On the Power Leakage Problem in Beamspace MIMO Systems with Lens Antenna Array

(Invited Paper)

Tian Xie[1], Linglong Dai[1], Xinyu Gao[1], Haipeng Yao[2] and Xiaodong Wang[3]
[1]Tsinghua National Laboratory for Information Science and Technology (TNList),
Department of Electronic Engineering, Tsinghua University, Beijing, China
[2]School of Information and Communication Engineering,
Beijing University of Posts and Telecommunications, Beijing, China
[3]Department of Electrical Engineering, Columbia University, New York, USA
E-mail: xiet15@mails.tsinghua.edu.cn

***Abstract*— The recently proposed concept of beamspace MIMO can significantly reduce the number of power-hungry radio frequency (RF) chains in millimeter-wave (mmWave) massive MIMO systems. However, most existing studies ignore the power leakage problem in beamspace MIMO systems, which results in an obvious loss in the achievable sum rate. In this paper, a phase shifter network (PSN)-based precoding structure is proposed to solve this problem. Its key idea is to employ multiple phase shifters from each RF chain to select multiple instead of only one beam to collect most of the leaked power. Based on the proposed structure, a rotation-based precoding algorithm is further designed to maximize the signal-to-noise-ratio (SNR) of each user by rotating the channel gains of the selected beams to the same direction. Simulation results show that the proposed PSN-based precoding can effectively collect the leaked power to achieve the near-optimal sum rate, and enjoys a higher energy efficiency than the conventional precoding solutions.**

I. Introduction

Millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) is a promising technology for the future 5G wireless communications [1]. To reduce the number of power-hungry radio frequency (RF) chains in mmWave massive MIMO systems, the concept of beamspace MIMO has been proposed very recently [2], where a lens antenna array is utilized to convert the conventional spatial channel into the beamspace channel. Due to the limited scattering characteristics of mmWave channels, the beamspace channel presents an obvious sparse structure, through which we can effectively reduce the number of required RF chains [4].

However, most existing studies on beamspace MIMO ignore the power leakage problem. Since the lens antenna array elements are fixed, while the actual angles of departure (AoDs) of different paths are continuously distributed, the power of a path inevitably leaks onto several beams [2]. In the conventional beamspace MIMO precoding schemes [4], [5], where one beam is selected for each path, only a small proportion of the channel power can be collected, which results in an obvious loss in the signal-to-noise ratio (SNR). A straightforward solution to this power leakage problem is utilizing more RF chains to collect the leaked power of one channel path. Such solution can indeed alleviate the power leakage problem. However, it requires much more RF chains, which greatly increases the energy consumption and hardware complexity of the beamspace MIMO system.

In this paper, a novel phase shifter network (PSN)-based precoding structure is proposed to solve the power leakage problem in beamspace MIMO systems[1]. Unlike the conventional precoding structure where one RF chain can only select one beam, one RF chain can select multiple beams via multiple phase shifters in the proposed PSN-based precoding structure, thus collecting most of the leaked channel power. To deal with the non-convex constant modulus constraints on the RF domain precoder, we further design a rotation-based precoding algorithm to maximize the SNR for each user, where the channel gains of the selected beams are rotated to the same direction. Simulation results demonstrate that the proposed PSN-based precoding can efficiently solve the power leakage problem to achieve the near-optimal sum rate. In addition, the energy efficiency (EE) performance of the proposed PSN-based precoding also outperforms conventional precoding schemes.

Notations: a, $\mathbf{a}$, $\mathbf{A}$, and $\mathcal{A}$ denote a scalar, a vector, a matrix, and a set, respectively. $\mathbb{C}$ is the set of complex numbers. $[\mathbf{a}]_i$ is the *i*th element of $\mathbf{a}$. $\mathbf{A}^H$ denotes the conjugate transpose of $\mathbf{A}$. $\mathbb{E}(\cdot)$ is the expectation of a random variable. $|\cdot|$ denotes the absolute value of a complex number, or the cardinality of a set, and $||\cdot||$ denotes the 2-norm of a vector. Finally, $\mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$ and $\mathcal{N}(\mathbf{0}, \mathbf{I}_N)$ denote the complex Gaussian distribution and Gaussian distribution with expectation $\mathbf{0}$ and covariance $\mathbf{I}_N$, respectively, where $\mathbf{I}_N$ is the $N \times N$ identity matrix.

