

Hybrid Precoding for Multi-user Massive MIMO Systems Based on Equivalent Channel

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Hybrid Precoding for Multi-user Massive MIMO Systems Based on Equivalent Channel

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Abstract

Utilizing millimeter-wave (mmWave) band with massive MIMO architecture is deemed as an available paradigm for the future 6G wireless systems to cater the increasing demands in communication rates, in which hybrid precoding is a promising solution to reduce hardware cost and power consumption while maintains almost the same spectrum efficiency. In this paper, for multi-user massive MIMO systems, a new hybrid precoding scheme is presented based on the concept of equivalent channel by designing the analog precoder at the transmitter and the analog combiner at the receiver jointly. Specifically, after the optimal analog precoder/combiner for each user has been derived based on the equivalent channel of the individual sub-channel via exploiting the singular value decomposition (SVD) technique, the total baseband digital precoding is implemented with the block diagonalization method to suppress inter-user interference. In this way, not only high spectrum efficiency can be achieved, but also the computational complexity to realize hybrid precoding is decreased. To further verify the superior performance of the proposed hybrid precoding, simulation results are presented with different parameter settings.

Index Terms

Massive MIMO, Millimeter wave communication, Hybrid precoding, Equivalent channel, Multi-user

I. INTRODUCTION

With the explosive increasing in the rate demands of wireless communication, the current communication frequency band is becoming crowder and crowder. Hence, obtaining other available frequency bands or adopting edge-cutting techniques with higher spectral efficiency seems the key to apply wireless communications more widely. In the past decade, for enhanced spectrum efficiency or decreased spectrum consumption, some novel schemes and concepts have been proposed, such as cooperative communication, cognitive communication, edging computing, and so on [1], [2], [3]. Nevertheless, expanding wireless communication band to millimeter-wave (mmWave) seems the essential solution. However, mmWave signals have severe path-fading in propagation, which renders the receiver have no enough power to

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complete decode reliably. To this end, massive multiple-input-multiple-output (MIMO) antenna architecture has emerged as the times require. For massive MIMO systems, the great degree of space freedom can be leveraged to implement precoding, through which the beams of the transmitted signals can be directed to the receiver, and the receiver can obtain more power gain for decoding.

When the precoding is implemented in fully digital domain, not only high spectral efficiency can be obtained, but also the optimal precoding matrix can be derived directly. However, fully digital precoding needs each antenna being connected to a candidate radio frequency (RF) chain. Hence, for a massive MIMO terminal, hundreds even thousands of RF chains are required, which needs much hardware cost and power consumption is extremely high as well, so it is usually unbearable for ordinary terminals. To decrease such hardware cost and power consumption with fully digital precoding schemes, digital/analog hybrid precoding concept has been proposed. In the massive MIMO systems with hybrid precoding, the transmitted symbols are connected to much less RF chains after baseband digital precoding being implemented, and then the up-conversion signals are connected to antennas after analog precoding being operated. Unfortunately, in the process to obtain the analog precoding matrix and the baseband digital matrix, the fully digital precoding matrix can not be decomposed into two small matrices directly with given dimensions, so the analog precoding matrix and baseband precoding matrix needs complex operation and the degree of approximation on matrix decomposition affects the energy efficiency of the massive MIMO systems as well. Consequently, much research work has been carried out around hybrid precoding, and some novel schemes have been proposed in the past several years, which can be roughly divided into following two categories.

A. Hybrid precoding for single-user massive MIMO systems

One of the pioneer research on hybrid precoding was presented in [4], where hybrid precoding was formulated as a sparse matrix reconstruction problem and the simultaneous orthogonal-matching-pursuit (SOMP) scheme was proposed. However, its computational complexity is very high. Since then, much work has been done on how to simplify or avoid the search process in SOMP. Combining with local search techniques, an enhanced SOMP scheme was presented in [5]. Integrating turbo equalizer with tabu search algorithm, a scheme with near-optimal performance was proposed with predetermined phase-shifter code-books in [6]. To select the optimal analog vectors to act as analog phase-shifters, the correlation between the array response matrix and the digital optimal precoder was utilized in [7]. To decrease the

computational complexity, a hybrid precoding scheme with stochastic approximation was proposed in [8]. Combining the concept of equivalent/intermediate channel and singular value decomposition (SVD) techniques, a series of low-complexity hybrid precoding schemes were proposed in [9], [10], [11], and the proposed scheme in [11] was extended to multi-user scenarios as well.

