obstacles exist. Therefore, it is essential for THz communications to have line-of-sight (LoS) links between the transmitter and receiver. Motivated by this consideration, IRS can be deployed to create the additional LoS links by judiciously reflecting the received signals, and thus, enhancing the THz signals strength and extending the coverage of the THz communications.

B. Application Scenarios

Based on the above discussions, next we briefly introduce three potential application scenarios for UWB THz IRS communications.

1) Indoor Communications: UWB THz is an attractive candidate frequency band to provide the ultra-high transmission rate for the indoor short distance communications. Indeed, the 0.252-0.325 THz has been selected by the IEEE 802.15.3d standard to support tens of Gbps data rate [6]. However, the existence of various obstacles in indoor environments often makes it difficult to build a LoS link. The deployment of IRS, e.g. on an indoor wall or ceiling, can help create a virtual direct LoS link, and thus, improving the quality-of-service of users.

2) Dense Building Communications: As mentioned earlier, THz signals are vulnerable to blocking obstacles. Thus, the presence of several dense buildings makes it difficult to build a direct link, or such a link will be very weak. Therefore, it is necessary to apply IRS to change the signals transmission direction so as to establish a virtual direct LoS link between the transmitter and receiver, improving the strength of the received signals.

3) UAV Communications: Recently, UAV communications have received much attention from both academia and industry due to their high flexibility and low deployment cost. Furthermore, LoS links between the UAV and ground users can usually be built to improve the system performance. However, conventional UAVs are typically equipped with active antennas, and the power consumption can be very huge, especially with a large number of antennas. This often results in a limited service time due to the battery-powered UAV. By integrating the UAV with an energy-efficient IRS, forming a THz UAV IRS, one does not only provide ultra high rate but also decreases the power consumption and prolongs the service time. In UAV-based systems, the IRS can be deployed at the UAV or on the ground.
C. State-of-the-Art

There are only few works considering THz IRS communications [7]-[10]. Towards decreasing the power consumption, the authors in [7] apply the sparse RF chain antenna structure at the BS. Furthermore, a joint channel estimation and hybrid precoding scheme is proposed to maximize the system throughput. Similarly, to obtain the channel state information (CSI), an effective beam training scheme is developed in [8]. Consequently, the corresponding hybrid beamforming is designed for maximizing the transmission rate. UAV-assisted THz IRS communications is investigated in [9], where the authors consider a single-antenna BS to analyze and optimize the UAV trajectory. The authors in [10] study the secure transmission problem, and jointly design the BS active beamforming and IRS passive beamforming to improve the system security.

Current works mainly focus on the narrow band systems, where the research methods or adopted techniques are similar to those proposed in conventional low frequency or millimeter wave IRS communications. Since the THz band enjoys the ultra-wide bandwidth, it is important to study new challenges and techniques for the UWB THz IRS communications. In particular, we will analyze whether the conventional sparse RF antenna structures are still suitable. Major challenges and key techniques are also introduced.

III. MAJOR CHALLENGES

In this section, we identify the major challenges faced by UWB THz IRS communications, including the huge power consumption and the high loss in beam gain.

A. Huge Power Consumption for the Active Antennas Elements at the BS

Generally, for THz systems, the BS is equipped with a large number of antennas to form the high gain directional beam for improving the strength of the THz signals. However, when the BS is equipped with a large scale antenna array, the hardware power consumption is huge for the THz systems. This is because the power consumption for a single RF chain at THz frequency (about 250 mW) is almost ten times higher than that at low frequency (about 30 mW) [11]. If each antenna is connected to a unique RF chain as in the traditional structure, the large number of antennas will lead to a huge power consumption. Therefore, several sparse RF chain antenna structures have been developed, where the number of RF chains is much lower than that of the antennas. In this case, multiple antennas are connected to one RF chain via several low-power consumption PSs, such as the fully-connected structure and static/dynamic subarray structure. Although the existing sparse RF chain antenna structures are very effective in decreasing the power consumption for the mmWave or narrowband systems without causing much system performance loss, they may not be as effective for the UWB THz IRS systems. The reasons are as follows: the beam directions at different subcarriers are often different (i.e., beam split), and thus, yielding severe loss in beam gain under the conventional hybrid precoding schemes due to the frequency independent characteristic of the PSs. Therefore, how to obtain a high system performance with minimum power consumption is a major challenge.