II. System Model

We consider a typical beamspace massive MIMO system in mmWave frequency, where the base station (BS) is equipped with a lens antenna array with N antennas and N_{RF} RF chains to simultaneously serve K single-antenna users [4]–[6]. The

[1]Simulation codes are provided to reproduce the results presented in this paper: http://oa.ee.tsinghua.edu.cn/dailinglong/publications/publications.html.

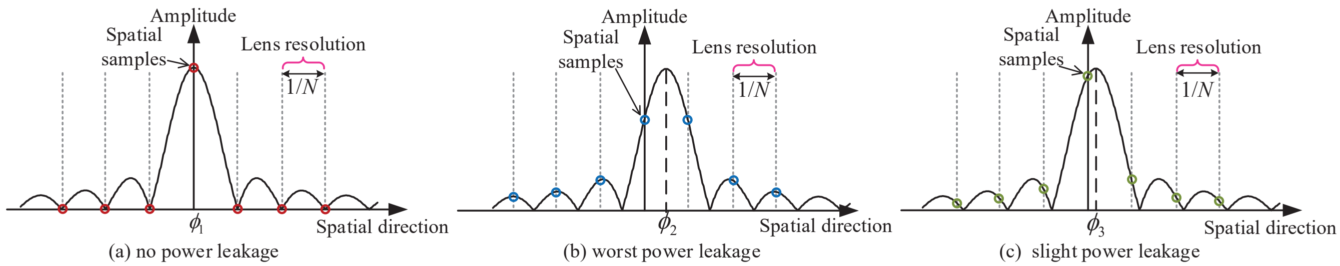

Fig. 1. Illustration of the power leakage problem: (a) No power leakage: AoD of the path perfectly matches the spatial samples of the lens; (b) The worst power leakage: AoD of the path is in the middle of two spatial samples of the lens; (c) The slight power leakage: AoD of the path slightly mismatches the spatial samples of the lens.

received signal $\mathbf{y} \in \mathbb{C}^{K\times 1}$ at all K users can be presented as

$$\mathbf{y} = \mathring{\mathbf{H}}^H \mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathring{\mathbf{H}} = \left[\mathring{\mathbf{h}}_1, \mathring{\mathbf{h}}_2, \cdots, \mathring{\mathbf{h}}_K\right] \in \mathbb{C}^{N\times K}$ is the beamspace channel matrix with $\mathring{\mathbf{h}}_k \in \mathbb{C}^{N\times 1}$ presenting the beamspace channel vector for the kth user, $\mathbf{x} \in \mathbb{C}^{N\times 1}$ denotes the transmit signal at the BS, and $\mathbf{n} \in \mathbb{C}^{K\times 1}$ is the additive white Gaussian noise (AWGN) vector following the distribution $\mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I}_K)$, where σ^2 is the noise covariance. To meet the power constraint, we have $||\mathbf{x}||^2 \leq P_{\mathrm{T}}$, where P_{T} is the total transmit power. From the perspective of signal processing, the role of the lens antenna array can be viewed as a unitary $N\times N$ spatial discrete fourier transform matrix $\mathbf{U}$ [3], [7], whose rows contain N orthogonal steering vectors

$$\mathbf{U} = \left[\mathbf{a}(\hat{\phi}_1), \mathbf{a}(\hat{\phi}_2), \cdots, \mathbf{a}(\hat{\phi}_N)\right]^H, \tag{2}$$

where $\mathbf{a}(\phi) \in \mathbb{C}^{N\times 1}$ represents the steering vector for the spatial direction ϕ, and the spatial directions $\hat{\phi}_i = \frac{1}{N}\left(i - \frac{N+1}{2}\right), i = 1, 2, \cdots, N$ cover the entire space [5]. Thus, the relationship between the beamspace channel matrix $\mathring{\mathbf{H}}$ and the spatial channel matrix $\mathbf{H}$ can be presented as

$$\mathring{\mathbf{H}} = \mathbf{U}\mathbf{H} = \left[\mathbf{U}\mathbf{h}_1, \mathbf{U}\mathbf{h}_2, \cdots, \mathbf{U}\mathbf{h}_K\right], \tag{3}$$

where $\mathbf{h}_k \in \mathbb{C}^{N\times 1}$ is the spatial channel vector for the kth user.

