Antenna Selection for Multi-User MIMO at Millimeter-Wave Spectrum with Lens Antenna Arrays

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***Abstract*—The recent concept of beamspace multiple-input-multiple-output (MIMO) enables the millimeter-wave (mmWave) MIMO system to reduce the radio-frequency chains by utilising beam selection and yet achieve near-optimal sum-rate performance. In this work, we study the lens antenna array as the transmit antenna at the base station for mmWave multi-user MIMO (MU-MIMO) system. Due to the direction-based energy focusing property of the array, the beam selection is able to reduce to antenna selection without significant performance degradation as that using traditional antenna selection. For this mmWave MU-MIMO system, direction-based antenna selection method is proposed, where the inter-user interference, resulting from the case that the same antenna is selected for different users with high probability, is considered and solved by a re-selection based on minimization of sum-rate loss. Simulation results show that spectral and energy effectiveness of the proposed antenna selection method for the mmWave MU-MIMO using lens antenna array.**

***Index Terms*—Lens antenna array, mmWave communication, antenna selection, massive MIMO**

I. Introduction

MmWave systems have been considered as a promising technique to meet ever-increasing rate demands on wireless network due to possible orders-of-magnitude larger bandwidth and high dimensional MIMO operation resulting from the small wavelengths enabling a large number of antennas to be packed into a given physical aperture [1]–[3]. However, one key challenge of implementing massive MIMO at mmWave frequencies is the requirement of a large number of radio-frequency (RF) chains, which leads to unaffordable hardware cost and energy consumption.

To reduce cost and yet achieve high array gain and spatial multiplexing, hybrid analog/digital precoding has been proposed [4], where the analog beamforming is implemented through the network of a large number of phase shifters. An alternative solution is the concept of beamspace MIMO which is proposed in the pioneering work [5], by employing the discrete lens array. Since mmWave channels have the dominant line-of-sight (LoS) path and very limited scattered clusters, it is possible to only select a small number of beams according to the sparse channel, where each beam corresponds to a single RF chain. Further to this, several beam selection schemes have been studied in previous works [6]–[8], using a simplified antenna system known as critically spaced uniform linear arrays (ULAs). In [6], Sayeed and Brady proposed a simple approach to select the beam with maximum magnitude (MM). Amadori *et al.* [7] studied the beam selection schemes with regards to maximum signal-to-interference-plus-noise ratio (SINR) and maximum capacity criteria, where the appropriate beams are selected by the low-complexity decremental/incremental algorithm. An interference-ware (IA) beam selection was proposed in [8] to address the problem of inter-user interference when the same beam is assigned to different users, where the key is to divide users into interfering and non-interfering groups.

However, the analog beamformers based on phase shifters are not simple circuits at mmWave, and it is demonstrated that the analog beamformer based on switches (and thus antenna selection) is a simpler solution by the expense of losing some beamforming gain [3]. With the development of antenna technology, the lens antenna array has gained increasing interest, where the electromagnetic (EM) lens is used fundamentally to direct signals towards to different points on focal surface, on which the antenna elements are properly placed [9]–[11]. In other words, the lens antenna array has the property of *direction-dependent energy focusing*. Due to the property of lens antenna array along with the sparse nature of mmWave channels, it can be expected that performing antenna selection with the lens antenna array it is possible to reduce hardware complexity while guaranteeing a near optimal spectral performance.