As the essence of hybrid precoding is use two low-dimensional matrices to approach the optimal digital fully precoding matrix, which can be obtained easily, alternating optimization and matrix decomposition techniques are available, and some hybrid precoding schemes are proposed based on it. After system spectral efficiency maximization was approximated to a sub-optimization problem, a hybrid precoding with low computational complexity was presented via an alternative method in [12]. Similarly, with the concept of equivalent channel, an alternating optimization technique was used to design analog phase-shifter in [13]. To further improve system energy efficiency, transmitter RF chains selection was considered when alternating minimization method was utilized to optimize hybrid precoding in [14]. Omitting the constraints on the hybrid precoding matrix during matrix decomposition, a hybrid RF and baseband precoding/combining scheme for multi-stream transmission was proposed in [15]. In [16], obtaining the optimal precoding matrices was decomposed into multiple precoding sub-matrix optimization problems, and then a hybrid beamforming scheme was proposed. In [17], for sub-array structure, the system capacity optimization was decomposed into a series of subproblems, and a near-optimal hybrid precoding scheme was proposed in iterative mode.

B. Multi-user massive MIMO systems

For multi-user scenarios, some novel schemes have also been proposed. In [18], a hybrid block diagonalization method was presented to maximize system spectral efficiency, where analog precoding/combining was utilized to obtain large array gain and digital precoding/combining was exploited to delete inter-user interference, respectively. Considering the scenario of multiple pairs sharing the same spectrum, a heuristic method for joint hybrid precoding/combining was conceived to improve the spectral efficiency with reduced computational complexity in [19]. In [20], a flexible adaptive overlapped subarray architecture was proposed for analog precoder to maximize energy efficiency. In [21], to maximize the achievable sum-rate, a novel hybrid precoding scheme was presented by introducing interference-free achievable rate. To balance the energy efficiency and the system sum-rate when it is set that the analog phase-shifter is under two-bits resolution, a low-complexity hybrid precoding was proposed in [22]. In [23],

the authors proposed a hybrid precoding scheme based on subspace insights in the hope of reducing the computational complexity. For unmanned aerial vehicle (UAV) systems, multiple key enabling techniques with mmWave beamforming were articulated in [24]. In [25], for fully-connected and one-stream-per-subarray architectures, the achievable spectral efficiency was investigated when initial beam acquisition and data communication phases were jointly considered to implement hybrid precoding.

The above hybrid precoding schemes are designed for the multi-user massive MIMO systems with perfect CSI. However, perfect CSI sometimes is difficult to obtain. Hence, hybrid precoding with imperfect CSI also attracts much interesting. A new view on multi-user hybrid massive MIMO systems from the perspective of array signal processing was presented in [26], and then hybrid precoding and channel estimation strategies were proposed as well. Based on the generic channel covariance, after the analytical sum-rate expression of beamforming was presented, the authors proposed a joint statistical beamforming and user scheduling algorithm in [27]. To reduce the signaling overhead of channel estimation, a randomized channel sparsifying hybrid precoding scheme was proposed in [28]. The authors proposed a hybrid precoding algorithm with limited feedback in [29]. In [30], when quantized CSI feedback and sub-connected structure are considered, the performance comparison between analog and hybrid precoding schemes was investigated. With the long-term and instantaneous CSI, a two-stage precoding scheme was proposed in [31]. In [32], a hybrid beamforming scheme with partial interfering beam feedback was proposed for codebook-based multi-user MIMO systems. By abstracting the nonlinear baseband precoding effect, the idea of RF precoding was formulated separately as a solution in [33] to balance the error performance of signal detection with the channel tracking accuracy.

In this paper, for multi-user massive MIMO systems, a novel hybrid precoding based on equivalent channel is presented. The main contributions are listed as follows.

