PCA-BD-Based Broadband Hybrid Precoding for Multi-user Massive MIMO Systems

Tianye Zhu
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
3120200876@bit.edu.cn

Yiwei Sun
Future Mobile Technology Lab
China Mobile Research Institute
Beijing, China
sunyiweiyjy@chinamobile.com

Dongxuan He
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
dongxuan_he@bit.edu.cn

Hua Wang
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
wanghua@bit.edu.cn

2022 IEEE 22nd International Conference on Communication Technology (ICCT) | 978-1-6654-7067-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICCT56141.2022.10073175

***Abstract*—Hybrid precoding has shown to be an effective method in massive multiple-input multiple-output (MIMO) systems.To enable the design of hybrid precoding in multi-user massive MIMO-OFDM systems, a principal component analysis (PCA) and block diagonalization (BD) based precoding method is proposed in this paper.In particular, to mitigate the frequency-selective characteristic of broadband channel and eliminate the interference in multi-user scenarios, the proposed design of hybrid precoding can be divided into two steps.First, relying on PCA, the frequency-flat universal radio frequency (RF) precoder is extracted from a set of frequency-selective RF precoders, which enables the design of RF precoder/combiner.Next, the baseband precoder/combiner is designed accordingly with the help of BD, which can eliminate interference effectively. Simulation results demonstrate the superiority of our proposed solution when compared to the state-of-the-art schemes in terms of sum spectral efficiency (SSE), bit error rate (BER) performance and the robustness to channel disturbances.**

***Index Terms*—Massive MIMO, hybrid precoding, principal component analysis (PCA), block diagonalization (BD)**

I. Introduction

Massive multiple-input multiple-output(MIMO), which can enhance the spectral efficiency (SE) significantly, has been regarded as one of the key technologies of the fifth generation (5G) [1]. In addition, hybrid precoding, which can reduce the unacceptable hardware cost and power consumption, has been proposed to satisfy the design requirements of massive MIMO systems, thus receiving research attention widely [2].

Due to its comparable performance and low complexity, hybrid precoding has been widely investigated, especially in point-to-point systems [3]–[5]. For example, as the basis of hybrid precoding, a classical scheme is proposed in [3], where the baseband (BB) precoding maps the data streams into the radio frequency (RF) link. In [4], compressive sensing (CS) is utilized in the design of hybrid precoding with the help of orthogonal matching pursuit(OMP) algorithm. In [5], to enable the hybrid precoding design with low-resolution analog phase shifters, cross-entropy(CE)-based algorithm is adopted. However, the above works only consider the hybrid precoding design in point-to-point systems and ignore the inter-user interference, which turns to be the main challenge in multi-user(MU) systems [6], [7]. To this end, several works about hybrid precoding in MU systems have been considered. For instance, a limited feedback hybrid precoding scheme only considering single-stream transmission is proposed in [6], and a hybird block diagonalization (BD) precoding scheme is proposed in [7] to support multi-stream transmission.

Nevertheless, [6] and [7] only consider the single-carrier transmission scheme, which can not satisfy the ever-increasing data rate demand. As a solution, it is urgent to investigate the multi-carrier transmission schemes [8]–[10]. In detail, based on Grim-Schmidt orthogonalization (GSO) and greedy algorithm, [8] proposes a low-complexity near-optimal hybrid precoding scheme to realize hybrid precoding in multi-carrier systems. As a modification of [8], greedy algorithm is adopted in [9] to design RF precoding on all subcarriers of each user simultaneously. Besides, two downlink hybrid precoding schemes are proposed in [10], which are based on projected gradient method and alternating minimization (AM) method, respectively.

The above works have shown solutions to hybrid precoding in multi-carrier transmission by obtaining frequency-flat RF precoder with the help of matrix factorization, which is computationally complicated. Moreover, the above methods inevitably introduce approximation errors and eventually lead to a non-negligible performance loss. Different from matrix factorization-based schemes, [11] proposes a principal component analysis(PCA)-based hybrid precoding scheme to design RF precoder directly. However, this PCA-based hybrid precoding scheme in [11] is only suitable to point-to-point systems with low interference elimination ability. To this end, it is worth studying the extension of the above method to

This work was supported in part by the National Key Research and Development Program of China under Grant 2020YFB1807900, in part by the National Natural Science Foundation of China under Grant 62101306. The work was also supported by Datang Linktester Technology Co. Ltd.

