THz Precoding for 6G: Challenges, Solutions, and Opportunities

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Abstract

Benefiting from the ultra-wide bandwidth, terahertz (THz) communication is becoming a promising technology for future 6G networks. In order to support the desired coverage, precoding by using a large-scale antenna array is an essential technique for THz communication to overcome the severe path loss of THz signals. In this article, we systematically investigate the dominant THz precoding techniques for future 6G networks, with the highlight of its key challenges and opportunities. Specifically, we first clarify the major differences between millimeter-wave and THz channels, based on which we reveal the key challenges of THz precoding, such as the distance-dependent path loss, the beam split effect, the high power consumption, and so on. To address these challenges, five representative THz precoding techniques: analog beamforming, hybrid precoding, delay-phase precoding, dynamic RF chains based precoding, and reconfigurable intelligent surface based precoding, are extensively investigated in terms of their different structures, designs, most recent results, and pros and cons. We also provide simulation results of spectrum and energy efficiencies to compare these typical THz precoding schemes to draw some insights for their applications in future 6G networks. Finally, several important open issues and potential research opportunities, such as the integrated sensing and communication, are pointed out and discussed.

Introduction

In February 2020, ITU officially launched the research work on 6G for the next-generation wireless networks. Various perspectives on 6G believe that 6G will empower full-dimensional wireless connectivity and coverage from indoor scenario to space scenario. Meanwhile, 6G will also support new vertical applications, such as holographic communications and extremely-high-definition video transmissions [1]. To realize the 6G visions above, the peak data rate, which is an important key performance indicator for wireless communications, is expected to be more than 1 Tb/s [1]. However, the bandwidth provided by the 5G millimeter-wave band (e.g., 2 GHz bandwidth in 30–100 GHz [2]), is not able to support such a high data rate. Compared with mmWave band, terahertz (THz) band (0.1 THz-10 THz) can provide much more bandwidth, for example, more than 20 GHz, to realize an ultra-high data rate [1,

3]. Thus, THz communication has been widely considered as an essential technology for future 6G networks [1, 3].

Nevertheless, it is known that THz signals seriously suffer from the severe path loss, for example, 120 dB/100 m at 0.6 THz [3], which makes it difficult to realize the desired coverage. Precoding is one of the most promising solutions to solve this problem without increasing the transmit power. Specifically, by generating directional beams with high array gains using large-scale antenna arrays, precoding can concentrate the transmitted power in some specific directions to compensate for the severe path loss [4]. Thanks to the very small wavelengths of THz signals, very-large-scale antenna arrays can be used in THz communications supporting the generation of pencil beams with very narrow beam width and very high array gains, which can significantly compensate for the severe path loss. As a result, THz precoding is an indispensable technique for future 6G networks [3]. Unfortunately, although precoding has been extensively studied in 5G mmWave systems, there are some new challenges for THz precoding due to the different characteristics of THz channels compared with mmWave channels, which should be identified and solved to enable a powerful 6G system.

In this article, we systematically investigate the dominant THz precoding techniques for future 6G networks, with the highlight of its key challenges and potential opportunities. Specifically, we clarify the major differences between mmWave and THz channels, based on which the key challenges for THz precoding are revealed, such as the distance-dependent path loss, the beam split effect, the high power consumption, and so on. To address these challenges, we summarize the evolution of THz precoding technique, and highlight five typical THz precoding techniques, that is, analog beamforming, hybrid precoding, delay-phase precoding, dynamic RF chains based precoding, and reconfigurable intelligent surface (RIS) based precoding. Systematic comparison of these THz precoding techniques is discussed in terms of their different structures, designs, pros and cons. In addition, we also provide simulation results to compare these THz precoding schemes. More importantly, in the end of this article, we point out several important open issues and discuss the potential research opportunities for THz precod-

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ing. Different from existing survey papers on THz communications, for example, focusing on several cutting-edge techniques [1], signal processing [5], or array design [6], this article focuses on new challenges and solutions on THz precoding technology and gives a detailed introduction. We believe that this article would inspire and stimulate more innovative ideas and solutions for this important research topic of THz precoding for future 6G wireless networks.

CHALLENGES OF THz PRECODING

The THz band can be used to greatly increase the transmission rate in various application scenarios in the future 6G, such as indoor communication, mobile communication, and satellite communication, and so on [1]. Among the above application scenarios, precoding is an essential technique to fulfill the potential performance of THz communications. In this section, we first introduce the fundamental principle of precoding. Then, we identify the major differences between THz and mmWave channels, based on which the key challenges for THz precoding will be revealed.