- With the concept of equivalent channel, the optimal analog vectors are obtained to form the analog phase-shifters, which can improve the system performance in spectral efficiency.
- SVD technique is utilized to obtain the analog phase-shifters when equivalent channel is constructed, which can reduce computational complexity.
- Hybrid precoding is decomposed into two independent stages, where analog phase-shifters are designed for maximizing the spectral efficiency of each user, and digital precoding/combining is aimed for deleting inter-user inference. It simplifies the process of hybrid precoding.
- Simulation results show that the proposed hybrid precoding can obtain high spectral efficiency with

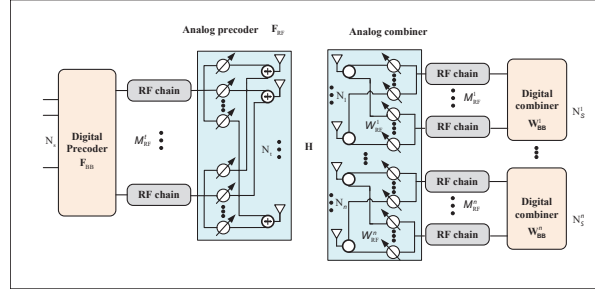


Fig. 1: The considered model of Multi-user massive MIMO systems.

low computational complexity.

The rest of the paper is organized as follows. In Section II, the considered system model is presented, and its hybrid precoding is formulated as well. In Section III, the hybrid precoding for multi-user massive MIMO systems is presented. Simulation results are presented to show the performance of the proposed hybrid precoding scheme in Section IV. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL AND FORMULATION

A multi-user massive MIMO system with fully-connected architecture is considered in this paper, which is shown as Fig. 1. In the downlink stage, the base station equipped with M_{RF}^t RF chains and N_t antennas transmits signals to n users simultaneously with the same spectrum. For user j , let N_j and M_{RF}^j denote the number of the receive antennas and RF chains, and N_S^j represent the number of transmitted data streams from the base station. Hence, the total number of transmitted data streams from the base station is $\sum_{i=1}^n N_S^i$, which is denoted as N_S for expression simplification. For reducing hardware cost and power consumption, the case with minimal RF chains is considered, hence $M_{RF}^t = N_S$. Let $\mathbf{H}$ be the total channel matrix, which is composed of all the channel matrices of each user, and it can be presented by $\mathbf{H} = [\mathbf{H}_1^T, \mathbf{H}_2^T, \dots, \mathbf{H}_n^T]^T$, where $\mathbf{H}_j$ is the channel matrix from the base station to user j , and its dimension is $N_j \times N_t$. The base station communicates with n users under the same spectrum simultaneously, and the precoding/combining of down link is investigated in this paper.

Accordingly, the received signals at user j can be shown as

$$Y_j = \sqrt{\rho} \mathbf{W}_{BB}^j \mathbf{W}_{RF}^j \mathbf{H}_j \mathbf{F}_{RF} \sum_{i=1}^n \mathbf{F}_{BB}^i \mathbf{x}_i + N_j, \quad (1)$$

where $\mathbf{F}_{RF}$ is the analog precoding matrix at the base station, and $\mathbf{F}_{BB}^j$ is the digital precoding matrix for user j . $\mathbf{x}_i$ is the transmitted symbol for user i , and it holds that $E[\mathbf{x}_i \mathbf{x}_i^*] = \frac{1}{N_i} \mathbf{I}_{N_i}$. $\mathbf{W}_{BB}^j$ and $\mathbf{W}_{RF}^j$ corresponds to the analog and digital combining matrices at user j , respectively. ρ is the average transmit

power, and N_j is the additive noise with Gaussian distribution $N(0, \sigma^2)$.

For user j , when its received signals are combined, the maximal achievable rate can be derived, which can be shown as

$$R_j = \log_2 \left(1 + \frac{\frac{\rho}{n} |\mathbf{W}_{BB}^j \mathbf{W}_{RF}^j \mathbf{H}_j \mathbf{F}_{RF} \mathbf{F}_{BB}^j|^2}{\frac{\rho}{n} \sum_{i \neq j} |\mathbf{W}_{BB}^j \mathbf{W}_{RF}^j \mathbf{H}_j \mathbf{F}_{RF} \mathbf{F}_{BB}^i|^2 + \sigma^2} \right). \quad (2)$$

Accordingly, the sum rate of the massive MIMO system can be denoted as $R = \sum_{j=1}^n R_j$, and our aim is to maximize it when hybrid precoding is designed.

III. THE PROPOSED HYBRID PRECODING SCHEME

In this section, a hybrid precoding scheme for multi-user massive MIMO systems is presented, which is composed of two stages. In the first stage, the analog precoding/combining matrix for each user is derived based on the concept of equivalent channel individually. Hence, each user can obtain the maximal achievable rate when inter-user interference is ignored. Then, digital precoding/combining is utilized to suppress the inter-user interference in the second stage. In this way, the massive MIMO system is promising to obtain the maximal sum rate in a low-complex manner. The procedures are detailed in the subsequent subsections.