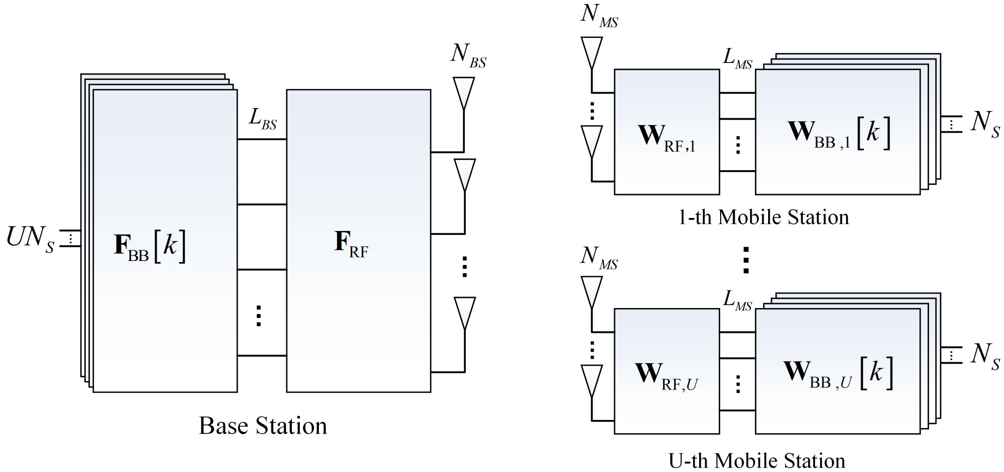

Fig. 1. The MU massive MIMO-OFDM hybrid precoding system.

design hybrid precoding with low complexity for broadband MU systems.

In this paper, we propose a PCA-BD-based broadband hybrid precoding scheme for MU massive MIMO systems. The main contributions are summarized as follows: 1)A PCA-based frequency-flat RF precoding design independent of matrix factorization is proposed, which reduces the computational complexity significantly. 2)Relying on the proposed PCA-based frequency-flat RF precoding scheme, a PCA-BD-based hybrid precoding scheme for MU scenarios is further proposed, which can suppress the inter-user interference effectively and improve the sum spectral efficiency (SSE) performance significantly. Simulation results verify the effectiveness of our proposed scheme, which outperforms the state-of-the-art hybrid precoding schemes.

II. System Model

As shown in Fig.1, we consider a downlink(DL) broadband MU massive MIMO system, where a base station (BS) serves U mobile stations (MSs) simultaneously on K subcarriers. In particular, the BS is equipped with $N_{\rm BS}$ antennas and $L_{\rm BS}$ RF chains, while each MS is equipped with $N_{\rm MS}$ antennas and $L_{\rm MS}$ RF chains to support $N_{\rm s}$ data streams. To ensure the effectiveness of transmission, the constraints of RF chains should be followed, i.e., $UN_{\rm s} \leq L_{\rm BS} \ll N_{\rm BS}$ and $N_{\rm s} \leq L_{\rm MS} \ll N_{\rm MS}$. Without loss of generality, we assume that $L_{\rm BS} = UL_{\rm MS}$. Moreover, the BB precoder serving the u-th MS and the RF precoder at the BS are $\{\mathbf{F}_{{\rm BB},u}[k]\}_{k=1:K}^{u=1:U}$ and $\mathbf{F}_{\rm RF} \in \mathbb{C}^{N_{\rm BS}\times L_{\rm BS}}$, respectively, and the BB combiner associated with the k-th subcarrier and the RF combiner at the u-th MS are $\{\mathbf{W}_{{\rm BB},u}[k]\}_{k=1:K}^{u=1:U}$ and $\mathbf{W}_{{\rm RF},u} \in \mathbb{C}^{N_{\rm MS}\times L_{\rm MS}}$, respectively. In particular, the BB precoder of the BS serving all MS at k-th subcarrier is defined as $\mathbf{F}_{\rm BB}[k] \in \mathbb{C}^{L_{\rm BS}\times UN_{\rm s}}$ with $\mathbf{F}_{\rm BB}[k] = [\mathbf{F}_{\rm BB,1}[k], \cdots, \mathbf{F}_{{\rm BB},U}[k]]$. Besides, the transmitted symbol vector is $\mathbf{s}[k] = [\mathbf{s}_1^T[k], \cdots, \mathbf{s}_U^T[k]]^T$ with $\mathbf{s}_u[k] \in \mathbb{C}^{N_{\rm s}\times 1}$ denoting the symbol sending to the u-th MS, where $\mathbb{E}[\mathbf{s}[k]\mathbf{s}^H[k]] = \mathbf{I}_{UN_s}$.

Considering the clustered millimeter wave (mmWave) channel containing $N_{\rm cl}$ clusters and $N_{\rm ray}$ multiple paths per cluster, the channel response at the d-th delay tap of the D-delay channel model can be expressed as [12]

$$\mathbf{H}_{u,d}=\sqrt{\frac{N_{\rm BS}N_{\rm MS}}{N_{\rm cl}N_{\rm ray}}}\sum_{l=1}^{N_{\rm cl}}\sum_{r=1}^{N_{\rm ray}}\alpha_{u,l,r}p_{{\rm rc},u}(dT_{\rm s}-\tau_{u,l,r})\mathbf{a}_{{\rm MS},u}\mathbf{a}_{\rm BS}^H, \tag{1}$$