B. The Large Loss in Beam Gain Due to the Two Stage Beam Split

Different from the low frequency narrowband systems, there exists beam split for the UWB THz systems, namely, beam directions produced by the BS at different subcarriers are different [5]. Furthermore, as shown in Fig. 1, the UWB THz IRS systems face a two stage beam split, including the first stage beam split from the BS to the IRS and the second stage beam split from the IRS to users.

Generally, the first stage beam split may cause two problems as shown in Figs. 1(c) and 1(d), namely “beam leakage” and “reflecting leakage”. The former means that the beam directions formed at several subcarriers deviate from the IRS, so that these THz signals cannot be reflected by the IRS, leading to a loss in the beam gain. The latter means that some of the IRS elements do not reflect any THz signals due to the small beam split, which decreases the reflecting efficiency. Note that the “beam leakage” or “reflecting leakage” is related to several factors, such as the number of the BS antennas, the IRS shape, the distance between the BS and IRS, and the carrier frequency. In addition, since the size of the receivers is relatively small, the second stage beam split leads to a loss in the beam gain, as shown in Fig. 1(e), namely, the beam directions reflected by the IRS at several subcarriers deviate...
from the receivers, and we call this “reflecting split”. Clearly, the two stage beam split may cause high loss in array gain for UWB THz IRS communications, and how to overcome the two stage beam split effects is another major challenge.

IV. KEY TECHNIQUES

To overcome the first stage beam split, we introduce three TD-based sparse RF chain antenna structures and the corresponding hybrid precoding that can realize the beam convergence and dispersal. Following this, we analyze the effect of the IRS deployment on the beam split.

A. TD-Based BS Antenna Structure

As mentioned earlier, for UWB THz IRS communications, how to overcome the two stage beam split effects is a major challenge, and the existing sparse RF chain antenna structures are not effective. Recently, it was shown that the TDs can be used to mitigate the beam split effect, and thus, several TD-based sparse RF chain antenna structures have been developed [5], [12], as shown in Fig. 2. First, the authors in [5] propose a fully-connected structure, where the PSs are connected to the RF chain via several TDs (i.e., Fig. 2(a)). This structure can obtain a better performance in restraining the beam split, but the hardware complexity is high and the number of the PSs is also huge. Later, the authors in [12] propose a subarray structure, where each PS (or antenna) is connected to only one TD (i.e., Fig. 2(b)). Although the hardware complexity of the subarray structure is low, it needs more TDs. Note that the power consumption for the THz TDs (e.g., 80 mW [13]) is much higher than that for the PSs (e.g., 30 mW). Under a large number of antennas, the number of the TDs is also large, which leads to the huge power consumption. To address this issue, we develop a sparse TD-based subarray structure as shown in Fig. 2(c), where multiple PSs (or antennas) are connected to one TD. In this way, the number of TDs can be effectively reduced, together with the power consumption and hardware complexity. In addition, compared with the first structure, all TDs can set the same delay for our designed structure, thereby simplifying the TD circuit control and design.

B. Delay-Based Hybrid Precoding

For the TD-based sparse RF chain antenna structure, the analog precoding, delay and digital precoding should be jointly optimized. In fact, the main objective of the TDs is to overcome the beam split effect. [5] first introduces how to realize the beam convergence by adjusting the TDs, while [12] studies how to disperse the beam by adjusting the TDs for serving more users. Different from the existing work, two beam split effects (“beam leakage” and “reflecting leakage”) need to be solved in the UWB THz IRS communications. In this way, we should first design the analog beamforming at the BS by adjusting the PSs to point the beam direction of the central subcarrier towards the IRS. For the “beam leakage” case, the overall beams should be converged by adjusting the TDs so that the IRS can reflect all received beams. For the “reflecting leakage” case, the overall beams should be dispersed by adjusting the TDs so that the beams can cover the entire IRS, thus improving the reflecting efficiency. Finally, the digital precoding should be designed to effectively integrating multi-user interference. In addition, beam split effects depend on the distance between the BS and IRS, the number of the BS antennas, the IRS deployment, the carrier frequency, etc. With the above procedure, the beam split challenge can be effectively mitigated using the delay-based hybrid precoding.