In this work, we study the lens antenna array as the transmit antenna in mmWave MU-MIMO systems. In order to suppress the inter-user interference resulting from a high probability of selecting the same antenna for different users, a direction-based two-stage antenna selection scheme is proposed. At the first stage, we select the nearest antenna elements to focal points for all users. Then, the antenna is re-selected for the users assigned with the same antennas at the previous stage, by minimizing rate-loss. In the re-selection problem, the

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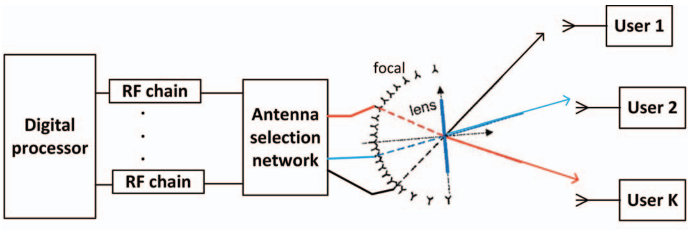

Fig. 1: Diagram structure of mmWave MU-MIMO with lens antenna array at BS.

shared antennas are exploited as useful information to reduce computational complexity.

The rest of the paper is organised as follows. The signal model of the lens antenna array enabled mmWave MU-MIMO system is described in Section II, and the two-stage antenna selection method is presented in Section III. In Section IV, simulations of performance of the proposed method are given. The paper is concluded in Section V.

II. Signal Model

We consider the downlink of a mmWave MU-MIMO system as shown in Fig. 1. The BS is equipped with a lens antenna array with N elements and uses N_{RF} RF transmission units, where $N > N_{RF}$. The BS simultaneously serves K single-antenna users. Without loss of generality, we assume $N_{RF} = K$ to guarantee the multi-user diversity.

The lens antenna array consists of an EM lens and discrete antenna elements located at the focal arc of the lens. For simplicity, the array is assumed to be critical spaced, i.e., the position of the n-th antenna element on the focal arc is denoted by coordinates $(F\cos(\theta_n), -Fsin(\theta_n), 0)$ with $\tilde{\theta}_n = sin(\theta_n), \forall n$. A lens antenna array is parametrized by the normalized aperture $\tilde{A} = A/\lambda^2$ and the normalized azimuth dimension $\tilde{D} = D/\lambda$, where A and D are respectively the size and azimuth dimension of the lens aperture, and λ denotes the free-space wavelength. Due to the assumption of critical spacing in the array, the number of antenna elements has a relation to $\tilde{D}$, that is $N = 1 + \lfloor 2\tilde{D} \rfloor$ [10], where $\lfloor \cdot \rfloor$ denotes floor function.

A. Traditional MU-MIMO Model

For the downlink of a traditional MU-MIMO system with linear precoding at the BS, let the received signals of K users be denoted by the K-dimensional vector:

$$\mathbf{y} = \mathbf{H}^H \mathbf{V}\mathbf{x} + \mathbf{z}, \tag{1}$$

where $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_K]$ is the matrix containing channels of all users, $\mathbf{h}_k \in \mathbb{C}^{N\times 1}, k = 1, \cdots, K$. $\mathbf{V} \in \mathbb{C}^{N\times K}$ is the precoding matrix with the total power constraint, i.e., $\mathbb{E}\{\|\mathbf{V}\|_F^2\} = P$, where P is the total transmit power. $\mathbf{x} = [x_1, \cdots, x_K]^T$ represents the data symbols intended to K users satisfying $\mathbb{E}\{\mathbf{x}\mathbf{x}^H\} = \mathbf{I}_K$, and $\mathbf{z} \in \mathbb{C}^{K\times 1}$ is the vector of additive white Gaussian noises (AWGN) with zero-mean and variance σ^2, corrupted at K users.

The widely used Saleh-Vlenzula channel model for mmWave communications [4], [6], [7] is adopted, and one has the channel vector of user k:

$$\mathbf{h}_k = \sum_{l=0}^{L} \alpha_{k,l}\mathbf{a}(\phi_{k,l}), \quad k = 1, \cdots, K \tag{2}$$

where $\alpha_{k,l}$ is the complex gain of the l-th path to user k, and $\mathbf{a}(\phi_{k,l})$ represents the response vector of the transmit antenna corresponding to the direction of the l-th path. Specifically, index $l = 0$ represents the LoS path, while $l = \{1, 2, \cdots, L\}$ are the non-LoS components.

