Iterative Hybrid Precoder and Combiner Design for mmWave Multiuser MIMO Systems

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***Abstract*— This letter investigates analog/digital hybrid precoder and combiner design for millimeter wave (mmWave) multiuser multiple-input multiple-output (MU-MIMO) systems. We propose a novel iterative algorithm for the joint hybrid precoder and combiner design by exploiting the duality of the uplink and downlink MU-MIMO channels. For the initialization stage, the proposed algorithm selects the analog precoder-combiner pair based on the orthogonal matching pursuit (OMP) algorithm to enhance the channel gain, while mitigating the multiple access interference, and obtains the digital combiner via minimum mean square error criterion. Then, the proposed algorithm enhances the performance gradually at each iteration via joint design of the uplink and downlink precoders/combiners. Simulation results demonstrate the significant performance advantages of the proposed precoder and combiner design compared with existing hybrid beamforming algorithms.**

***Index Terms*— mmWave, MIMO communications, hybrid precoding, multiuser.**

I. INTRODUCTION

MILLIMETER wave (mmWave) communications with high frequencies enable a large antenna array in massive multiple-input multiple-output (MIMO) systems to be packed in a small physical dimension [1]. The large antenna array can provide sufficient gain by precoding and combining to overcome the free-space pathloss of mmWave channel. On the other hand, massive MIMO with a very large antenna array enables the base station (BS) to simultaneously serve a set of users through the use of precoding [2].

Conventional full-digital precoder and combiner are realized with a large number of expensive radio frequency (RF) chains and energy-intensive analog-to-digital converters (ADCs), which make it impractical in mmWave communication systems due to much higher carrier frequency and wider bandwidth. Recently, economic and energy-efficient analog/digital hybrid precoder and combiner have been advocated to tackle this issue. This hybrid precoding approach applies a large number of analog phase shifters to implement high-dimensional RF precoder and a small number of RF chains for low-dimensional digital precoder to provide the necessary flexibility to perform multiplexing techniques [3].

The extensions of the hybrid beamforming to multiuser mmWave systems have been investigated in [4] and [5].

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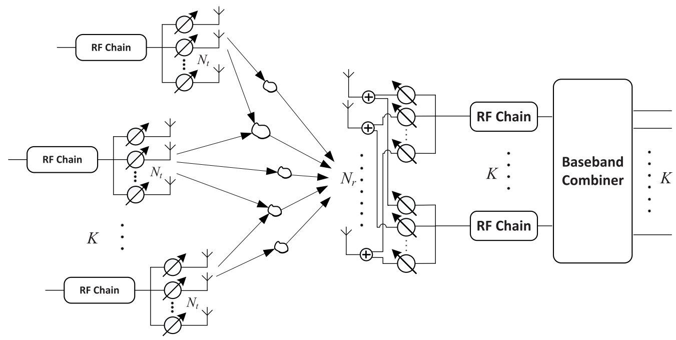

Fig. 1. The mmWave MU-MIMO system, in which K users with analog-only precoder simultaneously transmit to a BS employing hybrid combiner. Assume scatterer-sharing channels where users may have overlapped paths.

However, in these algorithms, the analog precoder and combiner are designed to maximize the desired channel gain without considering the interference from other users, which cannot be effectively mitigated with low-dimensional digital precoders. In [6], a hybrid beamforming algorithm was developed to manage the inter-user interference at both analog and digital beamforming stages. However, this work only considered multiple-input single-output (MISO) systems with an unfortunately notable performance gap away from the full-digital case.

In this letter, we consider a mmWave uplink multiuser multiple-input multiple-output (MU-MIMO) system and propose a novel iterative hybrid precoder and combiner design to combat the multiple access interference in the scatterer-sharing circumstance. For the initialization stage, the analog precoder and combiner are first jointly selected to maximize the channel gain as well as mitigate the interference based on orthogonal matching pursuit (OMP) method. Then, with given baseband effective channel, the digital MMSE combiner at the BS is computed to further suppress the interference. In an effort to improve the performance, we propose to iteratively design the precoders/combiners by exploiting the duality of the uplink and downlink MU-MIMO channels. Simulation results show that our proposed algorithm offers significant performance improvement compared to existing hybrid schemes in various simulation settings.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a mmWave MU-MIMO uplink system as illustrated in Fig. 1. A BS, equipped with N_r antennas and N_{RF} RF chains, is communicating with K ($K \leq N_{RF}$) users. Each user is equipped with N_t antennas and only one RF chain due to the limitation of hardware cost and power consumption [4]–[6]. We further assume that the BS uses K out of N_{RF} available RF chains to simultaneously serve K users.