where $\mathbf{a}_{\rm BS} = \frac{1}{\sqrt{N_{\rm BS}}}[1, e^{j\pi\sin\theta_{\rm BS}}, \cdots, e^{j(N_{\rm BS}-1)\pi\sin\theta_{\rm BS}}]^T$ and $\mathbf{a}_{{\rm MS},u} = \frac{1}{\sqrt{N_{\rm MS}}}[1, e^{j\pi\sin\theta_{{\rm MS},u}}, \cdots, e^{j(N_{\rm MS}-1)\pi\sin\theta_{{\rm MS},u}}]^T$ denote the array response vector of the BS and the u-th MS. $\theta_{{\rm MS},u}$, $\theta_{\rm BS}$, $\tau_{u,l,r}$, and $\alpha_{u,l,r}$ are the azimuth angles of arrival/departure (AoA/AoD), delay, and complex path gain, respectively, $p_{{\rm rc},u}()$ denotes the pulse shaping filter with $T_{\rm s}$ representing the sampling duration. The frequency domain channel response is $\mathbf{H}_u[k] = \sum_{d=1}^{D}\mathbf{H}_{u,d}\exp(-j2\pi kd/K)$. Accordingly, the channel matrix in frequency domain is given by

$$\mathbf{H}_u[k] = \mathbf{A}_{{\rm MS},u}\Delta_u[k]\mathbf{A}_{\rm BS}^H, \tag{2}$$

where $\mathbf{A}_{\rm BS} \in \mathbb{C}^{N_{\rm BS}\times N_{\rm cl}N_{\rm ray}}$ and $\mathbf{A}_{{\rm MS},u} \in \mathbb{C}^{N_{\rm MS}\times N_{\rm cl}N_{\rm ray}}$ denote the steering vectors of BS/MSs, and the diagonal matrix $\Delta_u[k] \in \mathbb{C}^{N_{\rm cl}N_{\rm ray}\times N_{\rm cl}N_{\rm ray}}$ represents channel gain.

III. PCA-Based RF Precoder/Combiner Design

In this section, a PCA-based RF precoder/combiner design for mmWave massive MIMO-OFDM systems is proposed, where the foreknow channel matrix based RF combiner design at the MS is presented first and equivalent BB channel based RF precoder design at BS is introduced next.

To ensure high transmission efficiency, the channel matrix $\mathbf{H}$ should follow [7]: 1) Sufficiency of channel matrix rank, i.e., $rank(\mathbf{H}) \geq UN_{\rm s}$; 2) High antenna gain, the singular value of $\mathbf{H}$ should be sufficiently large to provide enough gain for each stream.

A. RF combiner design at the MS

Based on the constant mode constraint (CMC) of RF combiner and rank sufficiency requirement of $\mathbf{H}_{\rm u}[k]$, $\mathbf{W}_{\rm RF,\mathit{u}}$ can be formulated as

$$\mathbf{W}_{\mathrm{RF},u} = \mathbf{U}_{\mathrm{RF},u} \begin{bmatrix} \frac{1}{\sqrt{N_{\mathrm{MS}}}}\mathbf{I}_{L_{\mathrm{MS}}} \\ \mathbf{0}_{(N_{\mathrm{MS}}-L_{\mathrm{MS}})\times L_{\mathrm{MS}}} \end{bmatrix}, \tag{3}$$

where $\mathbf{U}_{\mathrm{RF},u}$ is a unitary matrix. We define the intermediate channel of the u-th MS as $\mathbf{H}_{\mathrm{int},u}[k] = \mathbf{W}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k]$.

Accordingly, the design of RF combiner at the u-th MS turns to maximizing the singular values of $\mathbf{H}_{\mathrm{int},u}[k]$. To this end, we first rewrite $\mathbf{H}_{\mathrm{int},u}[k]$ as

$$\begin{aligned} \mathbf{H}_{\mathrm{int},u}[k] &= \mathbf{W}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k] \\ &= \begin{bmatrix} \frac{1}{\sqrt{N_{\mathrm{MS}}}}\mathbf{I}_{L_{\mathrm{MS}}} & \mathbf{0}_{L_{\mathrm{MS}}\times(N_{\mathrm{MS}}-L_{\mathrm{MS}})} \end{bmatrix} \mathbf{U}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k]. \end{aligned} \tag{4}$$

Ignoring the scaling effect of $\frac{1}{\sqrt{N_{\mathrm{MS}}}}$, the operation of (4) equals to extract the first L_{MS} column of $\mathbf{U}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k]$. Meanwhile, due to the fact that $\mathbf{U}_{\mathrm{RF},u}$ is a unitary matrix, the singular values of $\mathbf{H}_u[k]$ and $\mathbf{U}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k]$ are the same. As a result, the maximization of the singular value of $\mathbf{H}_{\mathrm{int},u}[k]$ is equivalent to extracting the L_{MS} largest singular values of $\mathbf{H}_u[k]$. Here, the singular value decomposition (SVD) of $\mathbf{H}_{\mathrm{int},u}[k]$ at the k-th subcarrier can presented as

$$\mathbf{H}_u[k] = \mathbf{U}_u[k]\mathbf{\Sigma}_u[k]\mathbf{V}_u^{H}[k]. \tag{5}$$

Subsequently, it can be inferred that the frequency-selective RF combiner at u-th MS is $\mathbf{W}_{\mathrm{opt},u}[k] = \mathbf{U}_u[k]$ [4].