B. Lens Antenna Enabled Dimension-Reduced MU-MIMO

In the lens antenna array, its array response vector is expressed as [10]:

$$\mathbf{a}(\phi) = [\sqrt{A} sinc(n - \tilde{D}\tilde{\phi})]_{n\in\mathcal{I}_N}, \tag{3}$$

where $sinc(x) \triangleq \frac{sin(\pi x)}{\pi x}$, and $\tilde{\phi} = sin(\phi) \in [-1, 1]$ represents the spatial frequency related to the physical direction ϕ ($\phi \in [-\pi/2, \pi/2]$). $\mathcal{I}_N = \{n - (N-1)/2 | n = \{1, \cdots, N\}\}$ is a symmetrical set of antenna indices centered at 0. It is observed from (3) that for a given physical direction ϕ the transmit power is mainly contributed by the antenna element located close to the focal point $\tilde{D}\tilde{\phi}$; whereas, the contributions from antenna elements located far away from the focal point, i.e., antennas with $|n - \tilde{D}\tilde{\phi}| \gg 1$, can be ignored.

Utilizing the aforementioned array property along with the sparse nature of mmWave channels, it is possible to select a small number of antenna elements for transmission, while the majority of channel power can be captured. In particular, we select N_{RF} antennas out of N, the reduced-dimension MIMO channel with $N_{RF} \times K$ dimensions is given by $\boldsymbol{H}_{\mathcal{S}} = [\tilde{\boldsymbol{h}}_1, \cdots, \tilde{\boldsymbol{h}}_K]$ obtained by selecting N_{RF} rows from $\boldsymbol{H}$, where $\mathcal{S}$ with $|\mathcal{S}| = N_{RF}$ denotes the subset consisted of selected antennas. Each row of the $\boldsymbol{H}_{\mathcal{S}}$ represents the channel response of the selected transmit antenna to users. It is worth emphasizing that the use of lens in the antenna array makes the antenna selection different from that in the conventional antenna array, due to the direction-dependent energy focusing. Indeed, the antenna selection is equivalent to directional beam selection in the beamspace MIMO [5].

In this context, user k's signal is passed to an $N_{RF}\times 1$ digital precoding vector $\boldsymbol{v}_k$, where dimension of the precoding vector is reduced from N to N_{RF}, due to the antenna selection, where $k = 1 \cdots, K$. In other words, the number of RF chains used is reduced from N to N_{RF}. Let $\boldsymbol{V}_{\mathcal{S}} = [\boldsymbol{v}_1, \cdots, \boldsymbol{v}_K]$ be the dimension-reduced digital precoding matrix for all K users. Then, the lens antenna enabled dimension-reduced MU-MIMO model is given as following

$$\mathbf{y} = \mathbf{H}_{\mathcal{S}}^H \mathbf{V}_{\mathcal{S}}\mathbf{x} + \mathbf{z}, \tag{4}$$

We assume that the knowledge of the sparse channel including the directions (i.e., $\phi_{k,0}, \forall k$) of all users are perfectly known to the BS, which can be achieved by several state-of-the-art mmWave channel estimation methods based on compressive sensing, for example the one proposed in [4], [11]–[13].

III. Direction-Based Two-Stage Antenna Selection Scheme

In this section, we present a two-stage direction-based antenna selection (AS) scheme for the lens antenna array based mmWave MU-MIMO system, where the inter-user interference resulting from the same antennas shared by different users is considered. For the multi-user scenario, it has been proved that, with uniformly distributed K users, there is a high probability that the BS selects the same beam/antenna for different users, due to similar directions [8].