C. IRS Deployment

Before discussing the IRS deployment, we first analyze the reason for the beam split effects in UWB THz signals. With a large number of antennas at the transmitter or receiver, not all antennas of the receiver simultaneously receive the signals, namely, there exists signal delays among different antennas. In addition, for the low frequency multiple carriers, the ratio \( f_m/f_c \) can be approximated as 1, where \( f_m \) and \( f_c \) stand for the \( m \)th and central subcarrier frequency, respectively. However, for the UWB THz, the above approximation will not hold. Meanwhile, the selection of the space among adjacent antennas usually depends on the wavelength of the central subcarrier frequency. Based on the above reasons, the beamforming of the different subcarrier signals will generate different directions referred to as beam split, and the detailed analysis can be found in [15]. Furthermore, more antennas (elements) at the BS (IRS) lead to a larger signal delay among different antennas (elements) at the BS (IRS), which further amplifies the beam splits effects. Generally, the IRS is a planar structure, and the horizon and elevation directions can both form the beam split, aggravating the effects. Thus, the IRS deployments (sizes) also contribute to the beam split effects. As shown in Fig. 3, the large central IRS deployment (i.e., Scheme 1), distributed multiple rectangular IRS deployment (i.e., Scheme 2), distributed multiple square IRS (i.e., Scheme 3) and distributed large scale square IRSs deployment (i.e., Scheme 4), lead to different beam split effects. Our research finds that Scheme 4 owns...
the smallest beam split effects, but the deployment cost will be high. Detailed performance analysis is presented below.

V. Performance Analysis

In this section, we present simulation results to illustrate the system performance under different techniques. First, we show the effect of the IRS deployments on the system performance. As shown in Fig. 3, we assume that there is a $16 \times 16 = 256$ element IRS (i.e., Scheme 1), and then it is transformed into three other schemes, including Scheme 2, Scheme 3, and Scheme 4. Schemes 2 and 3 are used to compare the system performance under different shape deployments, while Scheme 4 is employed to study if more IRSs lead to a better system performance. In addition, we assume that the BS is equipped with a single antenna to serve a single user. The number of subcarriers is 64, while the bandwidth and central subcarrier frequency are 20 GHz and 200 GHz, respectively. Fig. 4 plots the relative subcarrier gain (each subcarrier gain is normalized based on the central subcarrier gain) under the four different IRS deployment schemes. Under the same condition, one can observe that the relative subcarrier gain is the lowest for the central IRS deployment (Scheme 1), and is the highest for Scheme 4. This means that more IRSs can yield a better system performance. We can also observe from Fig. 4 that Scheme 3 can achieve a higher relative subcarrier gain than Scheme 2. Considering that Schemes 2 and 3 have the same number of IRSs, and the only difference is the IRS shape, we can conclude that the square IRS deployment is better than the rectangular IRS deployment for the UWB THz IRS communications.

Next, we analyze the system performance under the TD-based sparse RF chain antenna structure. Based on the analysis in Section II, how to overcome the “beam leakage” and “reflecting leakage” is crucial. It is obvious that the BS should converge the beam for the “beam leakage” and broaden the beam for the “reflecting leakage”. To realize the above functions, we apply the proposed TD-based sparse RF chain subarray antenna structure (i.e., the third structure in Fig. 2). We assume that the BS is only equipped with a single RF chain, and 64 antennas are connected to the RF chain via the multiple TDs and PSs. Here, 4 antennas are grouped to connect to one TD. Figs. 5(a) and 5(b) show the relative gain with TDs and without TDs, respectively. One can observe that the beam angles of different subcarriers vary from each other when the TDs are not applied as shown in Fig. 5(a), where they remain the same when the TDs are applied, and thus, realize the beam coverage. Fig. 6 shows the beam broadening under TDs. Fig. 6(a) depicts beam split model for the conventional subarray antenna structure, and Figs. 6(b) and 6(c) show the beam broadening model under different numbers of TDs, where 16 TDs and 32 TDs are used, respectively. It is clear that more TDs can achieve a better performance in beam broadening. However, the TD elements are usually of high power consumption and hardware complexity.