For the spatial channel model, we adopt a widely used clustered channel representation based on the Saleh-Valenzuela (SV) channel model [8]

$$\mathbf{h}_k = \sqrt{\frac{N}{N_{\mathrm{cl}}^k N_{\mathrm{p}}^{(k,l)}}} \sum_{l}^{N_{\mathrm{cl}}^k} \sum_{i}^{N_{\mathrm{p}}^{(k,l)}} \beta_{k,l}^{(i)} \mathbf{a}(\phi_{k,l}^i), \tag{4}$$

where N_{cl}^k is number of clusters for the kth user, $N_{\mathrm{p}}^{(k,l)}$ is the number of paths within the lth cluster for the kth user, $\beta_{k,l}^{(i)}$ and $\phi_{k,l}^i$ denote the complex gain and the AoD for the ith path in the lth cluster of the kth user. The AoDs within a certain cluster $\phi_{k,l}^i, \forall i$ are distributed among $[\phi_{k,l} - \tau_{k,l}/2, \phi_{k,l} + \tau_{k,l}/2]$, where $\phi_{k,l}$ and $\tau_{k,l}$ are the average AoD and the angular spread of the lth cluster for the kth user [8]. For the typical uniform linear array (ULA) with N antenna elements, the steering vector is $\mathbf{a}_{\mathrm{ULA}}(\phi) = \frac{1}{\sqrt{N}}\left[e^{-j2\pi\phi i}\right]_{i\in\mathcal{I}(N)}$, where $\mathcal{I}(N) = \left\{s - \frac{N-1}{2}, s = 0, 1, \cdots, N-1\right\}$ [8]. In addition, the spatial direction can be defined as $\phi = \frac{d}{\lambda}\sin\theta$, where d is the antenna spacing, λ is the signal wavelength, and θ denotes the physical direction. In this paper, we consider the half-wavelength antenna spacing, where $d = \frac{\lambda}{2}$ [8].

III. PSN-Based Precoding for Beamspace MIMO

In this section, we first explain the normally ignored power leakage problem in beamspace MIMO systems. Then, we propose the PSN-based precoding structure and the rotation-based precoding algorithm to solve the power leakage problem.

A. Power Leakage Problem in Beamspace MIMO Systems

In the practical beamspace MIMO systems, the spatial sample points of the lens antenna array are finite and fixed, while the actual AoDs of paths are continuously distributed. Therefore, the AoD of one path can not perfectly match the spatial sample points of the lens antenna array. As a result, the power of one path will leak onto multiple beams in the beamspace channel [2], which is illustrated in Fig. 1. We derive the following **Lemma 1** to quantify how much power will be leaked.

Lemma 1. *Considering the single path case where $N_{cl}^k = 1$, $N_p^{(k,l)} = 1$ and the worst power leakage case in Fig. 1 (b), if we select only one beam with the highest power in the beamspace channel, the ratio between the leaked power and the total power will be:*

$$\eta = 1 - \frac{1}{2\sum_{i=1}^{N/2} \frac{\sin^2(\pi/2N)}{\sin^2((2i-1)\pi/2N)}}. \tag{5}$$

Proof: For simplicity, we drop the subscript k of users in the proof. According to (2), (3), (4), we have

$$\eta = 1 - \frac{[\mathring{\mathbf{h}}]_{\max}^2}{\sum_{i=1}^N [\mathring{\mathbf{h}}]_i^2} = 1 - \frac{\max_i \left(\mathbf{a}^H(\hat{\phi}_i)\mathbf{a}(\phi_{\mathrm{p}})\right)}{\sum_{i=1}^N \mathbf{a}^H(\hat{\phi}_i)\mathbf{a}(\phi_{\mathrm{p}})}, \tag{6}$$

where $[\mathring{\mathbf{h}}]_{\max}$ denotes the channel element with the highest power, and ϕ_{p} is the AoD of this path. For ULA, we have

$$\eta = 1 - \frac{\max_{\mathcal{X}_i} \frac{\sin^2(N\pi\mathcal{X}_{\mathrm{i}})}{N^2\sin^2(\pi\mathcal{X}_{\mathrm{i}})}}{2\sum_{i=1}^{N/2} \frac{\sin^2(N\pi\mathcal{X}_i)}{N^2\sin^2(\pi\mathcal{X}_i)}}, \tag{7}$$