Let $\mathbf{f}_k \in \mathcal{F}$ be the analog precoder of the k-th user. $\mathcal{F}$ is the set of feasible RF precoders which are implemented by analog components like phase shifters, i.e. a set of $N_t \times 1$ vectors with quantized phases and constant magnitude entries, further normalized to satisfy $\mid \mathbf{f}_k(i) \mid^2 = \frac{1}{N_t}$, where $\mathbf{f}_k(i)$ is the i-th element of $\mathbf{f}_k$. The transmitted signal of the k-th user is

$$\mathbf{x}_k = \sqrt{p_k}\mathbf{f}_k s_k, \tag{1}$$

where s_k is the transmitted symbol of the k-th user, $\mathbb{E}\{|s_k|^2\} = 1$, and p_k is the k-th user transmit power.

Denote $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$, $k = 1, \ldots, K$, as the uplink MIMO channel for each user. The received signal at the BS can be written as

$$\mathbf{r} = \sum_{k=1}^{K} \sqrt{p_k}\mathbf{H}_k \mathbf{f}_k s_k + \mathbf{n}, \tag{2}$$

where $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I}_{N_r})$ is the complex Gaussian noise vector corrupting the received signal.

BS applies an $N_r \times K$ analog combining matrix $\mathbf{W}_{RF} \triangleq [\mathbf{w}_{RF_1}\ \mathbf{w}_{RF_2}\ \ldots\ \mathbf{w}_{RF_K}]$ followed by a $K \times K$ baseband digital combiner $\mathbf{W}_{BB} \triangleq [\mathbf{w}_{BB_1}\ \mathbf{w}_{BB_2}\ \ldots\ \mathbf{w}_{BB_K}]$ and the estimated signals at the BS are $\hat{\mathbf{s}} = \mathbf{W}_{BB}^H \mathbf{W}_{RF}^H \mathbf{r}$. It is noted that each analog combiner $\mathbf{w}_{RF_k}$ is chosen from a predefined codebook $\mathcal{W}$, whose entries are of quantized phases and constant amplitude $\frac{1}{\sqrt{N_r}}$. Let $\mathbf{w}_k \triangleq \mathbf{W}_{RF}\mathbf{w}_{BB_k}$ be the hybrid combiner of the k-th user. After the combining process at the BS, the estimated symbol of the k-th user can be expressed as

$$\hat{s}_k = \sqrt{p_k}\mathbf{w}_k^H \mathbf{H}_k \mathbf{f}_k s_k + \mathbf{w}_k^H \sum_{\substack{i=1 \\ i \neq k}}^{K} \sqrt{p_i}\mathbf{H}_i \mathbf{f}_i s_i + \mathbf{w}_k^H \mathbf{n}. \tag{3}$$

The mmWave MIMO channel can be described with the widely used multi-path channel model [3], in which the limited number of propagation paths are related to a few scatterers. Specifically, we construct the uplink channel $\mathbf{H}_k$ from the k-th user to the BS as

$$\mathbf{H}_k = \sqrt{\frac{N_t N_r}{L_k}} \sum_{m=1}^{L_k} \alpha_k^m \mathbf{a}_r(\theta_k^m)\mathbf{a}_t^H(\varphi_k^m), \tag{4}$$