PRINCIPLE OF THz PRECODING

Precoding is a channel adaptive technique, which pre-processes the transmitted signal based on the channel information at the transmitter [2]. Usually, THz precoding is separated by analog beamforming and digital precoding due to the application of hybrid analog-digital precoding structure.

The most important function of analog beamforming is to generate directional pencil beams to compensate for the severe path loss of THz signals. To realize this goal, incremental phase shifts should be compensated at different antenna elements. Generally, the array gain realized by beamforming is proportional to the antenna number. Considering the antenna spacing is usually set as half of the wavelength and the wavelength of THz signals is very small, we can employ very-large-scale antenna array (e.g., 1024-element [3]) in THz communications, which is much larger than that in mmWave communications (e.g., 256-element [2]). Therefore, the severe path loss can be compensated by a high-array-gain pencil beam, for example, 60 dB array gain [3].

On the other hand, the digital precoder is utilized to maximize the achievable rate or eliminating inter-stream/user interference. Generally, the digital precoder can be designed based on the equivalent channel after analog beamforming by using conventional principles, for example, singular value decomposition or zero-forcing [2].

KEY CHALLENGES

As one of the key techniques, precoding has already been extensively investigated in 5G mmWave networks [2]. Nevertheless, due to the different characteristics of THz channels compared with mmWave channels, there are some new challenges for THz precoding. Table I shows the major differences between mmWave and THz channels [3], based on which the key challenges for THz precoding are explained as follows:

Distance-Dependent Path Loss: Due to the significant molecular absorption, the propagation distance of THz signal will not only determine the value of path loss, but also affect the avail-

	mmWave	THz
Frequency band	30–100 GHz	0.1–1 THz
Bandwidth	Wide bandwidth	Ultra-wide bandwidth
Molecular absorption	Not significant	Significant
Propagation path number	A few paths	Line-of-sight (LoS) path dominant
Propagation path loss	Severe loss	More severe and distance-dependent
Number of antennas	large-scale antenna array	Very-large-scale antenna array
Beam width	Narrow beam	Pencil beam
Wideband effect	Beam squint	Beam split

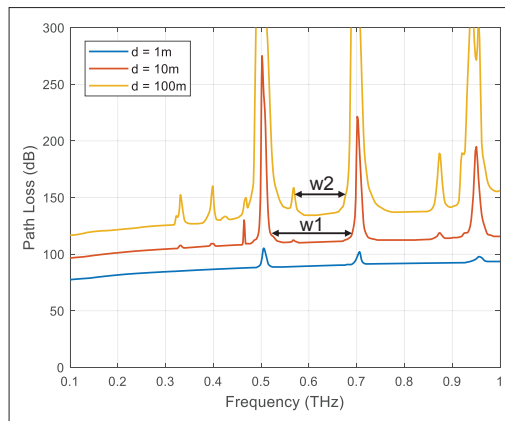TABLE 1. Comparison between mmWave and THz channels.

FIGURE 1. Distance-dependent path loss in THz band. The channel model considers the air with 10 percent relative humidity, where both the propagation loss and the loss caused by the molecular absorption of oxygen, water vapor, and other atmospheric compositions are considered [7].

able bandwidth [3]. Specifically, Fig. 1 illustrates the path loss in the THz band against the frequency for different transmission distances [3], where the sharp increase of path loss is induced by the molecular absorption. We can observe that the available bandwidth window is distance-dependent in THz band, for example, the available bandwidth window w1 for the transmission distance of 10 m is 0.51–0.68 THz, while the available bandwidth window w2 for the transmission distance of 100 m is 0.56–0.67 THz. This distance-dependent path loss is not significant in the mmWave band, but is quite obvious in the THz band. Since most existing precoding methods are mainly using unified available bandwidth window to serve different users at different distances, they may suffer from severe performance loss in THz communications. Therefore, the distance-dependent path loss has to be addressed for THz precoding.

Beam Split Effect: To carry out precoding, the most widely utilized signal processing components to realize phase shifts are analog phase-shifters (PSs). Generally, the required phase shifts are related to the wavelength, which is determined by the carrier frequency. This is not a matter for narrowband systems with a small frequency range. However, in wideband systems with a large frequency range, since the PSs can only realize frequency-in-
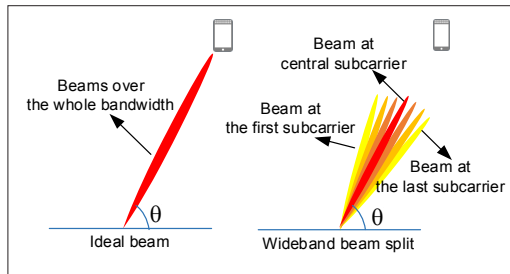
FIGURE 2. THz wideband beam split effect.

dependent phase shifts, the beams generated by PSs may disperse to the surrounding directions, and thus introduces the array gain loss [8]. This effect is called as beam squint in mmWave systems [2], where the array gain loss is not serious. However, as shown in Fig. 2, the ultra-wide bandwidth and the very narrow pencil beam in THz systems will significantly aggravate this effect, where the beams at different frequencies may split into different directions far away from the target user. Therefore, this beam split effect will result in much more severe performance loss for THz precoding, and consequently lead to the unacceptable degradation of the achievable rate performance [8].

