Broadband Hybrid Precoding Scheme Based on Cyclic Delay in Terahertz Communications

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ABSTRACT The terahertz communication system with traditional hybrid precoding structure has the problem of beam diffusion. This problem leads to the serious loss of achievable rate and offsets the performance gain caused by bandwidth increase, so a broadband hybrid precoding scheme based on cyclic delay is proposed in this paper. Firstly, a broadband hybrid precoding framework based on cyclic delay is constructed. A delay element is placed at each antenna of the traditional full-connected hybrid precoding structure. Thus, a frequency-dependent phase shift is accomplished to compensate the beam diffusion. Then, the unit delay of delay element at each antenna is determined by maximizing the array gain of the sub-carriers, but there is a problem that the unit delay is not uniform. Finally, through the design of analog precoding, the unity of the unit delay can be realized, while maximizing the array gain of each sub-carrier. The simulation results show that the proposed scheme can achieve 100% array gain at any sub-carrier, and is suitable for solving the problem of beam diffusion under different bandwidth and different number of transmit antennas. Compared with the existing schemes, the achievable rate of the proposed scheme is very close to that of the full-digital precoding scheme, and has the advantage of high energy efficiency.

INDEX TERMS THz communication, beam diffusion, cyclic delay, broadband hybrid precoding.

I. INTRODUCTION
In the future, wireless communication will be characterized by ultra-high speed and ultra-high number of connections, which will bring huge challenges to the design and deployment of wireless communication systems [1]. Terahertz (THz) communication, which is able to provide tens of times the bandwidth of millimeter wave (mmWave) communication, has attracted much attention. It is considered as a promising technology to support ultra-high data rates in future wireless communications [2]. However, with the increase of carrier frequency, the attenuation of THz signal becomes more and more serious, which becomes an important problem in THz communications [3]. Fortunately, the wavelength of the THz signal is so small that large arrays of antennas can be equipped in the transceiver. Therefore, large antenna arrays in massive multiple input and multiple output (MIMO) technology are used to provide directional array gain to compensate such severe attenuation [4]. The hybrid precoding structure has a great attraction for THz-MIMO system, due to the sparsity of THz channels. The multiplexing gain of massive MIMO can be fully realized by using a small number of radio frequency (RF) chains through hybrid precoding, so as to alleviate the huge power consumption of RF chains [5], [6].

In the existing hybrid precoding systems, the analog precoding consists of directional beams aligned with the spatial direction of the channel path, which can achieve full array gain, this is feasible for narrowband systems. However, for broadband mmWave systems, due to the spatial directions at different sub-carrier frequencies are different, the traditional analog precoding is implemented by frequency-independent phase shifters, the obvious array gain loss is caused, which is called mmWave beams strabismus. In order to solve this problem, a hybrid precoding scheme with beamwidth control is proposed in [7]. However, as the beam width increases, power loss inevitably exists in the main beam direction, which reduces the achievable rate of the system, resulting in low system energy efficiency. The authors in [8] have proposed the beam splitting technology, which dynamically divides the entire antenna array associated with RF chains into multiple sub-arrays to generate multiple beams pointing to different directions. In [9], combining the transmitter and receiver, the hybrid precoding problem is expressed as a sparse reconstruction problem by using the spatial sparse scattering...
structure of mmWave. The optimal unconstrained performance limit can be approximated by using the tracking principle. In reference to the beam strabismus problem in mmWave communication, the authors in [10] provides a transmission scheme for beam strabismus compensation in a broadband wireless communication system. A constant modulus analog precoder is designed, which can achieve maximum average beam gain with limited frequency variations in the bandwidth range. Since the bandwidth of the THz signal is much larger, the path components are split into completely separated spatial directions on different sub-carrier frequencies, which makes the above method ineffective for THz communication. In addition, the phase-controlled beams generated by the phase shifters can only achieve high array gain near the center frequency, the severe array gain loss is serious at most sub-carrier frequencies, this problem is called the beam diffusion problem in THz communication. Beam diffusion leads to the serious loss of achievable rate and offset the performance gain caused by bandwidth increase. The problem of beam diffusion has first proposed in [11]. In order to compensate the gain loss of the array, a delayed phase precoding structure was proposed. This structure introduces a delay network between the RF chains and the traditional phase-shifting network, and converts the phase-controlled analog precoding into the jointly delayed phase-controlled analog precoding. Through the joint control of delay and phase, the problem of beam diffusion can be effectively alleviated under the lower bandwidth. The diversity technology based on cyclic delay (CD) can provide periodic cyclic shift of the signal in the frequency domain [12]. CD can provide the feasibility for the design of hybrid precoding scheme, which can adapt to broadband transmission, and has high energy efficiency.