where we assume that there exists L_k paths/scatterers in the k-th user uplink channel. The channel gain of each path is α_k^m, which is complex and independently and identically Gaussian distributed with zero mean and variance of $1/L_k$. θ_k^m and $\varphi_k^m \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ are the angle of arrival (AoA) and angle of departure (AoD), respectively. $\mathbf{a}_r(\theta)$ and $\mathbf{a}_t(\varphi)$ represent the normalized receive and transmit array response vectors associated with AoA θ and AoD φ, respectively. It is noted that the array response vectors $\mathbf{a}_r(\theta)$ and $\mathbf{a}_t(\varphi)$ are only determined by the transmit and receive antenna array structures. We assume that uniform linear arrays (ULAs) are applied at BS and each user for simplicity and $\mathbf{a}_r(\theta)$ is then given by

$$\mathbf{a}_r(\theta) = \frac{1}{\sqrt{N_r}}[1, e^{j\frac{2\pi}{\lambda}d\sin(\theta)}, \ldots, e^{j(N_r-1)\frac{2\pi}{\lambda}d\sin(\theta)}]^T \tag{5}$$

where λ is the signal wavelength, and d is the distance between antenna elements. The steering vectors at users, $\mathbf{a}_t(\varphi)$, can be written in a similar fashion.

It has been verified that rough surface and tiny building cracks can cause diffuse scattering in mmWave channel and the diffuse range increases as the wavelength shrinks [7]. Therefore, it is highly possible that different users share some common scatterers as shown in Fig. 1. If the signals from different users are transmitted via propagation paths with a common scatterer, then these signals have similar AoAs at the BS and cannot be correctly separated by combiners. Therefore, this scatterer-sharing multi-path channel we considered in this paper can cause more severe inter-user interference.

We assume the BS has the accurate knowledge of $\mathbf{H}_k$, $k = 1, \ldots, K$, via uplink channel estimation. Given the received signal at the BS in (3), the signal-to-interference-plus-noise ratio (SINR) of the k-th user is formulated by

$$\gamma_k = \frac{|\sqrt{p_k}\mathbf{w}_k^H \mathbf{H}_k \mathbf{f}_k|^2}{\sum_{i=1, i\neq k}^{K} |\sqrt{p_i}\mathbf{w}_k^H \mathbf{H}_i \mathbf{f}_i|^2 + \sigma^2 \|\mathbf{w}_k\|^2} \tag{6}$$

and the achievable sum-rate of the uplink system is

$$R = \sum_{k=1}^{K} \log(1 + \gamma_k). \tag{7}$$

In this work, we aim to jointly design the analog precoder $\mathbf{f}_k$, as well as the analog combiner $\mathbf{w}_{RF_k}$ and baseband combiner $\mathbf{w}_{BB_k}$ to maximize the system sum-rate. The objective function can be formulated as

$$\begin{aligned} \left\{\{\mathbf{w}_{RF_k}^{\star}, \mathbf{w}_{BB_k}^{\star}, \mathbf{f}_k^{\star}\}_{k=1}^{K}\right\} &= \arg\max \sum_{k=1}^{K} \log(1 + \gamma_k) \\ \text{s. t. } \mathbf{w}_{RF_k} &\in \mathcal{W},\ k = 1, \ldots, K, \\ \mathbf{f}_k &\in \mathcal{F}, \quad k = 1, \ldots, K. \end{aligned} \tag{8}$$

The optimization of (8) is obviously a non-convex NP-hard problem. In the next section, we turn to seek a sub-optimal hybrid precoder and combiner design to reduce the complexity but still achieve the satisfactory performance.

III. Proposed Hybrid Precoder and Combiner Design

In this section, we first introduce a joint hybrid precoder and combiner design scheme to combat the paths overlapping circumstance which can cause severe interference. In an effort to improve the performance, we then propose to further iteratively compute the precoder and combiner by exploiting the duality of the uplink and downlink MU-MIMO channels.