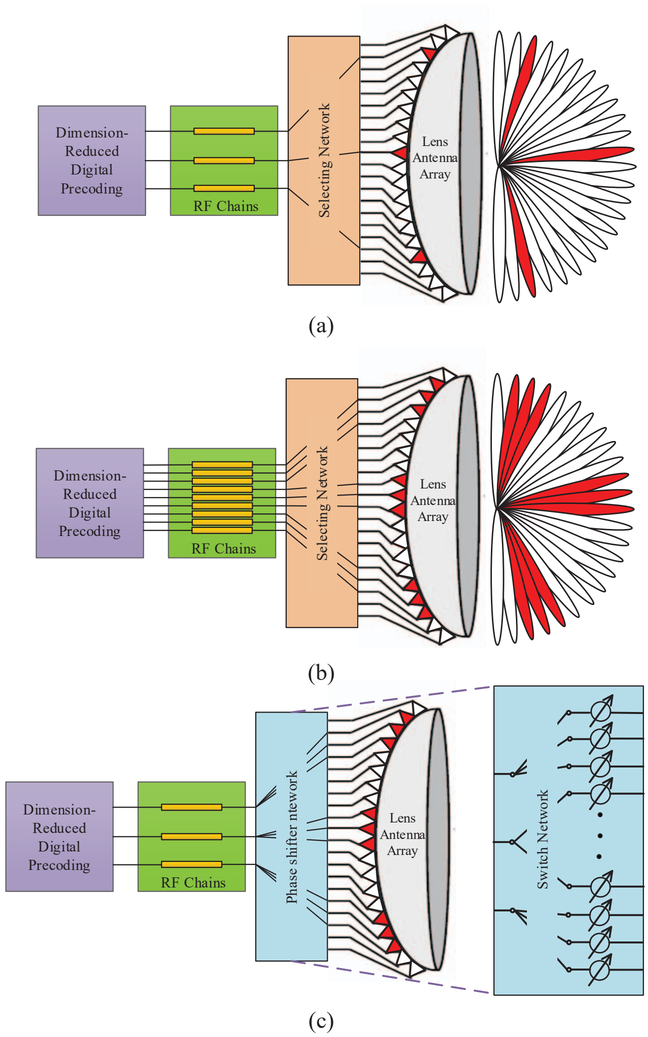

Fig. 2. Different precoding structures in beamspace MIMO: (a) The conventional single beam precoding structure; (b) The multiple beam via multiple RF chains precoding structure; (c) The proposed phase shifter network based precoding structure.

where $\mathcal{X}_i = \hat{\phi}_i - \phi_\text{p}$. From Fig. 1 (b), we can find that $\mathcal{X}_i = (2i-1)/2N$ in the worst power leakage case. Thus, we have

$$\eta = 1 - \frac{1}{2\sum_{i=1}^{N/2} \frac{\sin^2(\pi/2N)}{\sin^2((2i-1)\pi/2N)}}. \quad (8)$$

■

From **Lemma 1**, we can find that the power leakage is serious even for the simplest single path case. For example, $\eta \approx 0.595$ when $N = 256$, which implies that if we only select one beam for one path, about 60% channel power will be leaked, which incurs an obvious loss in SNR.

B. Proposed PSN-based Precoding

In the conventional beamspace MIMO systems illustrated in Fig. 2 (a), where the power leakage problem is not considered, only one beam is selected via one RF chain for one user, which is named as single beam precoding (SB) in this paper [4], [5]. The power consumption of the single beam precoding can be modeled as

$$P_\text{SB} = P_\text{T} + P_\text{BB} + P_\text{RF}K + NKP_\text{SW}, \quad (9)$$