Therefore, a broadband hybrid precoding scheme based on CD is proposed in this paper. First, a hybrid precoding framework based on CD is constructed. A delay element is placed at each antenna of the traditional full-connected hybrid precoding structure. Thus, a frequency-dependent phase shift is introduced to compensate the beam diffusion. Then, by maximizing the array gain of the sub-carriers, the unit delay at each antenna is determined, but there is a problem that the unit delay is not uniform at each antenna. Finally, the unity of each delay element can be realized through the design of analog precoding, while maximizing the array gain of each sub-carrier. Simulation results show that the proposed scheme can achieve 100% array gain at any sub-carrier while ensuring high energy efficiency, and is suitable for solving the beam diffusion problem under different bandwidths and different number of transmit antennas.

II. SYSTEM MODEL
The framework of broadband hybrid precoding structure based on CD is shown in Fig.1. Considering the THz massive MIMO downlink single-user communication system, based on the full-connected structure of hybrid precoding. In order to achieve broadband transmission, orthogonal frequency division multiplexing (OFDM) technology of M sub-carrier is adopted. Then the received signal of the user at the m-th sub-carrier can be expressed as

$$y_m = H_m^H W A D_m S_m + n_m$$  \hspace{1cm} (1)

where $m \in [0, \ldots, M - 1]$, $y_m \in \mathbb{C}^{N_r \times 1}$ denotes the number of receiving antennas equipped by the user. $H_m \in \mathbb{C}^{N_t \times N_r}$ denotes the channel vector of m-th sub-carrier, and $N_t$ denotes the number of transmit antennas equipped by the base station. $A \in \mathbb{C}^{N_t \times N_{RF}}$ denotes the analog precoding composed of frequency-independent phase shifters, the constraint of each element is $|A_{l,i}| = \frac{1}{\sqrt{N_t}}$, which is the same for all sub-carriers, and $N_{RF}$ denotes the number of RF chains. $D_m \in \mathbb{C}^{N_{RF} \times N_t}$ denotes the digital precoding of sub-carrier, while $||AD_m||_2 = P$ denotes the transmission power. $N_s$ is the number of data streams, and satisfies $N_s = N_r \leq N_{RF} \leq N_t$. $n_m \in \mathbb{C}^{N_r \times 1}$ denotes the noise of m-th sub-carrier, obeying a complex Gaussian distribution with a mean value of 0 and a variance of $\sigma^2$.

![FIGURE 1. The framework of broadband hybrid precoding structure based on CD.](image)

For THz channel, a widely used statistical channel model uniform linear array (ULA) based on ray-tracing technology is considered [13]. In this paper, we consider the ULA for simplicity, but the analysis of the beam diffusion and the correspondingly proposed CD architecture can be easily extended to the uniform planar array (UPA), which has similar channel form as ULA. $f_c$ denotes the center frequency, and $f$ denotes the bandwidth. The center frequency of m-th sub-carrier is $f_m = f_c + \frac{f}{M}(m - 1 - \frac{M - 1}{2})$, $m = 0, 1, \ldots, M - 1$. The channel vector of m-th sub-carrier is expressed as

$$H_m = \sum_{l=1}^{L} \lambda_l e^{-j2\pi f_c l} f_{l}(\theta_{l,m}) f_{l}(\phi_{l,m})^H$$  \hspace{1cm} (2)

where $L$ denotes the number of resolvable paths, and satisfies $L = N_{RF} = N_s$. $\lambda_l$ and $k_l$ denote the path gain and path delay of the l-th path, respectively. $\theta_{l,m}, \phi_{l,m} \in [1, -1]$ denote the spatial direction of the base station and the user of the l-th path and m-th sub-carrier, respectively, and $f_{l}(\theta_{l,m}), f_{l}(\phi_{l,m})$.
are the array response of the base station and the user. \( f_l(\theta_{l,m}) \)

is expressed as

\[
f_l(\theta_{l,m}) = \frac{1}{\sqrt{N_t}}[1, e^{j\pi \theta_{l,m}}, \ldots, e^{j\pi (N_t-1)\theta_{l,m}}]^T
\]