According to [13], the frequency domain MIMO channel matrices $\{\mathbf{H}_u[k]\}_{k=1,\cdots,K}$ have the same dominant subspace, and $\mathbf{W}_{\mathrm{RF},u}$ is identical for all subcarriers. This observation motivates us to design the RF combiner $\mathbf{W}_{\mathrm{RF},u}$ by PCA method [14], where the original data set can be reconstructed from its principal components. More specifically, the frequency-flat $\mathbf{U}_{\mathrm{RF},u}$ can be regarded as the principal components of the original frequency-selective RF combiner set $\mathbf{W}_{0,u} = [\mathbf{W}_{\mathrm{opt},u}[1]\cdots\mathbf{W}_{\mathrm{opt},u}[K]]$. Next, SVD approach is adopted to acquire a stable solution of principal components with low complexity [15]. $\mathbf{W}_{0,u}$ can be decomposed by SVD as

$$\mathbf{W}_{0,u} = \mathbf{U}_{\mathbf{W}_{0,u}}\mathbf{\Sigma}_{\mathbf{W}_{0,u}}\mathbf{V}_{\mathbf{W}_{0,u}}^{H}, \tag{6}$$

where $\mathbf{U}_{\mathbf{W}_{0,u}}$ corresponds to the principal components. i.e., $\mathbf{U}_{\mathrm{RF},u} = \mathbf{U}_{\mathbf{W}_{0,u}}$. Owing to the CMC of phase shifters, the RF combiner at u-th MS based on equal gain transmission (EGT) [7] can be expressed as

$$\mathbf{W}_{\mathrm{RF},u} = \frac{1}{\sqrt{N_{\mathrm{MS}}}}\exp(j\angle(\mathbf{U}_{\mathbf{W}_{0,u}})). \tag{7}$$

B. RF precoder design at BS

Then, relying on the well-designed $\mathbf{W}_{\mathrm{RF},u}$, the RF precoder at BS can be calculated. Here, the equivalent BB channel $\{\mathbf{H}_{\mathrm{eq}}[k]\}_{k=1,\cdots,K}$ after RF precoding is given by

$$\mathbf{H}_{\mathrm{eq}}[k] = \begin{bmatrix} \mathbf{W}_{\mathrm{RF},1}^{H}\mathbf{H}_1[k] \\ \mathbf{W}_{\mathrm{RF},2}^{H}\mathbf{H}_2[k] \\ \vdots \\ \mathbf{W}_{\mathrm{RF},U}^{H}\mathbf{H}_U[k] \end{bmatrix} \mathbf{F}_{\mathrm{RF}} = \mathbf{H}_{\mathrm{int}}[k]\mathbf{F}_{\mathrm{RF}}, \tag{8}$$

where $\mathbf{H}_{\mathrm{int}}[k]$ denotes the intermediate channel for all MSs. Similar to the design of RF combiner at MS, we first express $\mathbf{F}_{\mathrm{RF}}$ as

$$\mathbf{F}_{\mathrm{RF}} = \mathbf{U}_{\mathrm{RF}} \begin{bmatrix} \frac{1}{\sqrt{N_{\mathrm{BS}}}}\mathbf{I}_{L_{\mathrm{BS}}} \\ \mathbf{0}_{(N_{\mathrm{BS}}-L_{\mathrm{BS}})\times L_{\mathrm{BS}}} \end{bmatrix}, \tag{9}$$

where $\mathbf{U}_{\mathrm{RF}} \in \mathbb{C}^{N_{\mathrm{BS}}\times N_{\mathrm{BS}}}$ is a unitary matrix. Accordingly, $\mathbf{H}_{\mathrm{eq}}[k]$ can be rewritten as

$$\mathbf{H}_{\mathrm{eq}}[k] = \mathbf{H}_{\mathrm{int}}[k]\mathbf{U}_{\mathrm{RF}} \begin{bmatrix} \frac{1}{\sqrt{N_{\mathrm{BS}}}}\mathbf{I}_{L_{\mathrm{BS}}} \\ \mathbf{0}_{(N_{\mathrm{BS}}-L_{\mathrm{BS}})\times L_{\mathrm{BS}}} \end{bmatrix}. \tag{10}$$

To maximize the singular value of $\mathbf{H}_{\mathrm{eq}}[k]$, the L_{BS} largest singular values of $\mathbf{H}_{\mathrm{int}}[k]$ should be extracted. As such, SVD is adopted to $\mathbf{H}_{\mathrm{int}}[k]$ as follows

$$\mathbf{H}_{\mathrm{int}}[k] = \mathbf{U}_{\mathrm{int}}[k]\mathbf{\Sigma}_{\mathrm{int}}[k]\mathbf{V}_{\mathrm{int}}^{H}[k]. \tag{11}$$

Typically, the conventional SVD-based frequency-selective RF precoder can be presented as $\mathbf{F}_{\mathrm{opt}}[k] = \mathbf{V}_{\mathrm{int}}[k]$, and PCA method could be employed to extract frequency-flat $\mathbf{U}_{\mathrm{RF}}$ from $\{\mathbf{F}_{\mathrm{opt}}[k]\}_{k=1,\cdots,K}$. Moreover, considering the frequency-selective RF precoder set $\mathbf{F}_0 = [\mathbf{F}_{\mathrm{opt}}[1]\cdots\mathbf{F}_{\mathrm{opt}}[K]]$, its SVD can be presented as

$$\mathbf{F}_0 = \mathbf{U}_{\mathbf{F}_0}\mathbf{\Sigma}_{\mathbf{F}_0}\mathbf{V}_{\mathbf{F}_0}^{H}. \tag{12}$$