The proposed AS scheme begins by selecting K antenna indices for K users based on the knowledge of their directions, $\phi_{k,0}$. In particular, user k's antenna is selected to satisfy

$$n_k^\star = \left\{ n \in \mathcal{I}_N \left| |n - \tilde{D}\tilde{\phi}_{k,0}| \le \delta \right. \right\}, k = \{1, \cdots, K\}, \tag{5}$$

where $\delta > 0$ is a threshold based on the idea that, once the distance between any antenna element and the given focal point is larger than δ, the element's contribution to signal emission can be ignored. Note that the K antennas selected by (5), $\{n_k^\star\}_{k=1}^K$, define most of the channel power. If antenna selected for each user is unique (i.e., $n_k^\star \neq n_{k'}^\star, \forall k \neq k'$), using the antenna subset $\mathcal{S} = \{s_k = n_k^\star\}_{k=1}^K$ is able to achieve a near-optimal performance in the mmWave MU-MIMO system. In contrast, if one antenna is assigned to different users (i.e., $n_k^\star = n_{k'}^\star, \forall k \neq k'$), the users will suffer serious inter-user interference.

In order to deal with the potential inter-user interference, we check whether the same antenna is selected for different users. Accordingly, users are divided into two groups – interfering users (IUs) and non-interfering users (NIUs) groups. Let the set, $\mathcal{M}_{NIU}$, denote the set of NIUs with uniquely selected antennas, and let the set, $\mathcal{M}_{IU}$, denote the set of users with shared antennas. For an NIU $k \in \mathcal{M}_{NIU}$, the antenna selected by (5) is applicable. $\mathcal{S}' = \{s_k = n_k^\star\}_{k \in \mathcal{M}_{NIU}}$ is therefore the subset of selected antenna for NIUs, where $\mathcal{S}' \subseteq \mathcal{S}$.

For IUs, we propose to re-select appropriate unique antennas for them, where the previously selected and shared antenna indices can be exploited as useful information to reduce complexity of the AS algorithm. Denote by subset $\tilde{\mathcal{S}} = \{s_k\}_{k \in \mathcal{M}_{IU}}$ the antenna subset for IUs obtained by antenna re-selection, where we have $\tilde{\mathcal{S}} \cup \mathcal{S}' = \mathcal{S} \subset \mathcal{I}_N$ and $\tilde{\mathcal{S}} \cap \mathcal{S}' = \varnothing$. Due to the unavoidable sum-rate loss occurred by the antenna re-selection, for IUs their antennas are re-selected through minimizing the sum-rate loss. Employing the available CSIT, in this work, the linear zero-forcing (ZF) precoder is considered as the reduced precoding matrix $\mathbf{V}_\mathcal{S} = \mathbf{H}_\mathcal{S}(\mathbf{H}_\mathcal{S}^H \mathbf{H}_\mathcal{S})^{-1}$. With the ZF precoding, the achievable sum-rate for a full system is given as [7]

$$R = K \log\left(1 + \frac{\gamma}{Ktr[(\mathbf{H}^H\mathbf{H})^{-1}]}\right), \tag{6}$$

where γ represents the signal-to-noise ratio (SNR). Similarly, the sum-rate for the dimension-reduced system can be obtained by replacing $\mathbf{H}$ by $\mathbf{H}_\mathcal{S}$.

The potential antenna subset for re-selection is defined as $\tilde{\mathcal{I}}_N = \mathcal{I}_N \backslash \mathcal{S}'$, where $\mathcal{A} \backslash \mathcal{B}$ denotes a set whose entries are elements in set $\mathcal{B}$ deleted from set $\mathcal{A}$. According to [14, Lemma 3], the sum-rate loss by choosing antennas $\tilde{\mathcal{S}}$ from $\tilde{\mathcal{I}}_N$ can be written as

$$R_{loss} = K \times \log\left(1 + \frac{\gamma/Ktr[\mathbf{\Lambda}_\mathcal{D}]}{(tr[\mathbf{C}_{\tilde{\mathcal{I}}_N}])^2 + tr[\mathbf{C}_{\tilde{\mathcal{I}}_N}](\gamma/K + tr[\mathbf{\Lambda}_\mathcal{D}])}\right), \tag{7}$$