High Power Consumption: Two major reasons lead to high power consumption of THz precoding: low efficiency of hardware components and a large number of antennas. On one hand, compared with mmWave power-amplifiers (PAs) with efficiency about 20 to 30 percent, the efficiency of THz PAs usually cannot exceed 10 percent [9]. Besides, THz digital-to-analog converters (DACs) suffer large output signal attenuation as 2.3 dB/10 GHz with increasing frequency [10]. On the other hand, in widely adapted fully-digital precoding, each antenna element is connected to a dedicated radio-frequency (RF) chain, so precoding can be easily realized by baseband signal processing. However, since a single RF chain in THz band requires large power consumption (e.g., 250 mW [4]), a large number of antennas will result in huge power consumption. Although it can be relieved by replacing RF chains with analog components such as PSs (e.g., 30 mW [4]), the large number of PSs resulted by the large number of antennas makes THz systems still suffer from high power consumption.

Mixed Near-Field and Far-Field Propagation: In THz communication systems with very-large-scale antenna array at the transmitter, receivers tend to lie in the near-field region of the transmitter due to a large Rayleigh distance. For instance, the Rayleigh distance approaches 500 m at 300 GHz [11]. For receivers within this wide near-field range, the sphere wave assumption based channel should be considered. While, for the receivers out of the near-field range, the traditional far-field planar wave assumption based channel should be adapted. This mixed near-field and far-field propagation property may lead to challenges in two aspects. Firstly, traditional precoding schemes solely considering far-field planar wave assumption based channel may suffer performance loss because of the mismatch with near-field sphere wave assumption based channel. Secondly, traditional low-RF complexity precoding structures cannot make full use of different degree-of-freedoms (DoFs) provided by the

near-field channel and the far-field channel.

Blockage: THz communication mainly relies on the LoS path due to the high frequency. When the LoS path is blocked, the achievable capacity of THz channel is quite limited, which makes it hard to serve the users without LoS path. How to deal with the blockage by new precoding structure or scheme becomes a challenge for THz precoding.

THz Precoding Techniques

To relieve the hugh power consumption, THz precoding techniques are mainly based on low RF-complexity solutions by introducing analog components [3]. In this section, we will highlight five representative THz precoding techniques with low RF-complexity, as shown in Fig. 3.

Analog Beamforming

Hardware Structure: Analog beamforming is a basic precoding technique. The key idea is to utilize only one RF chain and a PSs network to reduce RF-complexity [12]. The hardware structure of analog beamforming is shown in Fig. 3, where the RF chain is connected to all antenna elements via PSs.

Analog Beamforming Design: Since only one RF chain is employed in analog beamforming, only one user with a single transmitted data stream can be served. Under this circumstance, the optimal beamforming design is to generate a beam towards the physical direction with the highest channel power, which is usually the LoS path direction in the THz channel.

Pros and Cons: By utilizing analog PSs and one RF chain, the analog beamforming requires quite low power consumption, where the number of PSs is equal to the antenna number. However, analog beamforming can only support single-stream transmission, which cannot be easily applied in multi-user or multi-stream scenarios because of the lack of digital precoding [2]. Besides, analog beamforming can only adjust the phase of the beamforming vector due to the hardware constraint, which will result in some performance loss [2].

Hybrid Precoding

Hardware Structure: To support multi-stream transmission with low power consumption, hybrid precoding with a few RF chains has been proposed [2, 4]. The key idea of hybrid precoding is to realize precoding by a large-dimensional analog beamformer realized by analog components (e.g., PSs) and a small-dimensional digital precoder realized by a small number of RF chains, where the number of RF chains is much smaller than the antenna number (e.g., 4 RF chains for 1024 antenna elements). Therefore, multiple streams can be transmitted simultaneously. There are several connection structures between RF chains and PSs. For example, the full-connected structure is shown in Fig. 3 [13], where each RF chain is connected to all antenna elements via PSs. Besides, the sub-connected structure is also widely considered [2], where each RF chain is only connected to a subset of antenna elements and the antenna elements connected by different RF chains are non-overlapping.