Therefore, we can get that $\mathbf{U}_{\mathrm{RF}} = \mathbf{V}_{\mathbf{F}_0}$. According to the CMC of RF precoder, the RF precoder at BS can be obtained as

$$\mathbf{F}_{\mathrm{RF}} = \frac{1}{\sqrt{N_{\mathrm{BS}}}}\exp(j\angle(\mathbf{V}_{\mathbf{F}_0})). \tag{13}$$

IV. BD-Based BB Precoder/Combiner Design

On the premise of the vested RF precoder/combiner, the design of BB precoder/combiner can be carried out. Specifically, given RF precoder $\mathbf{F}_{\mathrm{RF}}$ and RF combiner $\{\mathbf{W}_{\mathrm{RF},u}\}_{u=1,\cdots,U}$, the equivalent BB channel of the u-th MS can be expressed as

$$\mathbf{H}_{\mathrm{eq},u}[k] = \mathbf{W}_{\mathrm{RF},u}^{H}\mathbf{H}_u[k]\mathbf{F}_{\mathrm{RF}}. \tag{14}$$

To eliminate the inter-user interference, the low dimensional BD method is utilized to design BB precoder/combiner on the equivalent BB channel. Define the interference channel of the u-th MS from other MSs as

$$\mathbf{H}_u^{\mathrm{itf}}[k]{=}\left[\mathbf{H}_{\mathrm{eq},1}^{T}[k],\cdots\mathbf{H}_{\mathrm{eq},u-1}^{T}[k],\mathbf{H}_{\mathrm{eq},u+1}^{T}[k],\cdots,\mathbf{H}_{\mathrm{eq},U}^{T}[k]\right]^{T}, \tag{15}$$

and the SVD of $\mathbf{H}_{\rm u}^{\mathrm{itf}}[k]$ can be expressed as

$$\mathbf{H}_{\rm u}^{\mathrm{itf}}[k] = \mathbf{U}_{\rm u}[k]\mathbf{\Sigma}_v[k]\mathbf{V}_{\rm u}^{H}[k]. \tag{16}$$

We denote $\mathbf{V}_{\rm u}^{(L_{\mathrm{MS}})}[k]$ as a matrix composed of the L_{MS} left singular vectors corresponding to the L_{MS} smallest singular values of $\mathbf{V}_{\rm u}^{H}[k]$. Apparently, $\mathbf{V}_{\rm u}^{(L_{\mathrm{MS}})}[k]$ is exactly an orthogonal base of the null space of $\mathbf{H}_{\rm u}^{\mathrm{itf}}[k]$. Therefore, we have

$$\mathbf{H}_{\mathrm{eq},i}[k]\mathbf{V}_u^{(L_{\mathrm{MS}})}[k] = \begin{cases} \mathbf{H}_{\mathrm{eq},u}[k]\mathbf{V}_u^{(L_{\mathrm{MS}})}[k] & i = u \\ \mathbf{0} & i \neq u \end{cases}. \tag{17}$$

Based on (17), inter-user-interference-free multi-stream transmission can be realized. Next, the SVD of $\mathbf{H}_{\mathrm{eq},u}[k]\mathbf{V}_u^{(L_{\mathrm{MS}})}[k]$ can be expressed as

$$\mathbf{H}_{\mathrm{eq},u}[k]\mathbf{V}_u^{(L_{\mathrm{MS}})}[k] = \mathbf{U}_{\mathrm{u}}^0[k]\mathbf{\Sigma}_{\mathrm{u}}^0[k](\mathbf{V}_{\mathrm{u}}^0[k])^H. \quad (18)$$

As such, the BB precoder at BS can be formulated as

$$\mathbf{F}_{\mathrm{BB},u}[k] = \mathbf{V}_u^{(L_{\mathrm{MS}})}[k][\mathbf{V}_u^0[k]]_{:,1:N_s}. \quad (19)$$

Accordingly, the BB combiner at MS can be expressed as

$$\mathbf{W}_{\mathrm{BB},u}[k] = [\mathbf{U}_u^0[k]]_{:,1:N_s}. \quad (20)$$

V. Numerical Results

In this section, we present numerical results to validate the effectiveness of our proposed PCA-BD-based hybrid precoding scheme, especially considering the achievable SSE and BER performance. Here, the achievable SSE for MU mmWave massive MIMO-OFDM systems can be expressed as [16]

$$R = \frac{1}{K}\sum_{k=1}^{K}\sum_{u=1}^{U}\sum_{n=1}^{N_{\mathrm{s}}}\log_2\left(1+\frac{S_{k,u,n}}{I_{k,u,n}+N_{k,u,n}}\right), \quad (21)$$

where

$$S_{k,u,n} = \left|[\mathbf{W}_{\mathrm{BB},u}[k]]_{:,n}^H\mathbf{W}_{\mathrm{RF},u}^H\mathbf{H}_u[k]\mathbf{F}_{\mathrm{RF}}[\mathbf{F}_{\mathrm{BB},u}[k]]_{:,n}\right|^2 P_{u,n},$$