where the matrices $\mathbf{C}_{\tilde{\mathcal{I}}_N}$ and $\mathbf{\Lambda}_\mathcal{D}$ are respectively given as

$$\mathbf{C}_{\tilde{\mathcal{I}}_N} = (\mathbf{H}_{\tilde{\mathcal{I}}_N}^H \mathbf{H}_{\tilde{\mathcal{I}}_N})^{-1} \tag{8a}$$

$$\mathbf{\Lambda}_\mathcal{D} = \mathbf{C}_{\tilde{\mathcal{I}}_N} \mathbf{H}_\mathcal{D}^H (\mathbf{I} - \mathbf{H}_\mathcal{D} \mathbf{C}_{\tilde{\mathcal{I}}_N} \mathbf{H}_\mathcal{D}^H)^{-1} \mathbf{H}_\mathcal{D} \mathbf{C}_{\tilde{\mathcal{I}}_N}, \tag{8b}$$

and $\mathcal{D} = \tilde{\mathcal{I}}_N \backslash \tilde{\mathcal{S}}$ is the subset of antennas deleted from all potential antennas, and then the remaining antennas are desired for IUs.

Thanks to the monotonically increasing property of the logarithm function, when γ and $tr[\mathbf{C}_{\tilde{\mathcal{I}}_N}]$ are fixed, the optimal subset of antennas re-selected for IUs by minimizing sum-rate loss is equivalent to the optimization problem:

$$\tilde{\mathcal{S}} = \min_{n \in \tilde{\mathcal{I}}_N} tr[\mathbf{\Lambda}_\mathcal{D}], \tag{9}$$

where $|\tilde{\mathcal{S}}| = K - |\mathcal{S}'|$. Recall that the IUs' antennas previously selected by (5) can be exploited to reduce the re-search range. Specifically, we further divide the re-selection problem into several sub-problems, where denote by $\mathcal{M}_{IU,m}$, with $\sum_{m=1}^M |\mathcal{M}_{IU,m}| = |\mathcal{M}_{IU}|$, the m-th sub-group of IUs which are assigned by one antenna indexed, i.e., $n_k^\star = n_{k'}^\star = m^\star$, where $\{k, k'\} \in \mathcal{M}_{IU,m}$. Due to the direction-dependent energy focusing, we know that only antenna elements around $m^\star$ are useful for users in the sub-set $\mathcal{M}_{IU,m}$. Thus, there is no need to consider the distant antennas. In this context, $\tilde{\mathcal{I}}_{N,m} = [m^\star - \tilde{\delta}, m^\star + \tilde{\delta}] \subset \tilde{\mathcal{I}}_N$ is defined as the search range for $\mathcal{M}_{IU,m}$. It is demonstrated that $R(\mathcal{S}_1) < R(\mathcal{S}_2)$ if $|\mathcal{S}_1| < |\mathcal{S}_2|$, where $R(\mathcal{S})$ is the sum-rate achieved by using antenna subset $\mathcal{S}$ [14, Theorem 1]. Therefore, we have the following sub-problems

$$\tilde{\mathcal{S}}_m = \min_{n \in \tilde{\mathcal{I}}_{N,m}} tr[\mathbf{\Lambda}_{\mathcal{D}_m}], \quad \tilde{\mathcal{S}} = \cup_{m=1}^M \tilde{\mathcal{S}}_m, \tag{10}$$

where $\mathcal{D}_m = \tilde{\mathcal{I}}_{N,m} \backslash \tilde{\mathcal{S}}_m$. The proposed AS scheme is summarized as Algorithm 1.