A. Analog Precoding/Combining

When inter-user interference is omitted, the transmitted signals from the base station are precoded individually for maximal achievable rate. Similar to the single-user scenario in [10], the analog precoding/combining matrix for each user can be obtained.

Specifically, for an arbitrary user j , according to its channel matrix $\mathbf{H}_j$, the optimal fully digital precoding can be derived directly, which is denoted as $\mathbf{F}_{j,opt}$. Then, we decompose it with the SVD technique¹, which can be shown as

$$\mathbf{F}_{j,opt} = \mathbf{U}_o \Sigma_o \mathbf{V}_o^*. \quad (3)$$

According to the meaning of the SVD technique, it can be concluded that the matrix $\mathbf{U}_o$ and $\mathbf{V}_o$ are unitary, and Σ_o is diagonal. For the sake of simplification expression, they are rewritten as $\mathbf{U}_o = \{\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_{N_t}\}$, $\Sigma_o = \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_{N_S^j}\}$ and $\mathbf{V}_o = \{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_{N_S^j}\}$, respectively, where $\mathbf{u}_i$, $i \in \{1, 2, \dots, N_t\}$ and $\mathbf{v}_i$, $i \in \{1, 2, \dots, N_S^j\}$ are the column vectors with dimensions $N_t \times 1$ and $N_S^j \times 1$.

¹For each user, the number of RF chains is equal to that of transmitted data streams.

If let $\mathbf{F}_{RF}^j = \mathbf{U}_o(:, 1 : N_S^j) ./ |\mathbf{U}_o(:, 1 : N_S^j)|$ act as the analog precoding matrix, where $./$ denotes division operation between the corresponding elements of the numerator and denominator, the constraint on the amplitude to construct analog phase-shifter can be satisfied. Hence, when the qualified $\mathbf{F}_{RF}^j$ can be obtained by decomposing the fully digital precoding matrix directly, the fully digital precoding matrix should be $\tilde{\mathbf{F}}_{j,opt} = \mathbf{F}_{RF}^j \Sigma_o \mathbf{V}_o^*$. As we know, the fully digital precoding matrix is derived by operating SVD on the channel matrix, i.e., $\mathbf{H}_j = \mathbf{U}_F \Sigma \mathbf{V}_F^*$, where

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix}, \mathbf{V}_F = [\mathbf{V}_1 \ \mathbf{V}_2], \quad (4)$$

and the dimensions of Σ_1 and $\mathbf{V}_1$ are $N_j \times N_j$ and $N_t \times N_j$, respectively. Then, the optimal digital precoding matrix is obtained by $\mathbf{F}_{j,opt} = \mathbf{V}_1$. Hence, when it is set $\tilde{\mathbf{V}}_F = [\tilde{\mathbf{F}}_{j,opt} \ \mathbf{V}_2]$, the resultant channel should be $\tilde{\mathbf{H}}_j = \mathbf{U}_F \Sigma \mathbf{V}_F^*$. However, for user j , its real channel is $\mathbf{H}_j$. To this end, let $\tilde{\mathbf{H}}_j = \mathbf{G}_{au} \mathbf{H}_j$, then it can be derived that $\mathbf{G}_{au} = \tilde{\mathbf{H}}_j \mathbf{H}_j^* (\mathbf{H}_j \mathbf{H}_j^*)^{-1}$. It means that when the received signals are multiplied with the factor $\mathbf{G}_{au}$ before being combined, $\mathbf{F}_{RF}^j = \mathbf{U}_o ./ |\mathbf{U}_o|$ can be used to act as the analog precoding matrix at the transmitter accurately, and so only the analog combining needs to optimize during hybrid precoding/combining design. $\tilde{\mathbf{H}}_j$ is named as the intermediate channel from the base station to user j in our design.

For user j , with the intermediate channel matrix $\tilde{\mathbf{H}}_j$, the optimal fully digital combining matrix $\bar{\mathbf{W}}_{j,opt}$ can be obtained based on the MMSE criterion. Then, the final fully digital combining matrix can be shown as $\mathbf{W}_{j,opt} = \bar{\mathbf{W}}_{j,opt} \mathbf{G}_{au}$. With the SVD technique on $\mathbf{W}_{j,opt}$, the analog combining matrix can be obtained, i.e., $\mathbf{W}_{j,opt} = \mathbf{U}_r \Sigma_r \mathbf{V}_r^*$, and $\mathbf{W}_{RF}^j = \mathbf{U}_r ./ |\mathbf{U}_r|$. In the way, for each user, the analog precoding and combining matrices are obtained.