$$I_{k,u,n} = \sum_{i=1,i\neq n}^{N_{\mathrm{s}}}\left|[\mathbf{W}_{\mathrm{BB},u}[k]]_{:,n}^H\mathbf{W}_{\mathrm{RF},u}^H\mathbf{H}_u[k]\mathbf{F}_{\mathrm{RF}}[\mathbf{F}_{\mathrm{BB},u}[k]]_{:,i}\right|^2 P_{u,i}+ \sum_{v=1,v\neq u}^{U}\sum_{i=1}^{N_{\mathrm{s}}}\left|[\mathbf{W}_{\mathrm{BB},u}[k]]_{:,n}^H\mathbf{W}_{\mathrm{RF},u}^H\mathbf{H}_u[k]\mathbf{F}_{\mathrm{RF}}[\mathbf{F}_{\mathrm{BB},v}[k]]_{:,i}\right|^2 P_{v,i}.$$

$$N_{k,u,n} = \sigma^2||\mathbf{W}_{\mathrm{RF},u}\mathbf{W}_{\mathrm{BB},u}[k]||_{\mathrm{F}}^2,$$

with $S_{k,u,n}$,$I_{k,u,n}$,$N_{k,u,n}$, $P_{u,n}$, σ^2 denoting signal power, interference power, noise power, data stream power and noise variance, respectively.

Throughout this section, we consider a $U = 4$ MU MIMO-OFDM system with $K = 32$ subcarriers and delay $D = 8$, where $N_{\mathrm{BS}} = 64$ for BS, $N_{\mathrm{MS}} = 16$ for each MS. There are $N_{\mathrm{s}} = 2$ data streams transmitted between each MS and BS. Besides, each MS and BS are equipped with $L_{\mathrm{MS}} = N_{\mathrm{s}} = 2$ and $L_{\mathrm{BS}} = UL_{\mathrm{MS}} = 8$ RF chains, respectively. We assume the channel comprises $N_{\mathrm{cl}} = 8$ clusters of multipaths with $N_{\mathrm{ray}} = 10$ rays in each cluster, and all the AoAs/AoDs are uniformly distributed within $[0, \pi]$. The signal-to-noise ratio (SNR) is defined as $\sum_{u=1}^{U}\sum_{n=1}^{N_{\mathrm{s}}} P_{u,n}/\sigma^2$.

State-of-the-art solutions will be compared as benchmarks, which are detailed as follows

- DPC: The dirty paper coding scheme shown in [17], which is a kind of optimal fully-digital scheme [1].
- AM-MMSE: A two-step hybrid precoding scheme proposed in [10], where the RF combiner is designed based on SVD decomposition to maximize the SNR of receive signal and the BB combiners are designed by minimizing the mean square error (MSE) between the received signal and desired signal. The RF combiner and the BB combiners are alternatively updated until convergence.
- S-GHP: A precoding scheme based on greedy algorithm and LS criterion. In particular, the RF precoder is designed based on greedy algorithm with auxiliary matrices, and the BB precoder is designed under LS criterion.
- OSC: Over-sampling codebook(OSC) scheme, which is an extension of [18]. In detail, RF precoding design utilizes OSC instead of traditional DFT codebook with limited spatial resolution, and the BB precoding is designed by minimizing the sum-MSE between the transmit symbols and receive symbols.
- PCA-BD: Our proposed PCA-BD-based hybrid precoding scheme, as described in the previous two sections.

[1]The optimal fully-digital scheme can be regarded as the theoretical upper bound of hybrid precoding, which is hard to implement practically.

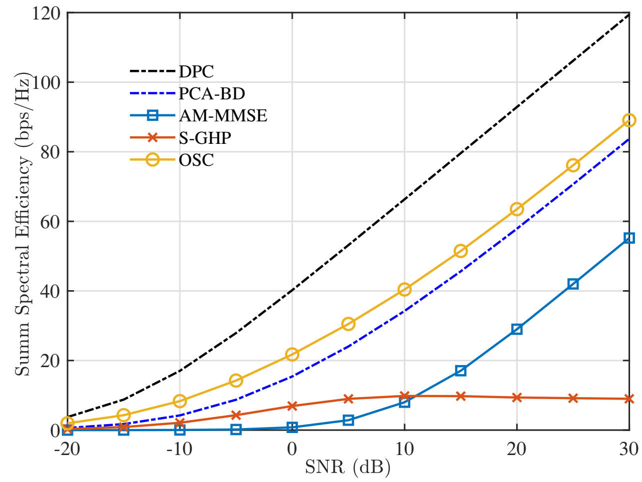

Fig. 2. SSE performance comparison of different hybrid precoding schemes.

We first examine the SSE performance in Fig. 2. It can be observed that, even though the theoretical upper bound obtained by optimal fully-digital scheme is hard to achieve, our proposed PCA-BD scheme and the OSC scheme show better SSE performance compared to AM-MMSE and S-GHP. In contrast to OSC, our proposed PCA-BD is independent of codebook, as such, OSC and PCA-BD can be applied to different application scenarios. Besides, due to its inability of inter-user interference elimination, the SSE performance of AM-MMSE, which makes full use of CSI to eliminate inter-stream interference, is limited. As for the S-GHP scheme, its performance converges to a constant as the increase of SNR. This is because S-GHP scheme designs RF precoder/combiner for all MSs simultaneously, which may make the precoder corresponding to a RF chain serves multiple MSs. As a result, S-GHP scheme fails to eliminate the inter-user interference in BB design, thus limit its performance.