where P_BB, P_RF, and P_SW denotes the power of baseband, RF chain, and switch, respectively. Due to the relatively smaller number of required RF chains, single beam precoding has a relatively lower energy consumption. However, as stated in the **Lemma 1**, single beam precoding can incur obvious SNR loss due to the severe power leakage problem in beamspace MIMO. On the other hand, a straightforward solution to the power leakage problem is leveraging more RF chains to collect more beams as shown in Fig. 2 (b), which is named as multiple beam via multiple RF chains (MBMRF) precoding. The power consumption of the MBMRF precoding can be modelled as

$$P_\text{MBMRF} = P_\text{T} + P_\text{BB} + P_\text{RF}B_\text{T} + NP_\text{SW}B_\text{T}, \quad (10)$$

where $B_\text{T} = \sum_k B_k$ is the total number of selected beams with B_k presenting the number of selected beams for the kth user. Although MBMRF precoding can collect the leaked power, it requires much more RF chains (e.g., $B_\text{T} = 3 \times 32 = 96$ when $K = 32$ and $B_\text{T} = 3$), thus resulting in higher hardware complexity and energy consumption.

To this end, we propose a phase shifter network (PSN)-based precoding for beamspace MIMO systems to solve the power leakage problem. In the proposed PSN-based precoding as shown in Fig. 2 (c), one RF chain can select multiple beams via an analog phase shifter network. To be specific, one RF chain is allowed to be connected to an arbitrary subset of the total N antennas through a switch network. However, one antenna can only be connected to at most one RF chain. Besides, there also exists a phase shifter to rotate the signals on each antenna. It is worth pointing out that the total number of phase shifters is N, which is not a large number. The power consumption of the proposed PSN-based precoding can be modelled as

$$P_\text{PSN} = P_\text{T} + P_\text{BB} + P_\text{RF}K + P_\text{SW}NK + P_\text{PS}B_\text{T}, \quad (11)$$

where P_PS denotes the power consumption of a phase shifter.

For the PSN-based precoding, the transmitted signal $\mathbf{x} \in \mathbb{C}^{N\times 1}$ can be expressed as

$$\mathbf{x} = \mathbf{P}_\text{RF}\mathbf{P}_\text{BB}\mathbf{s}, \quad (12)$$

where $\mathbf{P}_\text{RF} = \left[\mathbf{p}_\text{RF}^{(1)}, \mathbf{p}_\text{RF}^{(2)}, \cdots, \mathbf{p}_\text{RF}^{(N_\text{RF})}\right] \in \mathbb{C}^{N\times N_\text{RF}}$ is the RF precoder with $\mathbf{p}_\text{RF}^{(i)} \in \mathbb{C}^{N\times 1}$ presenting the ith column of $\mathbf{P}_\text{RF}$, $\mathbf{P}_\text{BB} = \left[\mathbf{p}_\text{BB}^{(1)}, \mathbf{p}_\text{BB}^{(2)}, \cdots, \mathbf{p}_\text{BB}^{(K)}\right] \in \mathbb{C}^{N_\text{RF}\times K}$ is the baseband precoder with $\mathbf{p}_\text{BB}^{(i)} \in \mathbb{C}^{N\times 1}$ presenting the ith column of $\mathbf{P}_\text{BB}$, and $\mathbf{s} \in \mathbb{C}^{K\times 1}$ is the source signal vector. Particularly, since the $\mathbf{P}_\text{RF}$ is realized through phase shifters and switches, $\mathbf{p}_\text{RF}^{(i)}$ should satisfy

$$\left|[\mathbf{p}_\text{RF}^{(i)}]_j\right| = \begin{cases} \frac{1}{\sqrt{B_i}}, & j \in \mathcal{B}_i, \\ 0, & \text{otherwise}, \end{cases} \quad (13)$$

where $\mathcal{B}_i$ denotes the set containing the indices of selected beams for the ith user. Due to the special hardware constraint in (13), conventional beamspace MIMO precoding algorithms [4], [5] are difficult to be extended to the proposed PSN-based precoding. Consequently, we need to design an efficient precoding algorithm to achieve the near-optimal performance, which is addressed in the next subsection.