IV. Simulations

In this section, we evaluate the performance of the proposed AS method for the mmWave MU-MIMO systems using the lens antenna array as transmit antenna. Each value is obtained by averaging results from 10000 Monte-Carlo simulations. The achievable sum-rate, $R = K \log(1 + \gamma/(Ktr[(\mathbf{H}_\mathcal{S}^H \mathbf{H}_\mathcal{S})^{-1}]))$, is considered as performance metric. The channel model of each user k is assumed that:

1) there are one LoS path and $L = 2$ NLoS paths;
2) multi-path gains follow Rician Fading with a Kappa ratio (i.e., the ratio between the LoS power and NLoS power) set to $\kappa = 10$ dB;

Algorithm 1: Direction-based antenna selection

Input: CSIT $\mathbf{H}$ including $\phi_{k,0}, k = 1, \cdots, K$,
Output: $\mathbf{H}_{\mathcal{S}}$, $\mathcal{S} = \{s_k\}_{k=1}^{K}$

$n_k^\star = \{n \in \mathcal{I}_N \,\| n - D\tilde{\phi}_{k,0}| < \delta\} \leftarrow \phi_{k,0}$;
if $n_k^\star \neq n_{k'}^\star, \forall k \neq k'$ **then**
  $k, k' \in \mathcal{M}_{NIU}$;
  $s_k = n_k^\star, k \in \mathcal{M}_{NIU}$;
if $n_k^\star = n_{k'}^\star = m^\star, \forall k \neq k'$ **then**
  $k, k' \in \mathcal{M}_{IU,m}, m = \{1, \cdots, M\}$;
  for $k = 1, \cdots, |\mathcal{M}_{IU,m}|$ **do**
    $s_k = \min_{n \in \tilde{\mathcal{I}}_{N,m}} tr[\mathbf{\Lambda}_{\mathcal{D}_m}]$;
    $\tilde{\mathcal{I}}_{N,m} = \tilde{\mathcal{I}}_{N,m} + \{s_k\}$;
return
$\mathcal{S} = \mathcal{S}' \cup \tilde{\mathcal{S}} = \{s_k\}_{k \in \mathcal{M}_{NIU}} \cup \left[\cup_{m=1}^{M} \{s_k\}_{k \in \mathcal{M}_{IU,m}}\right] \rightarrow \mathbf{H}_{\mathcal{S}}$;

3) $\phi_{k,0}$ follows uniform distribution in $[-\pi/2, \pi/2]$ while $\phi_{k,l}$ follows Laplace distribution with mean $\phi_{k,0}$ and an angle spread $10°$, where $l = 1, 2,\ k = 1, \cdots K$.

In the simulated lens antenna array, the normalized aperture is adopted as $\tilde{A} = 100$ and the normalized azimuth dimension is set to $\tilde{D} = 20$ as [10]. Accordingly, the number of antenna elements is $N = 41$.

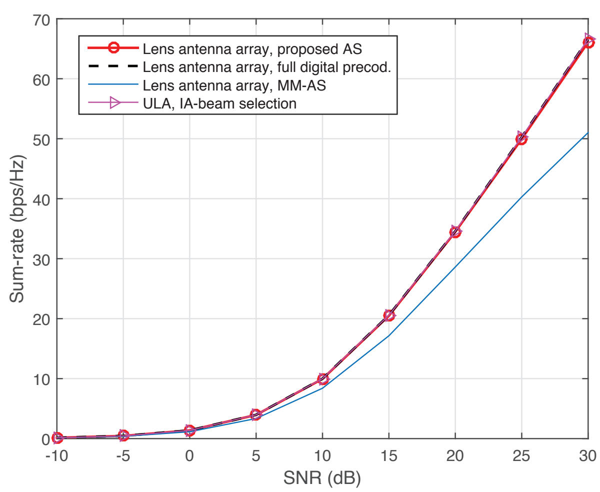

Fig. 2: Achievable sum-rate versus SNR.