(3)

where the spatial directions are the path directions in the spatial domain, which are determined by the physical propagation direction and the sub-carrier frequency. The spatial direction of the base station satisfies \( \theta_{l,m} = 2d\frac{m}{N_t} \sin \gamma_l \), where \( c \) denotes the speed of light, \( \gamma_l \in [-\pi/2, \pi/2] \) is the physical propagation direction of the path, and \( d = \frac{f}{c} \) denotes the fixed antenna spacing.

III. BROADBAND HYBRID PRECODING BASED ON CD

Since the bandwidth of the THz signal is much larger, the spatial directions of the channel at the sub-carriers of different frequencies are completely separated, so the beam diffusion effect in THz communication is equivalent to the problem of frequency-selective fading. The performance of frequency selectivity of the equivalent channel can be enriched by constructing CD network, which controls the time delay between signals [14].

A. DELAY NETWORK BASED ON CD

A delay element is placed at each antenna, where \( \Delta \) denotes the unit delay. The time delay on the \( p \)-th transmitting antenna on the \( l \)-th path is represented as \( \Delta_p = (p-1)\Delta \), where \( p \in \{1, \ldots, N_t\} \). The corresponding phase shift of the sub-carrier on the \( p \)-th antenna is \( e^{-j\frac{2\pi}{M}(p-1)\Delta} \). So the delay network is expressed as

\[
W = \text{diag}
\begin{bmatrix}
1, e^{-j\frac{2\pi}{M}\Delta}, \ldots, e^{-j\frac{2\pi}{M}(N_t-1)\Delta}
\end{bmatrix}
\]

(4)

each element is associated with the sub-carrier \( m \) and the unit delay \( \Delta \). Therefore, in the hybrid precoding with fully connected structure, the analog precoding based on frequency-independent phase control is converted into an equivalent analog precoding, that is jointly controlled by frequency-independent phase and frequency-dependent delay. The following section will focus on the parameter of \( \Delta \).

B. DETERMINATION OF THE UNIT DELAY \( \Delta \)

Considering the spatial direction \( \theta_{l,m} \) of the \( l \)-th path and \( m \)-th sub-carrier, the array gain of the beam implemented by the equivalent analog precoding vector \( \tilde{a}_l = WA_l \in \mathbb{C}^{N_t \times 1} \) on the spatial direction \( \theta_{l,m} \) is

\[
|g(\tilde{a}_l, \theta_{l,m})| = |f_{N_t}(\theta_{l,m})^H\tilde{a}_l|
\]

(5)

where \( \tilde{a}_l = f_{N_t}(\theta_{l,c}) \in \mathbb{C}^{N_t \times 1} \) is the frequency-independent analog precoding vector on the spatial direction \( \theta_{l,c} \). \( f_{N_t}(\theta_{l,m}) \in \mathbb{C}^{N_t \times 1} \) denotes the array response of the base station on the spatial direction \( \theta_{l,m} \), \( f_c \) denotes the center frequency, \( f_m = f_c + \frac{f}{M}(m - 1 - \frac{M-1}{2}) \) denotes the center frequency of \( m \)-th sub-carrier, and \( f \) denotes the bandwidth. The relationship between \( \theta_{l,c} \) and \( \theta_{l,m} \) can be expressed as \( \theta_{l,m} = \frac{f_m}{f_c}\theta_{l,c} \).

To maximize the array gain, (5) can be expressed as

\[
|g(a_l, \theta_{l,m})| = \frac{1}{N_t} \sum_{n=0}^{N_t-1} e^{-j\pi n(\frac{2m}{M}\Delta + \theta_{l,m} - \theta_{l,c})}
\]