C. Proposed Rotation-based Precoding Algorithm

In this subsection, we provide the rotation-based precoding algorithm design. Firstly, we define the equivalent channel between the RF chains and the users as $\bar{\mathbf{H}} = \mathbf{P}_{\text{RF}}^H \mathring{\mathbf{H}} = \left[\bar{\mathbf{h}}_1, \bar{\mathbf{h}}_2, \cdots, \bar{\mathbf{h}}_K\right]$. Here we assume that the channel state information of all users is available at the BS, which can be usually estimated by compressive sensing based channel estimation with low pilot overhead in practice [10]. In this paper, we consider a per-user power constraint that

$$||\mathbf{P}_{\text{RF}}\mathbf{p}_{\text{BB}}^{(k)}||^2 \leq \frac{P_{\text{T}}}{K}, \ \forall k. \tag{14}$$

Since the number of dominant clusters for each user is limited, and a large number of BS antennas can provide enough spatial resolution, we assume that the average AoDs of each user $\phi_{k,l}$ are separated from each other sufficiently [7]. Thus, a distinguish property of beamspace MIMO systems is that the inter-user interference (IUI) is not serious [7]. Hence, we formulate the optimal precoder design problem in the proposed PSN-based precoding as maximizing the SNR for each user

$$\begin{aligned}\left(\mathbf{P}_{\text{RF}}^{\text{opt}}, \mathbf{P}_{\text{BB}}^{\text{opt}}\right) = \arg\max_{\mathbf{P}_{\text{RF}}, \mathbf{P}_{\text{BB}}} \sum_{k=1}^{K} \left(\bar{\mathbf{h}}_k^H \mathbf{p}_{BB}^{(k)}\right)^2, \\ \text{s.t.} \quad (13), \ (14).\end{aligned} \tag{15}$$

The optimal solution to the baseband precoder in (15) is the matched filter (MF) precoder [9]:

$$\mathbf{p}_{\text{BB}}^{(k)} = \alpha_k \bar{\mathbf{h}}_k, \tag{16}$$

where α_k is the factor to normalize the transmit power for the kth user. By substituting (16) into (15), we can obtain the formulation of RF precoder design problem as

$$\begin{aligned}\mathbf{P}_{\text{RF}}^{\text{opt}} = \arg\max_{\mathbf{P}_{\text{RF}}} \sum_{k=1}^{K} \left(\alpha_k \bar{\mathbf{h}}_k^H \bar{\mathbf{h}}_k\right)^2, \\ \text{s.t.} \quad (13),\end{aligned} \tag{17}$$

where we remove the constraint on transmit power (14), since it can be satisfied through adjusting α_k. The objective function in (17) can be expanded as

$$\begin{aligned}\sum_{k=1}^{K} \left(\alpha_k \bar{\mathbf{h}}_k^H \bar{\mathbf{h}}_k\right)^2 &= \sum_{k=1}^{K} \alpha_k^2 \left(\left[\mathring{\mathbf{h}}_k^H \mathbf{p}_{\text{RF}}^{(k)}\right]^2 + \sum_{j \neq k}^{K} \left[\mathring{\mathbf{h}}_j^H \mathbf{p}_{\text{RF}}^{(k)}\right]\right)^2 \\ &\overset{(a)}{\approx} \sum_{k=1}^{K} \alpha_k^2 \left(\left[\mathring{\mathbf{h}}_k^H \mathbf{p}_{\text{RF}}^{(k)}\right]^2\right)^2,\end{aligned} \tag{18}$$

where in the approximation (a) we neglect the IUI term based on the aforementioned property in beamspace MIMO systems. Provided that the positions of non-zero elements in $\mathbf{p}_{\text{RF}}^{(k)}$ are known after beam selection, maximizing (18) equals rotating the selected elements in $\mathring{\mathbf{h}}_k$ to the same direction as

$$\frac{\left[\mathbf{p}_{\text{RF}}^{(k)}\right]_p}{\left[\mathbf{p}_{\text{RF}}^{(k)}\right]_q} = \left(\frac{\left[\mathring{\mathbf{h}}_k\right]_q}{\left[\mathring{\mathbf{h}}_k\right]_p}\right) \Bigg/ \left|\frac{\left[\mathring{\mathbf{h}}_k\right]_q}{\left[\mathring{\mathbf{h}}_k\right]_p}\right|, \forall p \in \mathcal{B}_k, \tag{19}$$

where $[\mathbf{p}_{\text{RF}}^{(k)}]_q, q \in \mathcal{B}_k$ is a reference element. The interpretation of (19) is shown in Fig. 3, where $[\mathring{\mathbf{h}}_k]_q$ and $[\mathring{\mathbf{h}}_k]_p$ are rotated to the same direction to maximize the combined value.