Fig. 2 shows the achievable sum-rates with varying SNRs, where $K = 10$ users are considered. In this simulation, we consider the performance of lens antenna array with different signal processing techniques: proposed AS scheme, MM-AS scheme [6] without suppressing inter-user interference, and full digital precoding (i.e., one dedicate RF chain is assumed for each of $N = 41$ antenna elements). Moreover, we also compare the performance of the lens antenna array to that of 41-element ULA with a half-wavelength spacing, where IA beam selection [8] is used. It is observed that the proposed AS method outperforms that of MM-AS by reducing the inter-user interference, since the dimension-reduced channel matrix $\mathbf{H}_{\mathcal{S}}$ obtained by MM-AS may be rank-deficient with high probability in the multi-user scenario. The near-optimal performance of the lens antenna enabled system with proposed AS scheme is verified, since its performance is the same as that with full digital precoder seen from the simulated results. It is also observed that the ULA-based beam selection is able to achieve the near-optimal sum-rate performance. However, in the ULA-based beam selection method a large network of phase shifters should be used; in the contrast, we use a simpler switches network to achieve the similar performance.

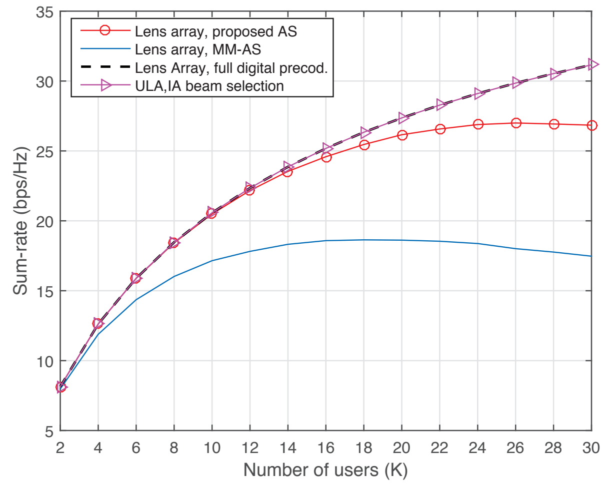

Fig. 3: Achievable sum-rate versus number of users, $SNR = 15$ dB.

Then, we consider the sum-rates with different user numbers and the results are given in Fig. 3. The sum-rate performance of the proposed AS method is inferior to that of full digital precoding and also the ULA-based beam selection when the number of users is greater than 16. This is because, when the number of users is relative large, it becomes more difficult to select unique antenna for each of K users for interference suppression. However, its performance is still better than that of MM-AS algorithm. Although the ULA-based beam selection still shows the near-optimal sum-rate performance, it is at the expense of hardware complexity as well as the computational complexity. In the existence of a large number of users, an efficient user selection algorithm is commonly employed.

Finally, we evaluate the energy efficiency of the proposed lens antenna based MU-MIMO system with antenna selection, where the energy efficiency is modified from that given in [7] by including the power consumption of RF beamformers (i.e., phase shifters in beam selection and switches in antenna selection). In particular, the energy efficiency is calculated as $\zeta = \frac{R}{P + P^\star + N_{RF} P_{RF}} (bits/Hz/W)$, where $P^\star = P_{ps} = 30$ (mW) is the power consumption of the phase shifters or $P^\star = P_{sw} = 5$ (mW) is the power consumption of the switches [3]. P_{RF} is power consumed per RF chain, set to 34.4 mW [7]. The energy