(6)

where step (a) is obtained from

\[
|\sum_{n=0}^{N_t-1} e^{-j\pi n a} e^{j(n-1)\pi a}| = \sin^2 \frac{\pi a}{\sin^2 \frac{\pi a}{2}}
\]

and Dirichlet function \( \Xi_{N_t}(x) = \frac{\sin N_t x}{\sin x} \). In \( \Xi_{N_t}(x) \), the maximum value of the function is \( N_t \) at \( x = 0 \), and with the increase of \( |x| \), the value of \( \Xi_{N_t}(x) \) decreases sharply [15]. Therefore, when \( \frac{2m}{M} \Delta + \theta_{l,m} - \theta_{l,c} = 0 \), the result of

\[
|\Xi_{N_t}(x)| = 1, \quad \Delta = \frac{(\theta_{l,c} - \theta_{l,m})M}{2m} = \frac{f d \sin \gamma_l}{c}(\frac{M+1}{2} - m)
\]

(7)

Equation (7) contains variable \( m \), so there is a problem that different sub-carriers require different \( \Delta \), that is, the unit delay of the delay element at each antenna is not uniform. This is because of that, the phase-controlled beams generated by different phase shifter are aligned with the spatial direction \( \theta_{l,c} \) of the center frequency \( f_c \), which results in a nonlinear relationship between \( f_c \) and the center frequency of each sub-carrier. In order to achieve the same unit delay, we carry out the design of analog precoding, which is aligned with the sub-carrier spatial direction of the maximum frequency.

C. DESIGN OF ANALOG PRECODING

The original analog beam-former \( A \) in (1) is \( A = [a_1, \ldots, a_l, \ldots, a_M] \in \mathbb{C}^{N_t \times N_M} \), which is the same for all the sub-carriers due to the use of traditional frequency-independent phase shifter. Assuming the center frequency of the maximum sub-carrier is \( f_0 \) as the reference sub-carrier, and the spatial direction is \( \theta_{l,0} \). Then the center frequency of \( m \)-th sub-carrier can be expressed as \( f_m = f_0 - m\frac{f}{M} \), and there is a linear relationship between the center frequency of each sub-carrier and the reference sub-carrier. The frequency-independent analog precoding vector \( a_l \in N_t \times 1 \) is redefined as

\[
a_l = f_{N_t}(\theta_{l,0}) = \frac{1}{\sqrt{N_t}}[1, e^{j\pi \theta_{l,0}}, \ldots, e^{j\pi (N_t-1)\theta_{l,0}}]^T
\]

(8)

By redefining the vector \( a_l \), the spatial direction of the phase-controlled beam-former generated by the phase shifter is \( \theta_{l,0} \). Then, (6) can be re-expressed as

\[
|g(a_l, \theta_{l,0})| = \frac{1}{N_t}|\Xi_{N_t}(\frac{2m}{M}\Delta + \theta_{l,m} - \theta_{l,0})|
\]

(9)

According to the maximization of (9) and the linear relationship between the center frequencies of each sub-carrier, we have

\[
\Delta = \frac{(\theta_{l,0} - \theta_{l,m})M}{2m} = \frac{f d \sin \gamma_l}{c}
\]

(10)
where the unit delay $\Delta$ has no relation to frequency. This means that the same time delay can compensate for beam diffusion at all sub-carriers. Thus, the problem of different sub-carriers requiring different $\Delta$ is solved, and the value of the delay element at each antenna is unified. In (10), the unit delay $\Delta$ is independent with the number of transmit antennas $N_t$, so it is suitable for solving the problem of beam diffusion effect under different number of transmit antennas.

### D. DESIGN OF DIGITAL PRECODING

In the hybrid precoding structure, the baseband signal passes through the digital precoder and the analog precoder successively. Therefore, the performance of digital precoding depends not only on the channel matrix, but also on the equivalent channel matrix jointly formed by the channel matrix and the analog precoding matrix. Therefore, the equivalent channel matrix $H_{m, eq}$ of the $m$-th sub-carrier can be expressed as

$$H_{m, eq} = H_m^H W A$$  \hspace{1cm} (11)

Singular value decomposition (SVD) based on the channel matrix decomposition is a commonly digital precoding algorithm [16]. The SVD of the equivalent channel is expressed as follows

$$H_{m, eq} = U_{m, eq} \Sigma_{m, eq} V_{m, eq}^H$$  \hspace{1cm} (12)

where $\Sigma_{m, eq}$ denotes the diagonal matrix, whose main diagonal elements is composed of the singular values of $H_{m, eq}$. $U_{m, eq}$ and $V_{m, eq}$ are unitary matrices. The first $N_{RF}$ columns of matrix $V_{m, eq}$ is taken as the digital precoding matrix.