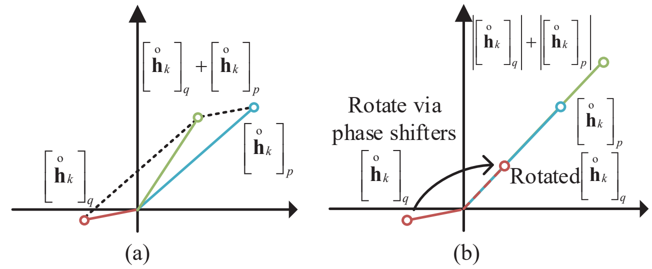

Fig. 3. Illustration of rotating the selected elements (a) combination without rotation; (b) combination with rotation.

By far, we have designed the combination approach of different selected beams and the remaining problem is how to collect the leaked power via beam selection. To this end, we provide a greedy beam selection algorithm, which first utilize the beam with the strongest power to position the cluster, and then greedily select the adjacent beams with highest leaked power. The overall procedure of the proposed rotation-based precoding algorithm is summarized in **Algorithm 1**.

Algorithm 1 The proposed rotation-based precoding algorithm

Input: $\mathring{\mathbf{H}}$, P_{T}, and B_k for each user.

Output: $\mathbf{P}_{\text{RF}}$, and $\mathbf{P}_{\text{BB}}$.

1: **For:** $k \leq K$ **do**
2: Initialize the selected beam index set $\mathcal{B}_k = \emptyset$, the neighbor beam index set $\mathcal{A}_k = \emptyset$ and $\mathbf{p}_{\text{RF}}^{(k)} = \mathbf{0}$;
3: $l_{\max} = \text{argmax}_{m=1,\cdots,N} |[\mathring{\mathbf{h}}_k]_m|$, and $\mathcal{B}_k = \mathcal{B}_k \bigcup \{l_{\max}\}$;
4: **repeat**
5: Update $\mathcal{A}_k$ according to $\mathcal{B}_k$;
6: $l = \text{argmax}_{m \in \mathcal{A}_k} |[\mathring{\mathbf{h}}_k]_m|$, and $\mathcal{B}_k = \mathcal{B}_k \bigcup \{l\}$;
7: Set $[\mathbf{p}_{\text{RF}}^{(k)}]_l$ based on (19), where $p = l, q = l_{\max}$;
8: **until** $|\mathcal{B}_k| = B_k$;
9: **end For:**
10: $\mathbf{P}_{\text{RF}} = [\mathbf{p}_{\text{RF}}^{(1)}, ..., \mathbf{p}_{\text{RF}}^{(K)}]$;
11: $\bar{\mathbf{h}}_k^H = \mathring{\mathbf{h}}_k^H \mathbf{P}_{\text{RF}}$, $\alpha_k = \frac{P_{\text{T}}}{K||\bar{\mathbf{h}}_k^H||^2}$, $\mathbf{p}_{\text{BB}}^{(k)} = \alpha_k \bar{\mathbf{h}}_k$;
12: $\mathbf{P}_{\text{BB}} = [\mathbf{p}_{\text{BB}}^{(1)}, ..., \mathbf{p}_{\text{BB}}^{(K)}]$.

In **Algorithm 1**, we sequentially design the RF precoder user by user. For each user, we search for the beam with the highest power to locate the cluster and also select this beam in step 3. In step 5, we update the neighbor beam index set $\mathcal{A}_k$ to satisfy that $\forall l \in \mathcal{A}_k$, there is an $l' \in \mathcal{B}_k$ such that l is adjacent to l'. Here, we call two beams are adjacent if the difference of their indices in any dimensions is at most one. To avoid

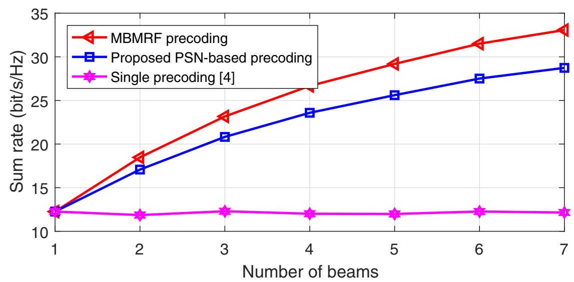

Fig. 4. Sum rate comparison against the number of beams.