Hybrid Precoding Design: The precoding design problem is to design analog beamformer and digital precoder based on channel informa-
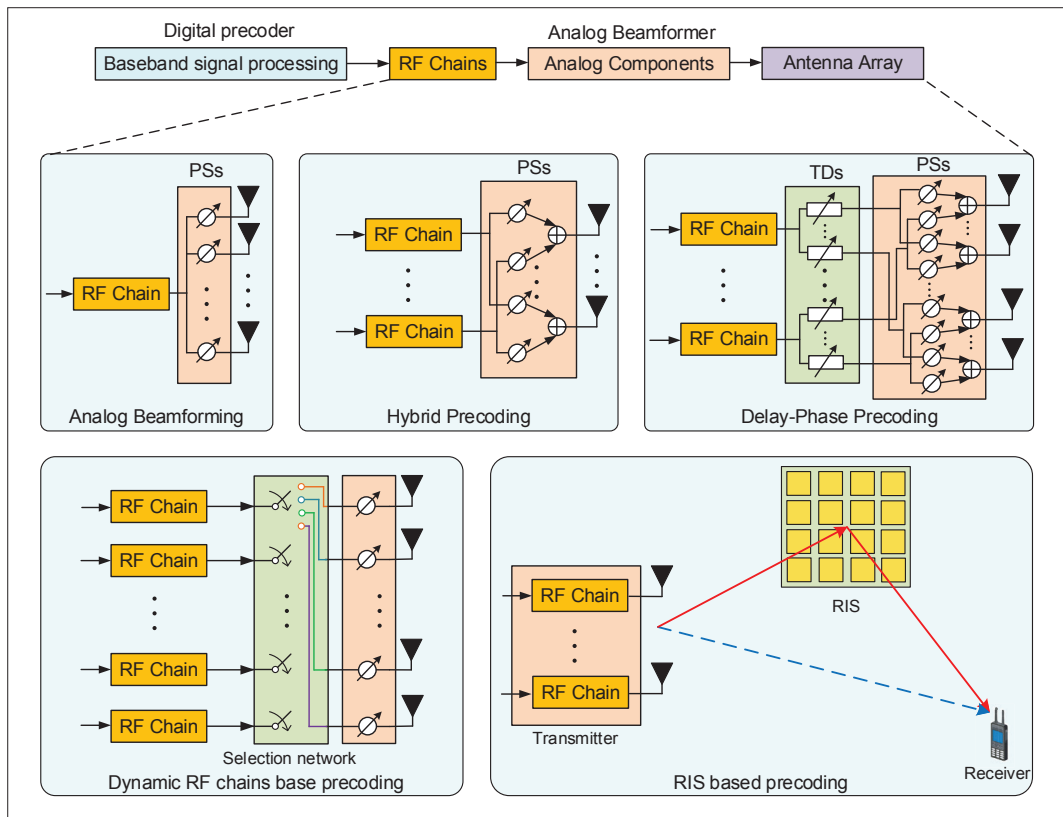
FIGURE 3. THz precoding techniques: analog beamforming, hybrid precoding, delay-phase precoding, Dynamic RF chains based precoding, and RIS based precoding.

tion to achieve the optimal achievable sum-rate performance. The hybrid precoding design can be divided into two categories.

Two-Stage Precoding Design: Due to the non-convex hardware constraint of analog beamformer, the optimization problem of hybrid precoding design is difficult to solve. Regardless of full-connected structure or sub-connected structure, a representative low-complexity method is two-stage precoding, where the analog beamformer and digital precoder are designed separately [4, 13]. Specifically, the analog beamforming is carried out for each user to maximize the array gain in the first stage. Then, in the second stage, the classical zero-forcing digital precoder is utilized to cancel the inter-user interferences. Thanks to the LoS path dominant property of the THz channel, the two-stage precoding has been proved to be able to achieve the near-optimal sum-rate performance.

Joint Optimization Based Precoding Design: Another category to design hybrid precoder is to jointly optimize the analog beamformer and digital precoder. Specifically, [14] proposed an alternatively iterative method for the full-connected structure, which alternately optimizes the digital precoder and analog beamformer without any restriction on the analog beamformer. For the sub-connected structure, a successive interference cancellation (SIC) based method was proposed in [2]. It firstly decomposes the non-convex hybrid precoding design problem into several convex sub-problems, each of which optimizes a subset of antenna elements. Then, the analog beamformer and digital precoder are obtained part by part following the procedure in SIC-based signal detection. Note that the complexity of joint optimization methods is

usually higher than that of the two-stage methods.