### E. HYBRID PRECODING ALGORITHM FLOW

We assume that the base station knows the channel matrix $H_m$ and the spatial direction $\theta_{l, 0}$. In order to cooperate with the singular value decomposition for the digital precoding, path gains are sorted in descending order and expressed as $|\lambda_1| > |\lambda_2| > \cdots > |\lambda_L|$. The pseudo-code of the proposed scheme is expressed as follows

First, the analog precoding vector $a_l$ for the $l$-th beam is calculated in step 2 to generate a phased-controlled beam towards the sub-carrier spatial direction $\theta_{l, 0}$, which is aligned with the maximum center frequency. Then, in step 3, the unit delay $\Delta$ of the beam is calculated according to (10). After that, the frequency-dependent delay network $W$ realized by the CD is calculated in step 4. Then in step 5, the analog precoding vector $\tilde{a}_l$ of the proposed structure is obtained, and the precoding matrix $A$ is synthesized in step 7. Finally, in steps 9, 10, and 11, the equivalent channel of the system is obtained, and the digital precoding matrix $D_m$ is generated through SVD.

### IV. SIMULATION RESULTS AND ANALYSIS

The simulation parameters are shown in Table 1.

The array gain of each sub-carrier at different bandwidths is shown in Fig.2. Assume the spatial direction of the reference sub-carrier is $\theta_{l, 0} = 0.5$. It can be seen from Fig.2 that with the increase of bandwidth $f$, the effect of beam diffusion becomes more serious. The traditional hybrid precoding can only achieve 100% array gain on a small range, most of the sub-carriers will suffer severe array gain loss. The delayed phase precoding scheme, with $K$ delay elements connected to each RF chain, proposed in [11], and a small number of delay elements were used to obtain advantages in energy consumption while guaranteeing achievable rate. To achieve a compromise between achievable rate and energy efficiency, $K$ is set to 16. In the case of $f = 5$GHz, the delayed phase precoding scheme can achieve almost flat array gain over the entire bandwidth. However, with the increase of bandwidth, for instance, $f = 20$GHz, the array gain of the delayed phase precoding scheme decreases significantly. The proposed scheme can achieve 100% array gain at any sub-carrier under all bandwidths, so it can be considered as an optimal solution to the beam diffusion problem. This is because of that, there is the variable of bandwidth $f$ in (10), which is suitable for solving the beam diffusion problem under all bandwidths.

Fig.3 and Fig.4 shows the achievable rate performance comparison between the proposed scheme and other existing methods, including the full-digital precoding scheme introduced as the optimal upper bound, the delayed phase precoding scheme in [11], the spatial sparse precoding scheme in [9], and the optimized broadband hybrid precoding proposed in [10]. The following equation (13) is used to

### TABLE 1. Simulation parameters.

| Parameters                        | Value   |
|-----------------------------------|---------|
| The number of transmit antennas   | $N_t = 256$ |
| The number of receiving antennas  | $N_r = 4$   |
| The number of channel paths       | $L = 4$     |
| The number of data streams        | $N_s = 4$    |
| The number of sub-carriers        | $M = 128$   |
| The number of RF links            | $N_{RF} = 4$ |
| The center frequency              | $f_c = 100$GHz |
calculate the achievable rate performance $R$ of each scheme

$$R = \frac{1}{M} \sum_{m=1}^{M} \log_2 \left( |W_n|^{H} W A D_{m} D_{m}^H A^H W^H H_m | \right)$$

(13)

Fig.3 and Fig.4 respectively show the achievable rate comparison of different schemes in the case of $f = 5$GHz and $f = 20$GHz. It can be seen from the two figures that due to the THz beam diffusion problem, neither the traditional optimized broadband hybrid precoding scheme nor the spatial sparse precoding scheme can make up for such serious performance loss. In Fig.3, the delayed phase precoding scheme can achieve nearly full-digital precoding, when the number of delay elements is $K = 16$ and the bandwidth is $f = 5$GHz. However, in Fig.4, when the bandwidth is increased to $f = 20$GHz, the achievable rate performance of the delayed phase precoding scheme is greatly reduced. In Fig.3 and Fig.4, the proposed scheme can achieve approximately the performance of the full-digital precoder under different bandwidth conditions. Therefore, the proposed scheme can solve the achievable rate loss caused by the beam diffusion effect and obtain near-optimal achievable rate performance.