In Fig. 3, the BER performance achieved by different hybrid precoding schemes are evaluated, where QPSK modulation is

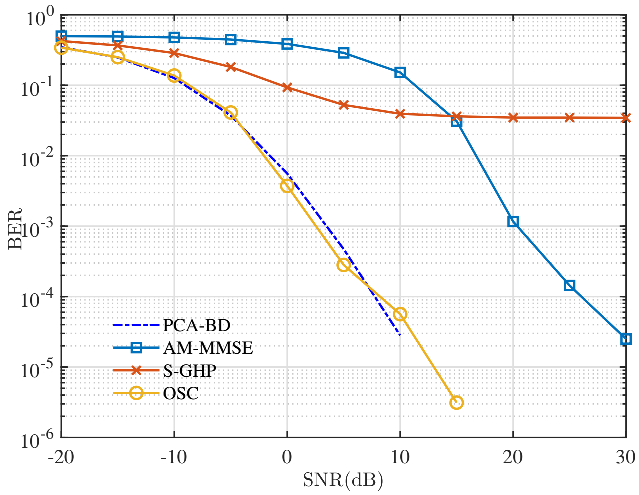

Fig. 3. BER performance comparison of different hybrid precoding schemes.

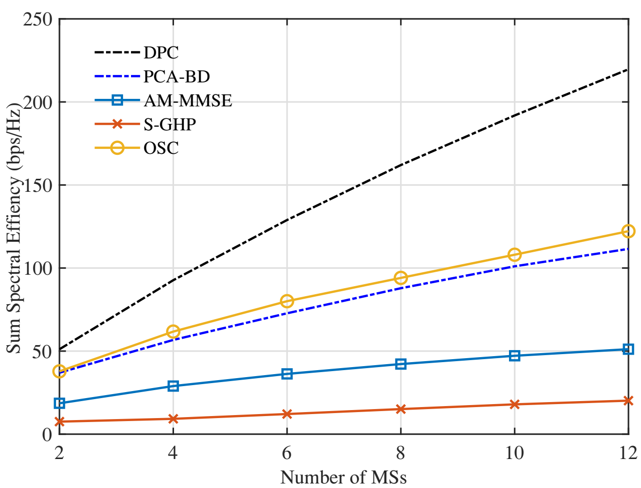

Fig. 4. SSE performance comparison of different hybrid precoding schemes with different number of MSs.

considered [2]. It can be observed that our proposed PCA-BD and OSC could improve the BER performance significantly, For example, PCA-BD and OSC have a 18dB performance gain when compared to AM-MMSE at the BER of 10^{-4} Moreover, as the increase SNR, the BER performance of proposed our PCA-BD even outperforms OSC, which validates the superiority of of our proposed scheme.

In Fig. 4, we plot the SSE versus the number of MSs for different schemes when SNR=20dB. Due to the fact that DPC can eliminate the inter-user interference notably, it shows the best SSE performance. Meanwhile, since PCA-BD and OSC can also eliminate the inter-user interference efficiently, as the increase of the number of MSs, the SSE of both PCA-BD and OSC increases gradually, which verifies the effectiveness of our proposed scheme. In contrast, the SSE achieved by the

[2]Due to the fact the DPC scheme only investigates the upper bound of SSE without specific precoder/combiner design, it is not included in this comparison.

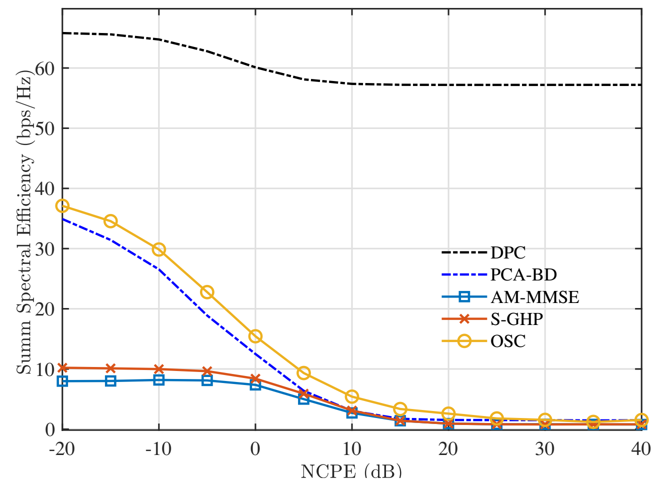

Fig. 5. SSE performance comparison of different hybrid precoding schemes under channel disturbance, $SNR = 10$dB.

AM-MMSE scheme and S-GHP scheme grow slowly, showing their limitation in eliminating inter-user interference.