VI. Open Issues and Research Opportunities

We highlight several open issues for the UWB THz IRS communications, and discuss the corresponding research directions and opportunities in this section.

A. AI/ML-Empowered Techniques

Due to ultra-high frequency and large array antennas at the BS and IRS, how to obtain CSI is a critical and challenging problem. Furthermore, joint beamforming design is also non-trivial due to the two-stage beam split. To address the above challenges, a potential solution is to apply AI/ML techniques. For example, by exploiting the channel sparsity, advanced neural networks can be designed to obtain the CSI with lower complexity. Consequently, intelligent beamforming and antenna selection can be applied to solve the complicated beamforming design problem. However, how to utilize the AI/ML techniques for THz IRS communications more effectively should be extensively investigated in the future.
B. Selection of the TDs

As shown in Fig. 2, several TD-based sparse RF chain antenna structures are designed. It is obvious that the TD is very important for overcoming the first stage beam split effect, and more TDs can result in higher performance. However, the large number of TDs will lead to high power consumption and hardware complexity, and thus, is difficult and inapplicable in practical hardware design. Therefore, we need to select the appropriate number of TDs to obtain a tradeoff between system performance and hardware complexity.

C. Discrete Phase Shift Design at the BS and IRS

For UWB THz IRS communications, when the BS uses a sparse RF chain antenna structure, the analog beamforming needs to be designed by adjusting the phase shifts, and the IRS reflects the received signals to form the directional beams by adjusting the phase shifts. Generally, continuously tuning the phase shifts at the BS and IRS can yield near optimal performance, and this is convenient to analyze. However, it is difficult and costly to implement in practice because of the complex hardware design. For example, when 16 levels of phase shift are required, 4 PIN diodes are needed for each element. With a large number of elements at the BS or IRS, it is very challenging to pack so many diodes within the limited physical space, and the controlling is also an issue. Accordingly, two stage discrete phase shifts at the BS and IRS should be jointly optimized, which is a new challenge.

D. Semantic Communications

Current communication technologies are mainly based on the Shannon physical capacity, and they are limited by the advanced encoding and modulations techniques. For future 6G wireless networks, semantic communications is a promising technique, and its core is to directly transmit “the meaning” of the information without encoding/decoding or modulation, which improves the transmission efficiency. However, how to apply this advanced technique in UWB THz IRS communications is a fruitful future research direction.

E. Sensing and Localization

In addition to provide the ultra-high data transmission rate, the THz frequency band is also attractive for high resolution sensing and localization due to its transmission characteristic, such as the fast tracking and millimeter-resolution wireless positioning. Furthermore, the IRS is also helpful for wireless sensing and localization. Therefore, how to integrate the communication, sensing and localization in THz IRS communication is a challenging and meaningful research direction.

F. Simultaneous Transmitting and Reflecting IRS Communications

To improve the efficiency of IRS communications, simultaneous transmitting and reflecting IRS (STAR-IRS) has been developed, which means that the IRS can simultaneously transmit and reflect the incident signals, thus improving coverage and transmission efficiency. However, for the UWB THz IRS communications, several issues should be explored, such as how to analyze the beam split for the transmit beamforming formed at the IRS, its effects on performance, and how to jointly optimize the transmission/reflection coefficients, and the IRS deployment.

G. Joint Active and Passive IRS Communications

Although a passive IRS can decrease the energy consumption and hardware complexity, the “double fading” effect yields a small achievable capacity gain. To solve this problem, active IRSs are considered in several existing works, where the signals can be amplified to break the “double fading” effect, thus improving the transmission efficiency. However, fully active IRS may cause large power consumption. Accordingly, there exists the tradeoff between the transmission efficiency and energy consumption and how to analyze joint active and passive IRS are promising directions. Furthermore, the beam split effect can be reduced by active IRS, which should also be explored.

VII. Conclusion

In this article, we studied UWB THz IRS communications, and introduced several potential application scenarios. We
presented major challenges and key techniques, where we carefully analyzed the two stage beam split and the effect of the IRS deployment on the system performance. Furthermore, we proposed a novel antenna structure with low hardware complexity and energy consumption, and validated its effectiveness via simulation results. Finally, we highlighted several key research directions and promising opportunities for future UWB THz IRS communications.

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