The Energy efficiency is affected by multiple factors, such as achievable rate $R$, total signal transmission power $P$, baseband power $P_{BB}$, RF chain power consumption $P_{RF}$, phase shifter power consumption $P_{SW}$, and delay power consumption $P_{TD}$, etc. Considering the structural differences between aforementioned schemes, the energy efficiency $\epsilon_{CD}$ of the proposed scheme is expressed as

$$\epsilon_{CD} = \frac{R_{CD}}{P + P_{BB} + N_{RF}P_{RF} + N_{RF}N_{t}P_{TD}}$$

(14)

The energy efficiency $\epsilon_{DPP}$ of the delayed phase precoding scheme in [11] is expressed as

$$\epsilon_{DPP} = \frac{R_{DPP}}{P + P_{BB} + N_{RF}P_{RF} + KN_{RF}P_{TD} + N_{RF}N_{t}P_{RF}}$$

(15)

Fig.5 shows the energy efficiency comparison of different precoding schemes when $f = 20$GHz, where the RF chain power consumption $P_{RF} = 300$mW, the baseband power consumption $P_{BB} = 200$mW, the phase shifter power consumption $P_{SW} = 40$mW, the delay power consumption $P_{TD} = 87.5$mW and the total base station transmit power $P = 32$mW. We can observe from Fig.5 that, the traditional frequency-independent optimized broadband hybrid precoding and spatial sparse precoding schemes owing a simple structure have a low energy consumption. However, due to the low achievable rate caused by the beam diffusion problem, the energy efficiency is low. Since the delay phase precoding scheme adopts a sub-connection structure between the RF chain and the delay elements, the required number of delay

The energy efficiency $\epsilon_{HP}$ of the traditional hybrid precoding structure represented by the spatial sparse precoding scheme proposed in [9] and [10] is expressed as

$$\epsilon_{HP} = \frac{R_{HP}}{P + P_{BB} + N_{RF}P_{RF} + N_{RF}N_{t}P_{RF}}$$

(16)
elements is $N_{RF}K$, while the number of delay elements in proposed scheme is $N$. When $K = 16$, the energy efficiency of the delayed phase precoding scheme [11] is higher than that of the proposed scheme, but its rate performance is far lower than the proposed scheme in Fig. 4. When the value of $K$ is increased to 64, the number of delay elements is the same in the delay phase precoding scheme and the proposed scheme. From (14) and (15), the two schemes have the same power consumption. In addition, the rate performance of the delay phase precoding scheme cannot be improved when $K > 16$, and the power consumption is going to increase as goes up, so the energy efficiency of the delay phase precoding scheme is lower than that of the proposed scheme. In [11], it has been proved that the delay phase precoding scheme can achieve much higher achievable rate by eliminating the achievable rate loss caused by the beam diffusion, and can provide a relatively good tradeoff between the rate performance and power consumption by using a small number of delay elements. Although the proposed scheme uses more delay elements, the performance of the array gain and the achievable rate is better than that of the delayed phase precoding scheme. Therefore, the proposed scheme can not only achieve the highest achievable rate performance, but also can get the relatively high energy efficiency. This indicates that the proposed scheme can provide a better tradeoff between the rate performance and power consumption, which is promising for future THz massive MIMO systems.

V. CONCLUSION

To solve the problem of beam diffusion in THz communication system, a broadband hybrid precoding scheme based on CD is proposed. Firstly, a hybrid precoding framework based on CD is constructed. A delay element is placed at each antenna of the traditional full-connected hybrid precoding structure, where frequency-dependent phase shift is introduced to compensate for beam diffusion. Then, by maximizing the array gain of the sub-carriers, the unit delay of the delay element at each antenna is determined, but the unit delay is not uniform. Finally, through the design of analog precoding, the unified delay element at each antenna is realized while ensuring the maximization of the array gain of each sub-carrier. Simulation results show that the proposed scheme can achieve 100% array gain at any sub-carrier while ensuring high energy efficiency, and it is suitable for solving the problem of beam diffusion under different bandwidths and different number of transmit antennas. In the future, we will further investigate the beam diffusion problem by considering the sub-connected structure for multi-user communication scenarios. Meanwhile, the beam diffusion problem in intelligent reflecting surfaces aided THz massive MIMO systems also requires further investigation.

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