B. Digital Precoding/Combining

After the analog precoding matrices of all the users have been obtained, the entire analog precoding matrix at the base station can be formed as $\mathbf{F}_{RF} = [\mathbf{F}_{RF}^1, \mathbf{F}_{RF}^2, \dots, \mathbf{F}_{RF}^n]$. Meanwhile, for each user, the analog combining matrix is also obtained, which is denoted as $\mathbf{W}_{RF}^j$, $j \in \{1, 2, \dots, n\}$. As the precoding/combining design in analog domain have been completed aiming for the maximal achievable rate for each user, and the remaining task is to suppress the interference among users via the precoding operation in digital domain². To this end, the equivalent channel of user j is constructed as $\tilde{\mathbf{H}}_j = \mathbf{W}_{RF}^j \mathbf{H}_j \mathbf{F}_{RF}$.

²As all the transmitted signals will be coupled together, which makes it difficult to delete the inter-user interference, the interference among users are suppressed at the base station via digital precoding.

Then, the entire multi-user equivalent channel can be constructed, which is denoted as

$$\mathbf{H}_{eq} = \begin{bmatrix} \tilde{\mathbf{H}}_1 \\ \tilde{\mathbf{H}}_2 \\ \vdots \\ \tilde{\mathbf{H}}_n \end{bmatrix}. \quad (5)$$

Then, to remove the inter-user interference, the digital precoder at the base station for each user are derived based on the equivalent channel $\mathbf{H}_{eq}$ via the block diagonalization technique. Specifically, to minimize the interference among users, the baseband precoding matrix at the base station for each user should be orthogonal to the equivalent channel matrix of other users. Consequently, for an arbitrary user j , its baseband precoding matrix $\mathbf{F}_{BB}^j$ should locate in all the null space of the equivalent channel matrices of other users, which means $\tilde{\mathbf{H}}_i \mathbf{F}_{BB}^j = 0$ for $i \in \{1, 2, \dots, n\}$ and $i \neq j$. For the sake of simplicity description, let $\bar{\mathbf{H}}_j$ be the complementary channel matrix of user j , which is shown as

$$\bar{\mathbf{H}}_j = [\tilde{\mathbf{H}}_1^T, \dots, \tilde{\mathbf{H}}_{j-1}^T, \tilde{\mathbf{H}}_{j+1}^T, \dots, \tilde{\mathbf{H}}_m^T]^T. \quad (6)$$

Then, the baseband precoding matrix $\mathbf{F}_{BB}^j$ of user j should lie in the null space of $\bar{\mathbf{H}}_j$. To obtain the null space, we decompose $\bar{\mathbf{H}}_j$ with the SVD technique, which can be shown as

$$\bar{\mathbf{H}}_j = \bar{\mathbf{U}}_j \bar{\Sigma}_j [\bar{\mathbf{V}}_j^{(m-1)}, \bar{\mathbf{v}}_j]^*. \quad (7)$$

Accordingly, $\bar{\mathbf{v}}_j$ is the null space of $\bar{\mathbf{H}}_j$, and so the relationship in (8) is satisfied.

$$\tilde{\mathbf{H}}_i \bar{\mathbf{v}}_j = \begin{cases} 0, i \neq j. \\ \tilde{\mathbf{H}}_j \bar{\mathbf{v}}_j, i = j. \end{cases} \quad (8)$$

Consequently, based on the block diagonalization technique, the inter-user interference can be eliminated, and the blocked matrix is shown as

$$\mathbf{H}_{eq}[\bar{\mathbf{v}}_1, \dots, \bar{\mathbf{v}}_n] = \begin{bmatrix} \tilde{\mathbf{H}}_1 \bar{\mathbf{v}}_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \tilde{\mathbf{H}}_n \bar{\mathbf{v}}_n \end{bmatrix}. \quad (9)$$

Thus, the final baseband precoder at the base station can be obtained, which is presented as

$$\mathbf{F}_{\text{BB}} = [\bar{\mathbf{v}}_1, \dots, \bar{\mathbf{v}}_n]. \quad (10)$$

In this way, the hybrid precoding/combining for multi-user MIMO systems is implemented. The entire procedure can be summarized in *Algorithm 1*.