As revealed earlier, it is a crucial challenge to mitigate the beam split effect for THz precoding. However, in wideband systems, the two-stage precoding designs based on *frequency-independent* PSs [13] will suffer from severe performance loss, since analog beams cannot be aligned with users. On the other hand, the joint optimization based precoding design can relieve the performance loss [14], but the performance is still restricted by PSs. An effective solution is to replace all PSs by time-delayers [12]. Utilizing the *frequency-dependent* phase shifts provided by time-delayers, the severe performance loss caused by the beam split effect can be mitigated.

Pros and Cons: In spite of more RF chains and higher power consumption on baseband digital processing compared with analog beamforming, hybrid precoding is able to achieve a better trade-off between achievable rate performance and power consumption by supporting multi-user or multi-stream transmissions. Specifically, the full-connected hybrid precoding structure can generate multiple beams, the number of which is equal to the number of RF chains. Since each beam utilizes all antenna elements, the optimal array gain and narrow beam width can be expected, which leads to satisfying performance. However, the number of PSs in the full-connected structure that is equal to the number of RF chains times the antenna number is quite large, which will still cause huge power consumption. In contrast, the sub-connected structure has the same number of PSs and antenna elements, which can further reduce power consumption. Nevertheless, since only part of antenna elements (a subset or several subsets) are exploited to generate a beam
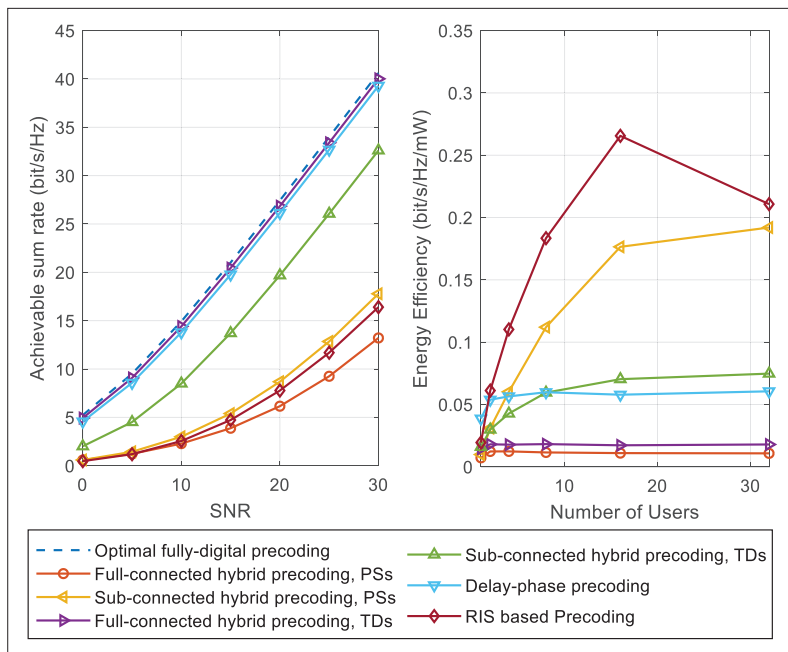
FIGURE 4. Achievable sum rate and energy efficiency for far-field scenario with bandwidth 20 GHz and transmission distance 200 m. The number of users in achievable sum rate performance is four.

for a certain user, the sub-connected structure usually suffers from the array gain loss.

DELAY-PHASE PRECODING

Hardware Structure: The wideband beam split effect can be addressed by replacing traditional PSs with time-delayers. In this way, a large number of time-delayers are required for the full-connected structure. However, THz time-delayers consumes much higher power (e.g., 100 mW [4]) than traditional PSs (e.g., 30 mW [4]), which lead to a significantly increase on power consumption. To compensate for the beam split effect with low power consumption, a delay-phase precoding structure has been recently proposed [8]. It introduces a time-delayers network between RF chains and traditional PSs network to realize *frequency-dependent* analog beamforming, but it has a significantly reduced number of time-delayers. Specifically, each RF chain is connected to several time-delayers, where the number of time-delayers is much smaller than the antenna number (e.g., 32 time-delayers per RF chain for 1024 antenna elements), and these time-delayers are connected to all the antenna elements via PSs in a sub-connected manner.

Delay-Phase Precoding Design: Unlike hybrid precoding where the analog beamformer is solely realized by PSs, the analog beamformer in the delay-phase precoding is divided into two concatenated parts. One is realized by PSs, and the other is realized by time-delayers. A two-stage precoding design method is proposed for delay-phase precoding [8]. In the first stage, the PSs generate frequency-independent beams towards different users similar to that in [13]. Then, the time delays provided by time-delayers connected to a certain RF chain are designed by a beam direction compensation mechanism based on the user physical direction and THz signal bandwidth. Therefore, the frequency-dependent beams can be aligned with different users over the whole ultra-wide band-

width. In the second stage, zero-forcing precoding is carried out separately for different subcarriers to mitigate multi-user interferences.