Finally, Fig.5 compares the robustness of different schemes to imperfect CSI caused by channel perturbation, which includes channel estimation error, CSI quantization in channel feedback or outdated CSI [11]. To depict the channel perturbation, normalized channel perturbation error (NCPE) is adopted, given by $\mathrm{NCPE} = \frac{\sum_{u=1}^{U}\sum_{k=1}^{K}||\mathbf{H}_u[k]-\mathbf{H}_{\mathrm{per},u}[k]||_F^2}{\sum_{u=1}^{U}\sum_{k=1}^{K}||\mathbf{H}_u[k]||_F^2}$, where the non-ideal channel is modeled as $\mathbf{H}_{\mathrm{per},u}[k] = \mathbf{H}_u[k]+\mathbf{N}_{\mathrm{per}}[k]$, $\mathbf{N}_{\mathrm{per}}[k] \sim \mathcal{CN}(0, \sigma_{\mathrm{per}}^2)$. It can be observed that, by completely eliminating the inter-user interference, DPC is influenced by channel perturbation slightly, which shows that the importance of inter-user interference elimination in MU precoding systems. Moreover, we can observe that the PCA-BD and OSC have better robustness than the AM-MMSE and S-GHP.

VI. Conclusion

In this paper, we investigated a PCA-BD-based hybrid precoding scheme in broadband MU massive MIMO systems. First, inspired by PCA, the frequency-flat RF precoder/combiner is designed by extracting the principal components of frequency-selective RF precoders. Then, based on the well-designed PCA-based RF precoder/combiner, BD method is utilized to design the BB precoder/combiner, which suppresses the inter-user interference effectively. Simulation results show the effectiveness of our proposed PCA-BD based hybrid precoding scheme considering its spectral efficiency, transmission reliability and robustness.

Acknowledgment

This work was supported in part by the National Key Research and Development Program of China under Grant 2020YFB1807900, in part by the National Natural Science Foundation of China under Grant 62101306. The work was also supported by Datang Linktester Technology Co. Ltd.

REFERENCES

[1] F. Rusek et al., “Scaling up MIMO: Opportunities and challenges with very large arrays,” *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013.

[2] X. Gao et al., “Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[3] O. El Ayach, R. W. Heath, S. Rajagopal and Z. Pi, “Multimode Precoding in Millimeter Wave MIMO Transmitters with Multiple Antenna Sub-arrays”, in *Proc. IEEE Global Commun. Conf. (GLOBECOM).*, pp. 3476–3480, 2013.

[4] O. E. Ayach et al., “Spatially sparse precoding in millimeter wave MIMO systems,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[5] Y. Zhang, X. Dong, and Z. Zhang, “Machine learning-based hybrid precoding with low-resolution analog phase shifters,” *IEEE Commun.Lett.*, vol. 25, no. 1, pp. 186–190, Jan. 2021.

[6] A. Alkhateeb et al.,“Limited feedback hybrid precoding for multiuser millimeter wave systems,” *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 6481–6494, Nov. 2015.

[7] W. Ni and X. Dong, “Hybrid block diagonalization for massive multiuser MIMO systems,” *IEEE Trans. Commun.* , vol. 64, no. 1, pp. 201–211, Jan. 2016.

[8] A. Alkhateeb and R. W. Heath, Jr., “Frequency selective hybrid precoding for limited feedback millimeter wave systems,” *IEEE Trans.Commun.*, vol. 64, no. 5, pp. 1801–1818, May 2016.

[9] J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, “Low-complexity multiuser hybrid precoding and combining for frequency selective millimeter wave systems,” in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun.*(SPAWC), 2018.

[10] J. P. Gonzlez-Coma et al., “Channel estimation and hybrid precoding for frequency selective multiuser mmWave MIMO systems,” *IEEE J. Sel. Topics Signal Process.*, vol. 12, no. 2, pp. 353–367, May 2018.

[11] Y. Sun et al., “Principal component analysis-based broadband hybrid precoding for millimeter-wave massive MIMO systems,” *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6331–6346, Oct. 2020.

[12] X. Wu et al., “Hybrid beamforming for multi-user massive MIMO systems,” *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 3879–3891, Sep. 2018.

[13] K. Venugopal et al., “Optimality of frequency flat precoding in frequency selective millimeter wave channels,” *IEEE Wireless Commun. Lett.*, vol. 6, no. 3, pp. 330–333, Jun. 2017.

[14] C. M. Bishop, *Pattern Recognition and Machine Learning.* New York, NY, USA: Springer, 2006.

[15] J. Shlens,“A Tutorial on Principal Component Analysis,” *Int J Remote Sens* , vol. 51, no. 2, 2014

[16] N. Uwaechia, N. M. Mahyuddin, M. F. Ain, N. M. A. Latiff, and N. F. Zaah, “On the spectral-efficiency of low-complexity and resolution hybrid precoding and combining transceivers for mmWave MIMO systems,” *IEEE Access*, vol. 7, pp. 109259–109277, 2019.

[17] N. Jindal et al., “Sum power iterative water-filling for multi-antenna Gaussian broadcast channels,” *IEEE Trans. Inf. Theory*, vol. 51, no. 4, pp. 1570–1580, Apr. 2005.

[18] J. Mao, Z. Gao, Y. Wu, and M.-S. Alouini, “Over-sampling codebook based hybrid minimum sum-mean-square-error precoding for millimeter wave 3D-MIMO,” *IEEE Wireless Commun. Lett.*, vol. 7, no. 6, pp. 938–941, Dec. 2018.