Algorithm 1 Hybrid precoding/combining scheme for multi-user massive MIMO systems.

- 1: Obtain the individual channel matrix $\mathbf{H}_j$, $j \in \{1, 2, \dots, n\}$, based on the entire channel matrix $\mathbf{H}$.
 - 2: For each user, operate the steps from Step 3 to Step 18.
 - 3: Operate the SVD technique on $\mathbf{H}_j$: $\mathbf{H}_j = \mathbf{U}_j \Sigma_j \mathbf{V}_j^*$.
 - 4: $\mathbf{F}_{j,\text{opt}} = \mathbf{V}(:, 1 : N_S^j) = [\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_{N_S^j}]$.
 - 5: Apply the SVD technique on $\mathbf{F}_{j,\text{opt}}$: $\mathbf{F}_{j,\text{opt}} = \mathbf{U}_F \Sigma_F \mathbf{V}_F^*$.
 - 6: $\hat{\mathbf{F}}_{\text{RF}}^j = \mathbf{U}_F(:, 1 : N_S^j)$ and $\mathbf{F}_{\text{RF}}^j = \hat{\mathbf{F}}_{\text{RF}}^j / \text{abs}(\hat{\mathbf{F}}_{\text{RF}}^j)$.
 - 7: $\bar{\mathbf{F}}_{j,\text{opt}} = \mathbf{F}_{\text{RF}}^j \Sigma_F \mathbf{V}_F^*$, $\bar{\mathbf{V}}_j = [\bar{\mathbf{F}}_{j,\text{opt}}, \mathbf{V}_j(:, N_S^j + 1 : N_j)]$.
 - 8: $\tilde{\mathbf{H}}_j = \mathbf{U}_F \Sigma_j \bar{\mathbf{V}}_j^*$.
 - 9: Let $\tilde{\mathbf{H}}_j = \mathbf{G}_{au} \mathbf{H}_j$, obtain $\mathbf{G}_{au} = \tilde{\mathbf{H}}_j \mathbf{H}_j^* (\mathbf{H}_j \mathbf{H}_j^*)^{-1}$.
 - 10: Based on the MMSE criterion, obtain the fully digital combining matrix $\hat{\mathbf{W}}_{j,\text{opt}}$ and get $\mathbf{W}_{j,\text{opt}} = \hat{\mathbf{W}}_{j,\text{opt}} \mathbf{G}_{au}$.
 - 11: Operating SVD on $\mathbf{W}_{j,\text{opt}}$: $\mathbf{W}_{j,\text{opt}} = \mathbf{U}_r \Sigma_r \mathbf{V}_r^*$, where $\mathbf{U}_r = \{\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_{N_{BS}}\}$, $\Sigma_r = \text{diag}\{\sigma_1, \sigma_2, \dots, \sigma_{N_s}\}$ and $\mathbf{V}_r^* = \{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_{N_s}\}^*$.
 - 12: $\tilde{\mathbf{W}}_{\text{RF}}^j = [\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_{N_s}]$.
 - 13: $\mathbf{W}_{\text{RF}}^j = \tilde{\mathbf{W}}_{\text{RF}}^j / \text{abs}(\tilde{\mathbf{W}}_{\text{RF}}^j)$, $\mathbf{W}_{\text{BB}}^j = (\mathbf{W}_{\text{RF}}^{j*} \mathbf{W}_{\text{RF}}^j)^{-1} \mathbf{W}_{\text{RF}}^{j*} \mathbf{W}_{j,\text{opt}}$.
 - 14: Form the entire analog precoder by $\mathbf{F}_{\text{RF}} = [\mathbf{F}_{\text{RF}}^1, \mathbf{F}_{\text{RF}}^2, \dots, \mathbf{F}_{\text{RF}}^n]$.
 - 15: Construct the equivalent channel $\tilde{\mathbf{H}}_j = \mathbf{W}_{\text{RF}} \mathbf{H}_j \mathbf{F}_{\text{RF}}$, $j \in \{1, 2, \dots, n\}$.
 - 16: Form the entire multi-user equivalent channel by $\mathbf{H}_{eq} = [\tilde{\mathbf{H}}_1^T, \tilde{\mathbf{H}}_2^T, \dots, \tilde{\mathbf{H}}_m^T]^T$.
 - 17: Construct the complementary channel matrix $\bar{\mathbf{H}}_j = [\tilde{\mathbf{H}}_1^T, \dots, \tilde{\mathbf{H}}_{j-1}^T, \tilde{\mathbf{H}}_{j+1}^T, \dots, \tilde{\mathbf{H}}_m^T]^T$, $j \in \{1, 2, \dots, m\}$.
 - 18: Find the null space via $\bar{\mathbf{H}}_j = \bar{\mathbf{U}}_j \bar{\Sigma}_j [\bar{\mathbf{v}}_j^{(m-1)}, \bar{\mathbf{v}}_j]^*$ for $j \in \{1, 2, \dots, n\}$.
 - 19: Obtain the digital precoder $\mathbf{F}_{\text{BB}} = [\bar{\mathbf{v}}_1, \dots, \bar{\mathbf{v}}_m]$.
 - 20: **return** $\mathbf{F}_{\text{BB}}, \mathbf{F}_{\text{RF}}, \mathbf{W}_{\text{RF}}^j$ and $\mathbf{W}_{\text{BB}}^j$, $j \in \{1, 2, \dots, m\}$.
-