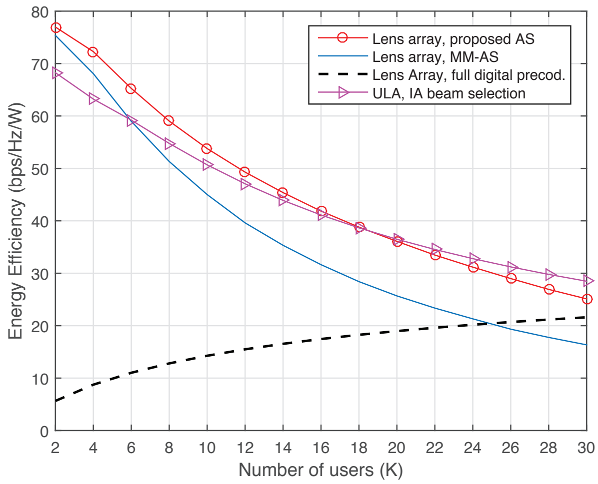

Fig. 4: Energy efficiency evaluation.

efficiency versus numbers of users, K (equivalent to N_{RF}), is illustrated in Fig. 4. We can observe that the energy efficiency obtained by the proposed antenna selection outperforms that obtained by full digital precoding and also that of the MM antenna selection scheme. Comparing the proposed antenna selection to ULA-based beam selection, we can observe that when the number of user is smaller than 18, the performance of the proposed antenna selection is better than that of the beam selection scheme.

V. Conclusion

In this paper, we proposed the lens antenna array as the transmit antenna for the mmWave MU-MIMO to reduce the number of RF chains required. For this system, the transmission scheme employs a simple two-stage direction-based antenna selection by utilizing the sparse nature of mmWave channels, thereby a near-optimal sum-rate performance can be achieved. In particular, the antenna selection is proposed based on a direction criterion, in which the inter-user interference is addressed by the re-selection of sub-problems with low complexity, through minimizing sum-rate loss and employing information of shared antennas.

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References

[1] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, 2011.

[2] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE access*, vol. 1, pp. 335–349, May 2013.

[3] R. Méndez-Rial, C. Rusu, N. González-Prelcic, A. Alkhateeb, and R. W. Heath, "Hybrid MIMO architectures for millimeter wave communications: Phase shifters or switches?" *IEEE Access*, vol. 4, pp. 247–267, Jan. 2016.

[4] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 831–846, Jul. 2014.

[5] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, Jul. 2013.

[6] A. Sayeed and J. Brady, "Beamspace MIMO for high-dimensional multiuser communication at millimeter-wave frequencies," in *Proc. IEEE Global Communications Conference (GLOBECOM)*, 2013, pp. 3679–3684.

[7] P. V. Amadori and C. Masouros, "Low RF-complexity millimeter-wave beamspace-MIMO systems by beam selection," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2212–2223, 2015.

[8] X. Gao, L. Dai, Z. Chen, Z. Wang, and Z. Zhang, "Near-optimal beam selection for beamspace mmWave massive MIMO systems," *IEEE Commun. Lett.*, vol. 20, no. 5, pp. 1054–1057, May 2016.

[9] Y. Zeng, R. Zhang, and Z. N. Chen, "Electromagnetic lens-focusing antenna enabled massive MIMO: Performance improvement and cost reduction," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1194–1206, 2014.

[10] Y. Zeng and R. Zhang, "Millimeter wave MIMO with lens antenna array: A new path division multiplexing paradigm," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1557–1571, Apr. 2016.

[11] L. Dai, X. Gao, S. Han, X. Wang, *et al.*, "Beamspace channel estimation for millimeter-wave massive mimo systems with lens antenna array," *arXiv preprint arXiv:1607.05130*, 2016.

[12] R. Qian, M. Sellathurai, and J. Chambers, "Direction-of-arrival estimation with single-rf espar antennas via sparse signal reconstruction," in *Proc. IEEE SPAWC*, 2015, pp. 485–489.

[13] R. Qian and M. Sellathurai, "Direction-of-arrival estimation with espar antennas using bayesian compressive sensing," in *Proc. IEEE ICASSP*, 2016, pp. 3076–3080.

[14] P.-H. Lin and S.-H. Tsai, "Performance analysis and algorithm designs for transmit antenna selection in linearly precoded multiuser MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 61, no. 4, pp. 1698–1708, May 2012.