A. Joint Hybrid Precoder and Combiner Design

This algorithm starts with jointly designing the analog beamformers $\mathbf{f}_k$ and $\mathbf{w}_{RF_k}$ for each user aiming at maximizing the corresponding channel gain as well as mitigating the interference. Let $\mathbf{G}_k \triangleq \sqrt{p_k}\mathbf{H}_k$ and $\mathcal{K}$ be the set of user indices. We first find the optimal analog precoder and combiner pair from codebook for each user to obtain the largest beamforming gain:

$$\left\{\widetilde{\mathbf{w}}_{RF_k}, \widetilde{\mathbf{f}}_k\right\} = \arg \max_{\substack{\mathbf{w}_{RF_k} \in \mathcal{W} \\ \mathbf{f}_k \in \mathcal{F}}} |\mathbf{w}_{RF_k}^H \mathbf{G}_k \mathbf{f}_k|,\ k \in \mathcal{K}, \tag{9}$$

and the resulting beamforming gain of each user is

$$\xi_k = |\widetilde{\mathbf{w}}_{RF_k}^H \mathbf{G}_k \widetilde{\mathbf{f}}_k|, \quad k \in \mathcal{K}. \tag{10}$$

Then, we choose the user k^* who exhibits the maximum analog beamforming gain

$$k^* = \arg \max_{k \in \mathcal{K}} \xi_k, \tag{11}$$

and assign the corresponding analog precoder $\mathbf{f}_{k^*}^\star = \widetilde{\mathbf{f}}_{k^*}$ and combiner $\mathbf{w}_{RF_{k^*}}^\star = \widetilde{\mathbf{w}}_{RF_{k^*}}$ to this user. For the other users in the updated set $\mathcal{K} = \mathcal{K} - k^*$ whose analog precoders and combiners need to be designed, we attempt to appropriately select precoders and combiners to actively avoid the interference from the users whose combiners have been determined. To achieve this goal, the component of determined combiner will be removed from other users' channels in such a way that the similar analog combiners would not be selected for the other users. Particularly, let $\mathbf{v}_i \triangleq \mathbf{w}_{RF_{k^*}}^\star$ be the component of the determined analog combiner for the i-th designed user. If $i > 1$, we also remove the component of previous determined combiner from $\mathbf{v}_i$ by a Gram-Schmidt based procedure:

$$\mathbf{v}_i = \mathbf{v}_i - \sum_{j=1}^{i-1} \mathbf{v}_j^H \mathbf{v}_i \mathbf{v}_j, \mathbf{v}_i = \mathbf{v}_i / \|\mathbf{v}_i\|. \tag{12}$$

Then, the rest users' channels are updated by an OMP fashion [3]:

$$\mathbf{G}_k = \left(\mathbf{I}_{N_r} - \mathbf{v}_i \mathbf{v}_i^H\right) \mathbf{G}_k, \quad k \in \mathcal{K}, \tag{13}$$

where $\mathbf{I}_{N_r}$ is an identity matrix of size N_r. Then, the analog precoder and combiner for all users can be successively selected using above procedure.

After all analog beamformer pairs have been determined, we can obtain the baseband effective channel $\widehat{\mathbf{h}}_k \triangleq \sqrt{p_k}\left(\mathbf{W}_{RF}^\star\right)^H \mathbf{H}_k \mathbf{f}_k^\star$ for each user. Then an MMSE baseband digital combiner is employed to further suppress the interference [5]:

$$\mathbf{w}_{BB_k}^\star = \left[\widehat{\mathbf{H}}\widehat{\mathbf{H}}^H + \sigma^2 \left(\mathbf{W}_{RF}^\star\right)^H \mathbf{W}_{RF}^\star\right]^{-1} \widehat{\mathbf{h}}_k, \quad k = 1, \ldots, K, \tag{14}$$

where $\widehat{\mathbf{H}} \triangleq [\widehat{\mathbf{h}}_1, \ldots, \widehat{\mathbf{h}}_K]$. This joint hybrid precoder and combiner design algorithm is summarized in Algorithm 1.