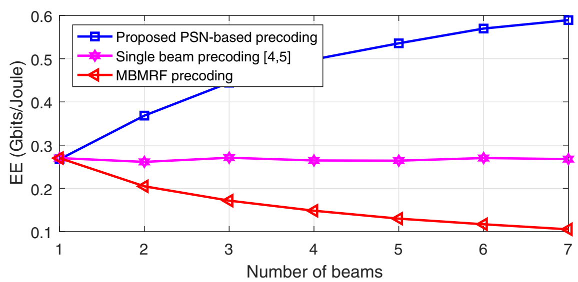

Fig. 5. Energy efficiency comparison against the number of beams.

repetitive selections, we also restrict that $\mathcal{A}_k \cap \mathcal{B}_k = \emptyset$. For example, if $\mathcal{B}_k = \{l, l+1\}$, we update $\mathcal{A}_k = \{l-1, l+2\}$. After that, the beam with the highest leaked power is selected from $\mathcal{A}_k$, and the corresponding $[\mathbf{p}_{\text{RF}}^{(k)}]_l$ is updated based on (19) in step 7. The above procedures (steps 4-7) are repeated until B_k beams are selected for the kth user as shown in step 8. After the RF precoder is determined in step 10, the baseband precoder is calculated based on (16) in step 11 and 12.

IV. Simulation Results

In this section, we evaluate the performance of the proposed PSN-based precoding through simulations. A typical mmWave beamspace massive MIMO system with lens antenna array is considered, where an $N = 512$-element ULA is employed at the BS to serve $K = 8$ users. The bandwidth of the system is 500 MHz, and the noise power spectral density is -174 dBm/Hz. The mmWave MIMO channel is generated according to (4), and the key parameters are chosen as: $N_{\text{cl}}^k = 1$ and $N_{\text{P}}^{(k,l)} = 10, \forall k, i$ is assumed for all users and clusters, and $\beta_{k,l}^{(i)}, \forall i, k, l$ follow the distribution $\mathcal{CN}(0,1)$ [8]; $\phi_{k,l}^i, \forall i$ are uniformly distributed within $[\phi_{k,l} - 10/N, \phi_{k,l} + 10/N]$. Finally, the energy efficiency (EE) is defined as the ratio between the sum rate and the power consumption. The power consumption models are defined in Section III-B, and $P_{\text{T}} = 100$ mW (20 dBm), $P_{\text{BB}} = 200$ mW, $P_{\text{RF}} = 240$ mW, $P_{\text{SW}} = 5$ mW, $P_{\text{PS}} = 30$ mW. For simplicity, the number of beams B_k is assumed to be same for all users.

The sum rate performance comparison against the number of beams is given in Fig. 4. Note that the number of beams only changes in the PSN-based precoding and MBMRF precoding, while the single beam precoding always selects one beam for each user. We can observe that the sum rate of the proposed PSN-based precoding is much higher than that of single beam precoding. Meanwhile, it is also close to the optimal MBMRF precoding, which indicates that the proposed PSN-based precoding is able to effectively solve the power leakage problem in beamspace MIMO systems.

The EE comparison against the number of beams is provided in Fig. 5, where we find that although the MBMRF precoding achieves a better sum rate performance, its EE is much lower than that of single beam precoding since a larger number of power-hungry RF chains is used. In comparison, the proposed PSN-based precoding enjoys the a much higher EE than single beam precoding and MBMRF precoding, since only some phase shifters with lower energy consumption are utilized to collect the leaked power.

V. Conclusions

In this paper, we propose a PSN-based precoding to solve the power leakage problem in beamspace MIMO systems, where one RF chain can select multiple beams via multiple phase shifters to collect most of the leaked channel power. Furthermore, we also design a rotation-based precoding algorithm to maximize the SNR for each user, where the channel gains of different selected beams are rotated to the same direction. Simulation results verify that the proposed PSN-based precoding is able to effectively solve the power leakage problem, and enjoy a higher EE than the conventional precoding schemes.

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