Pros and Cons: Delay-phase precoding converts the traditional one-dimensional analog beamformer into two-dimensional analog beamformer, that is, the sole control of the phase shifts is extended to the joint control of phase shifts and time delays. It has been proved that delay-phase precoding can achieve the near-optimal array gain over the whole bandwidth, while the required number of time-delayers can be significantly reduced (e.g., for 1024 antenna elements with 4 RF chains, the number of time-delayers can be reduced from 4096 to 128 [8]). Hence, the power consumption can be significantly reduced.

DYNAMIC RF CHAINS BASED PRECODING

Hardware Structure: Due to the near-field effect, the DoF of the THz channel with very-large-scale array increases as the distance between transmitter and receiver decreases. This makes traditional precoding structures with a fixed number of RF chains unable to fully utilize the channel DoF provided by the near-field channel or waste RF chains under the far-field channel. To solve this problem, the dynamic RF chains based precoding is proposed. Its key idea is to use multiple RF chains that can be flexibly configured to be active or inactive. Meanwhile, a selection network is used to configure the connection pattern between the active RF chains and antenna elements. In this way, the transmitter can flexibly select the number of RF chains according to the user channel, where both the near-field channel and the far-field channel are considered, thereby approaching the optimal achievable capacity without consuming extra power.

Dynamic RF Chains Based Precoding Design: The main difference of dynamic RF chains based precoding design is how to determine the number of active RF chains and the selection matrix between active RF chains and antenna elements. As proposed in [11], the number of RF chains can be decided according to the DoF of the channel at first. Then, the selection matrix is optimized to realize the best subarray pattern which maximizes spectrum efficiency. Finally, the analog beamformer and digital precoder are optimized based on the effective channel.

Pros and Cons: The dynamic RF chains based precoding can select an appropriate number of RF chains according to DoF change of the channel, which makes it enjoy high energy efficiency and can deal with the mixed near-field and far-field propagation. However, the selection network required for this structure is more complex. Besides, the current precoding design scheme can only adopt to channel with the LoS path. The case of multi-path channels requires further investigation.

RIS BASED PRECODING

Hardware Structure: To solve the blockage problem, the recently proposed new type of antenna array called RIS is promising [15]. RIS is composed of a large number of low-cost elements, which can reflect the incident signals with adjustable phase shifts. By using RIS as a passive relay between the transmitter and receiver, a new reliable path other than the LoS path is established,

and precoding at RIS can be realized by adjusting the phase shifts provided by RIS elements.

RIS Based Precoding Design: It is required to jointly design precoder at the transmitter and the RIS in RIS based precoding. This joint precoder design can be separated by designing precoder at the RIS to maximize the received power of the RIS supported path at first, and then designing the precoder at the transmitter to maximize the achievable rate. While, it is better to jointly optimize these two precoders by using an alternating optimization algorithm to realize different design goals, such as maximizing signal-to-interference-plus-noise ratio, minimizing transmit power, and maximizing the energy efficiency [15].

Pros and Cons: RIS based precoding can deal with the blockage problem in THz communications, which can realize reliable service without the LoS path. Thanks to the low-cost and low-power properties of RIS elements, the energy efficiency of RIS based precoding is usually high. However, a large number of RIS elements together with a large number of antenna elements at the transmitter results in huge computation complexity and channel acquisition overhead, which is an inevitable problem for RIS based precoding in practice.

PERFORMANCE COMPARISON

We provide simulation results of different precoding techniques. We consider a single-cell multi-user THz system with carrier frequency 350 GHz and 1024-element uniform linear array at the transmitter serving several single-antenna users. The THz ray-based channel model [14] with a single LoS path is considered. The number of RF chains is equal to the user number. The number of time-delayers (TDs) in delay-phase precoding is 32. Two-stage precoding methods [4, 8, 13] are carried out for hybrid precoding with phase-shifters (PSs) and TDs. For a fair comparison, we consider the RIS is employed near the transmitter and each element of the RIS can realize a 2-bit phase-shift [15]. Besides, the transmitted power is set to be 2 W [2]. The power of baseband processing, RF chain, PS, TD, and RIS element is set as 250 mW, 305.8 mW, 30 mW, 100 mW and 10 mW [4, 12, 15]. We consider the RF chain is composed of a 136 mW CMOS DAC [10], a 110 mW GaN mHEMT based mixer, a 16.8 mW CMOS oscillator, and a 43 mW SiGe HBT based low pass filter[4].