Algorithm 1 Joint Hybrid Precoder and Combiner Design

Input: $\mathcal{F}$, $\mathcal{W}$, p_k, $\mathbf{H}_k$, $k = 1, \ldots, K$.
Output: $\mathbf{f}_k^\star$, $\mathbf{w}_{RF_k}^\star$, $\mathbf{w}_{BB_k}^\star$.
Initialization: $\mathbf{G}_k = \sqrt{p_k}\mathbf{H}_k$, $\mathcal{K} = \{1, \ldots, K\}$.
for $i = 1 : K$
$\left\{\widetilde{\mathbf{w}}_{RF_k}, \widetilde{\mathbf{f}}_k\right\} = \arg \max_{\mathbf{w}_{RF_k} \in \mathcal{W}, \mathbf{f}_k \in \mathcal{F}} |\mathbf{w}_{RF_k}^H \mathbf{G}_k \mathbf{f}_k|, \forall k \in \mathcal{K}$;
$k^* = \arg \max_{k \in \mathcal{K}} |\widetilde{\mathbf{w}}_{RF_k}^H \mathbf{G}_k \widetilde{\mathbf{f}}_k|$;
$\mathcal{K} = \mathcal{K} - k^*$;
$\mathbf{f}_{k^*}^\star = \widetilde{\mathbf{f}}_{k^*}$, $\mathbf{w}_{RF_{k^*}}^\star = \widetilde{\mathbf{w}}_{RF_{k^*}}$;
$\mathbf{v}_i = \mathbf{w}_{RF_{k^*}}^\star$;
if $i > 1$, $\mathbf{v}_i = \mathbf{v}_i - \sum_{j=1}^{i-1} \mathbf{v}_j^H \mathbf{v}_i \mathbf{v}_j, \mathbf{v}_i = \mathbf{v}_i / \|\mathbf{v}_i\|$;
$\mathbf{G}_k = \left(\mathbf{I}_{N_r} - \mathbf{v}_i \mathbf{v}_i^H\right) \mathbf{G}_k$, $k \in \mathcal{K}$;
end for
$\mathbf{w}_{BB_k}^\star = \left[\widehat{\mathbf{H}}\widehat{\mathbf{H}}^H + \sigma^2 \left(\mathbf{W}_{RF}^\star\right)^H \mathbf{W}_{RF}^\star\right]^{-1} \widehat{\mathbf{h}}_k$;
Normalize $\mathbf{w}_{BB_k}^\star$ by $\mathbf{w}_{BB_k}^\star = \frac{\mathbf{w}_{BB_k}^\star}{\|\mathbf{W}_{RF}^\star \mathbf{w}_{BB_k}^\star\|}$.

B. Iterative Hybrid Precoder and Combiner Design

To further improve the performance, we then use the results in Section III-A as a start point and iteratively design the hybrid precoder and combiner by exploiting the duality of uplink and downlink channels. With given $\mathbf{W}_{RF}^\star$ and $\mathbf{W}_{BB}^\star$, we then consider the dual downlink transmission and have the downlink effective channel $\bar{\mathbf{H}}_k \triangleq \sqrt{p_k}\mathbf{H}_k^H \mathbf{W}_{RF}^\star \mathbf{W}_{BB}^\star$. Then, each $\mathbf{f}_k$ is designed again given the acquired $\bar{\mathbf{H}}_k$. Specifically, we first calculate the MMSE optimal analog combiner for the k-th user as:

$$\mathbf{p}_k = \left(\bar{\mathbf{H}}_k \bar{\mathbf{H}}_k^H + \sigma^2 \mathbf{I}_{N_t}\right)^{-1} \bar{\mathbf{H}}_k(k), \tag{15}$$

where $\bar{\mathbf{H}}_k(k)$ is the k-th column of $\bar{\mathbf{H}}_k$. The updated analog combiner of the k-th user is selected that has the maximum projection on $\mathbf{p}_k$:

$$\mathbf{f}_k^\star = \arg \max_{\mathbf{f}_k \in \mathcal{F}} \left|\mathbf{f}_k^H \mathbf{p}_k\right|. \tag{16}$$

After that, we reconsider the uplink transmission and define the uplink effective channel $\widetilde{\mathbf{H}} \triangleq [\widetilde{\mathbf{h}}_1, \ldots, \widetilde{\mathbf{h}}_K]$, $\widetilde{\mathbf{h}}_k \triangleq \sqrt{p_k}\mathbf{H}_k \mathbf{f}_k^\star$. The analog combiner $\mathbf{W}_{RF}^\star$ is reselected successively based on $\widetilde{\mathbf{H}}$ using a similar method introduced in Section III-A. Then, the digital combiner $\mathbf{W}_{BB}^\star$ is also obtained based on MMSE criterion.

We iteratively design $\mathbf{w}_{RF_k}$ and $\mathbf{w}_{BB_k}$ by considering uplink transmission and $\mathbf{f}_k$ by considering downlink transmission. The procedure stops until convergence is found. We summarize the iterative algorithm in Algorithm 2. Finally, we emphasize that the algorithms are implemented by BS and the index of selected analog precoder will be sent to each user via control channel.

Algorithm 2 Iterative Hybrid Precoder and Combiner Design

Step 1. Obtain $\bar{\mathbf{H}}$ based on Algorithm 1.
Step 2. Consider downlink transmission:
$\mathbf{p}_k = \left(\bar{\mathbf{H}}_k \bar{\mathbf{H}}_k^H + \sigma^2 \mathbf{I}_{N_t}\right)^{-1} \bar{\mathbf{H}}_k(k)$;
$\mathbf{f}_k^\star = \arg \max_{\mathbf{f}_k \in \mathcal{F}} \left|\mathbf{f}_k^H \mathbf{p}_k\right|$.
Step 3. Consider uplink transmission:
$\mathcal{K} = \{1, \ldots, K\}$, $\mathbf{d}_k = \widetilde{\mathbf{h}}_k$, $\forall k \in \mathcal{K}$;
for $i = 1 : K$
$\widehat{\mathbf{w}}_{RF_k} = \arg \max_{\mathbf{w}_{RF_k} \in \mathcal{W}} |\mathbf{w}_{RF_k}^H \mathbf{d}_k|$;
$\hat{k} = \arg \max_{k \in \mathcal{K}} |\widehat{\mathbf{w}}_{RF_k}^H \mathbf{d}_k|$;
$\mathcal{K} = \mathcal{K} - \hat{k}$, $\mathbf{w}_{RF_{\hat{k}}}^\star = \widehat{\mathbf{w}}_{RF_{\hat{k}}}$;
$\mathbf{d}_k = \mathbf{d}_k - (\mathbf{w}_{RF_{\hat{k}}}^\star)^H \widetilde{\mathbf{h}}_k \mathbf{w}_{RF_{\hat{k}}}^\star$, $k \in \mathcal{K}$;
end for
Obtain $\mathbf{w}_{BB_k}^\star$ for each user by (14);
Normalize $\mathbf{w}_{BB_k}^\star$ by $\mathbf{w}_{BB_k}^\star = \frac{\mathbf{w}_{BB_k}^\star}{\|\mathbf{W}_{RF}^\star \mathbf{w}_{BB_k}^\star\|}$.
Step 4. Repeat Step 2 and 3 until converge.

IV. Simulation Results

In this section, we illustrate the simulation results of the proposed iterative hybrid precoder and combiner design. Consider an MU-MIMO uplink system where the BS and each user are equipped with a 64-antenna and 16-antenna ULAs,

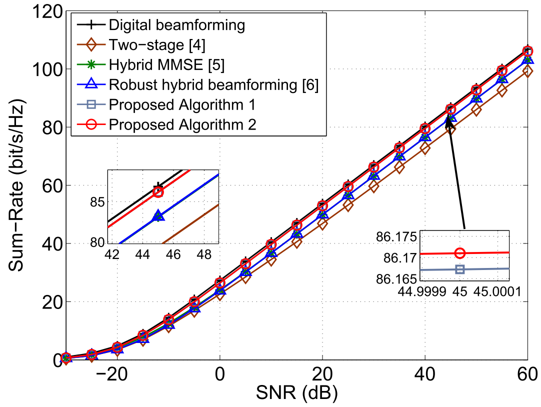

Fig. 2. Sum-rate versus SNR ($N_t = 16$, $N_r = 64$, $K = 4$).

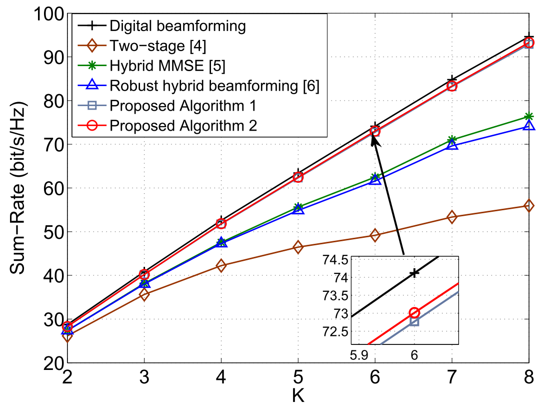

Fig. 3. Sum-rate versus the number of users K ($N_t = 16$, $N_r = 64$, SNR = 20dB).