We can observe from Fig. 4 that the hybrid precoding structures with PSs and RIS based precoding suffer from severe achievable sum-rate loss compared with the optimal full-digital precoding. This is because they cannot deal with the beam split effect. Since severe beam split effect occurs due to the narrower beam generated by more antenna number, the full-connected structure achieves even worse performance compared by sub-connected structure with PSs. By contrary, with the help of TDs, hybrid precoding structure using TDs can achieve better performance. Moreover, although the number of TDs is quite small, the delay-phase precoding can also achieve the near-optimal performance, which outperforms the sub-connected hybrid precoding with TDs by about 5 dB. The RIS based precoding enjoys the highest energy efficiency because of the use of low-power-consumption elements. Besides, the sub-connected structure enjoys higher energy efficiency than the full-con-
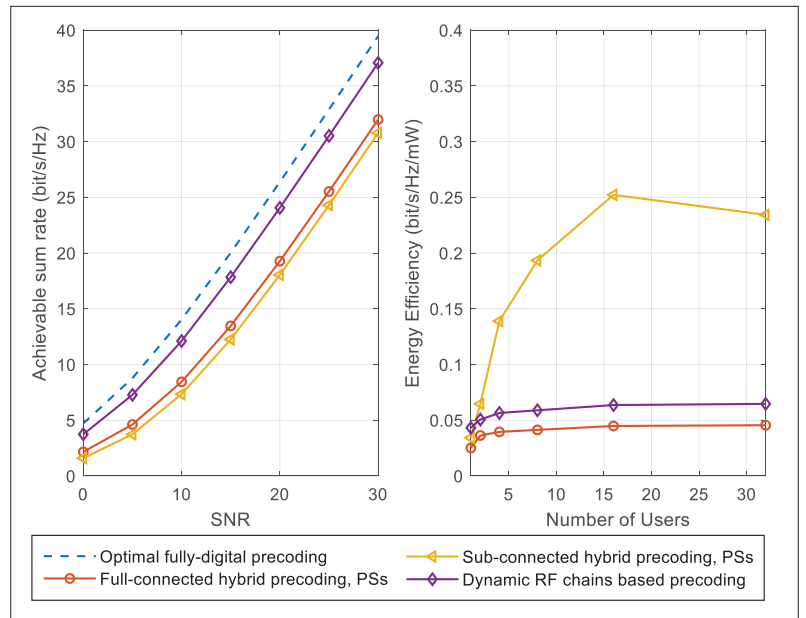

FIGURE 5. Achievable sum rate and energy efficiency for near-field scenario with bandwidth 1 GHz and transmission distance 30 m. The number of users in achievable sum rate performance is four.

nected structure. This is because the number of PSs or TDs in sub-connected structure is fixed as the number of users grows.

We can observe from Fig. 5 that the dynamic RF chains based precoding can realize the near-optimal achievable sum-rate performance in the near-field scenario. Since the dynamic RF chains based precoding considers the near-field propagation characteristics, it also outperforms the full-connected and sub-connected hybrid precoding. On the other hand, the sub-connected hybrid precoding structure still enjoys the highest energy-efficiency performance due to utilizing smaller number of PSs. Besides, the dynamic RF chains based precoding achieves higher energy-efficiency than the full-connected hybrid precoding structure.

OPEN ISSUES AND RESEARCH OPPORTUNITIES

In this section, we point out several open issues for THz precoding to empower future 6G networks, and the corresponding research opportunities are also discussed.

HARDWARE IMPAIRMENTS

Existing THz precoding studies are mainly based on the ideal hardware assumption. However, the actual performance of THz precoding will be degraded by inevitable hardware impairments [3], such as the non-linearity of power amplifier, In-phase/Quadrature imbalance, and so on. Therefore, accurate THz hardware impairments model, exact performance analysis, and the corresponding precoding calibration designs are still open problems to be investigated.

LOWER POWER CONSUMPTION

Although the representative THz precoding techniques discussed in this article can relieve the huge power consumption, they still consume a large amount of power. Therefore, further reduction of the power consumption is expected, such as using low-resolution ADC/DAC, low-resolution

> How to realize low-overhead and high-accuracy CSI acquisition is a major challenge of efficient THz precoding.

PSs or RIS [15]. The THz precoding design based on these low-power analog components requires further investigation from both hardware design and signal processing perspectives.

CHANNEL STATE INFORMATION ACQUISITION

Accurate channel state information (CSI) is essential for THz precoding [14]. However, huge-dimensional channel due to wide bandwidth and a large number of antennas makes THz systems suffer from huge CSI acquisition overhead. How to realize low-overhead and high-accuracy CSI acquisition is a major challenge of efficient THz precoding.