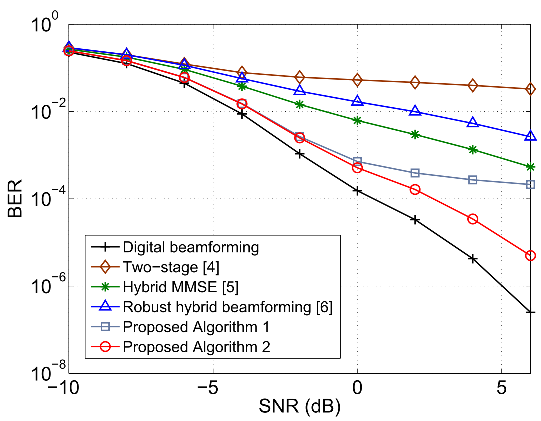

Fig. 4. Average BER versus SNR ($N_t = 16$, $N_r = 64$, $K = 4$).

respectively. The antenna spacing of all ULAs is $d = \frac{\lambda}{2}$. The AoA/AoD is assumed to be uniformly distributed in $[-\frac{\pi}{2}, \frac{\pi}{2}]$. We assume there exists 20 scatterers from which each user randomly select $3 \sim 6$ scatterers as propagation paths with a certain probability that users may share some common scatterers. For simplicity, the noise variance σ^2 is set to 1. We further assume the transmit power of each user is set equal. The codebooks consist of array response vectors as (5) with 128 angle resolutions which are uniformly quantized in $[-\frac{\pi}{2}, \frac{\pi}{2}]$. We compare our proposed design to three state-of-the-art algorithms: *i*) two-stage multiuser hybrid precoding [4], *ii*) hybrid MMSE beamforming [5], and *iii*) robust hybrid beamforming [6]. We also include the full-digital beamforming algorithm as the performance benchmark.

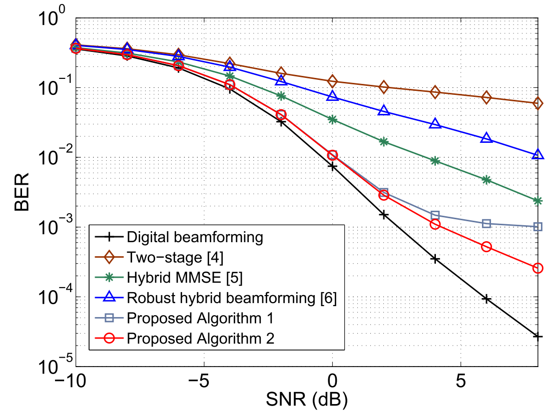

Fig. 5. Average BER versus SNR ($N_t = 16$, $N_r = 64$, $K = 8$).

Fig. 2 shows the average sum-rate versus signal-to-noise-ratio (SNR) over 10^6 channel realizations. It can be observed that our proposed algorithm outperforms the other state-of-the-art approaches and achieve near-optimal performance compared with the full-digital case. In Fig. 3, the sum-rate versus the number of users K is presented. It is noted that our proposed algorithm always outperforms its competitors and has the performance closest to the benchmark. This result indicates that our proposed hybrid beamforming design has a better resistibility of inter-user interference. In Figs. 4 and 5, we turn to consider BPSK transmission without any error coding and illustrate the bit-error-rate (BER) performance with $K = 4$ and $K = 8$, respectively. The proposed hybrid precoder and combiner design also has significant BER performance advantages over existing schemes.

V. Conclusions

In this paper, we proposed an efficient hybrid precoder and combiner design for mmWave MU-MIMO systems which maximizes the channel gain as well as mitigates the interference among different users. Simulation results demonstrated that our proposed algorithm has significant performance advantages over the state-of-the-art hybrid beamforming designs.

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