USER MOBILITY

Due to the very narrow beams in THz systems, the optimal precoder will vary fast when users are moving [8]. Therefore, efficient channel tracking schemes which can quickly calibrate the precoder and guarantee continuous service are vital. A simultaneous multi-beam based user tracking scheme is proposed with slow user movement [8]. While, more research is still required to cope with higher user mobility.

INTEGRATED SENSING AND COMMUNICATION

The high spatial and temporal resolution of the THz signal makes it suitable for sensing. Hence, THz integrated sensing and communication is considered as an important technique of 6G [1]. However, for beamforming design, a stable narrow beam needs to be provided to support communication, and fast scanning beams are required to support sensing. This conflict makes the beamforming design of THz integrated sensing and communication quite challenging.

OTHER ISSUES

There are other open issues for THz precoding, such as the accurate THz channel model, the complex design of very large THz antenna array, the low-power design of THz analog components, and so on, which require further investigation in the near future.

CONCLUSIONS

In this article, we systematically investigated the dominant THz precoding techniques for future 6G networks. We revealed the key challenges for THz precoding, and compared five representative THz precoding techniques. Specifically, analog beamforming has the simplest hardware structure. Hybrid precoding achieves a better trade-off between performance and power consumption. Delay-phase precoding, dynamic RF chains based precoding, and RIS based precoding can solve the challenges of beam split, mixed near-field and far-field propagation, and blockage. Finally, we identified several future research opportunities for THz precoding.

REFERENCES

[1] Z. Chen *et al.*, "Terahertz Wireless Communications for 2030 and Beyond: A Cutting-Edge Frontier," *IEEE Commun. Mag.*, vol. 59, no. 11, Nov. 2021, pp. 66–72.
[2] X. Gao *et al.*, "Energy-Efficient Hybrid Analog and Digital Precoding for Mmwave MIMO Systems With Large Antenna Arrays," *IEEE JSAC*, vol. 34, no. 4, Apr. 2016, pp. 998–1009.
[3] T. S. Rappaport *et al.*, "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access*, vol. 7, June 2019, pp. 78 729–57.
[4] S. A. Busari *et al.*, "Generalized Hybrid Beamforming for Vehicular Connectivity Using THz Massive MIMO," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, 2019, pp. 8372–83.
[5] H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, "An Overview of Signal Processing Techniques for Terahertz Communications," *Proc. IEEE*, vol. 109, no. 10, Oct. 2021, pp. 1628–65.
[6] D. Headland *et al.*, "Tutorial: Terahertz Beamforming, From Concepts to Realizations," *APL Photonics*, vol. 3, no. 5, Feb. 2018, pp. 51–101.
[7] J. M. Jornet and I. F. Akyildiz, "Channel Modeling and Capacity Analysis for Electromagnetic Wireless Nanonetworks in the Terahertz Band," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, Aug. 2011, pp. 3211–21.
[8] J. Tan and L. Dai, "Wideband Beam Tracking in THz Massive MIMO Systems," *IEEE JSAC*, vol. 39, no. 6, June 2021, pp. 1693–1710.
[9] X. Li *et al.*, "A 250-310 GHz Power Amplifier With 15-dB Peak Gain in 130-Nm SiGe BiCMOS Process for Terahertz Wireless System," *IEEE Trans. THz Sci. Technol.*, vol. 12, no. 1, July 2022, pp. 1–12.
[10] F. Buchali, "Beyond 1 Tbit/s Transmission Using High-Speed DACs and Analog Multiplexing," *Proc. Optical Fiber Commun. Conf. Exhibition (OFC'21)*, San Francisco, USA, 2021, pp. 1–56.
[11] Z. Wu *et al.*, "Distance-Aware Precoding for Near-Field Capacity Improvement," arxiv preprint arXiv: 2112.14598, Dec. 2021, pp. 1–12.
[12] E. Ghaderi *et al.*, "An Integrated Discrete-Time Delay-Compensating Technique for Large-Array Beamformers," *IEEE Trans. Circuits Syst. I: Reg. Papers*, vol. 66, no. 9, 2019, pp. 3296–3306.
[13] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, Nov. 2015, pp. 6481–94.
[14] R. Zhang *et al.*, "Hybrid Precoding Design for Wideband THz Massive MIMO-OFDM Systems With Beam Squint," *IEEE Syst. J.*, 2020, pp. 1–4.
[15] C. Huang *et al.*, "Multi-Hop RIS-Empowered Terahertz Communications: A DRL-Based Hybrid Beamforming Design," *IEEE JSAC*, vol. 39, no. 6, June 2021, pp. 1663–77.

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