C. Computational Complexity Analysis

From *Algorithm 1*, it can be seen that the process of analog precoding for each user is similar to the single-user scenario in [10]. Hence, in the first stage, the most execution time is spent on the SVD and matrix inversion operations. Specifically, for each user, three times SVD operations and three times matrix inversions are needed. As the computational complexity of the SVD on $\mathbf{F}_{j,\text{opt}}$ and the pseudo-inverse on the intermediate channel matrix is $O(N_t^2 N_S^j)$ and $O(N_t^2 N_j)$, respectively, the total computational complexity of *Algorithm 1* in the first stage is $nO(N_t^3)$. In the second stage, the most time-costing operation is the SVD on the complementary channel matrix for each user, and its computational complexity is $O(N_t^2 N_{j,\text{all}})$, where $N_{j,\text{all}}$ denotes the total number of antennas of all users except user j . Hence, the total computational

complexity of the hybrid precoding scheme for multi-user is $nO(N_t^3) + O(N_t^2 N_{j,all})$. As total user antenna $N_{j,all}$ is usually less than N_t , the total computational complexity can be approximated as $nO(N_t^3)$.

IV. SIMULATION RESULTS

To validate the availability of the proposed hybrid precoding scheme, simulation results are presented in this section. Without loss of generality, the cluster-based channel model is adopted to describe the characteristic of the massive MIMO systems. In the simulations, the number of cluster is set as 4, the number of per cluster is set as 10, and all the rays are spread with Laplacian distributed azimuth and elevation angles of arrival and departure. Meanwhile, it is supposed that all the clusters and rays are equal in transmit power and the spread angle is 7.5° . Furthermore, it is also assumed that the sector angles of the transmitted signals in azimuth and elevation domain are 60° and 20° , respectively.

To facilitate comparison and highlight the superior performance of the proposed scheme, some benchmark hybrid precoding strategies are also presented. Meanwhile, both the simulation results for the scenarios $N_t = 64$, $N_r = 16$ and $N_t = 256$, $N_r = 64$ are presented to insight the impact of antenna array scale on the system spectral efficiency and computational complexity. Furthermore, to qualitatively show whether there is an optimal setting for different SNRs, the spectral efficiencies with varying SNRs are presented.

The achievable spectral efficiency with the varying SNRs are shown as Fig. 2 and Fig. 3 for scenarios $N_t = 64$, $N_r = 16$ and $N_t = 256$, $N_r = 64$, respectively.

From the simulation results, we can see that the spectral efficiency of all the hybrid precoding schemes is increasing monotonously with the varying SNR. The proposed scheme outperforms other existing schemes in spectral efficiency, and it is almost the same with that of fully digital precoding. Meanwhile, it also can be observed that the antenna scale of massive MIMO architecture is larger, the achievable spectral efficiency is higher.

With the varying number of paths, the sum spectral efficiencies are also simulated for scenarios $N_t = 64$, $N_r = 16$ and $N_t = 256$, $N_r = 64$, respectively. The simulation results are shown in Fig. 4 and Fig. 5, from which it can be seen the proposed scheme can always obtain higher spectral efficiency than other existing scheme, and it is also better than that of fully digital precoding when the number of paths is more than 5 for the scenario $N_t = 64$, $N_r = 16$. As the proposed scheme combines the precoding at the transmitter and the combining at the receiver jointly, which does not depend on the fully digital precoding matrix, the achievable spectral efficiency is larger than that of fully digital scheme.

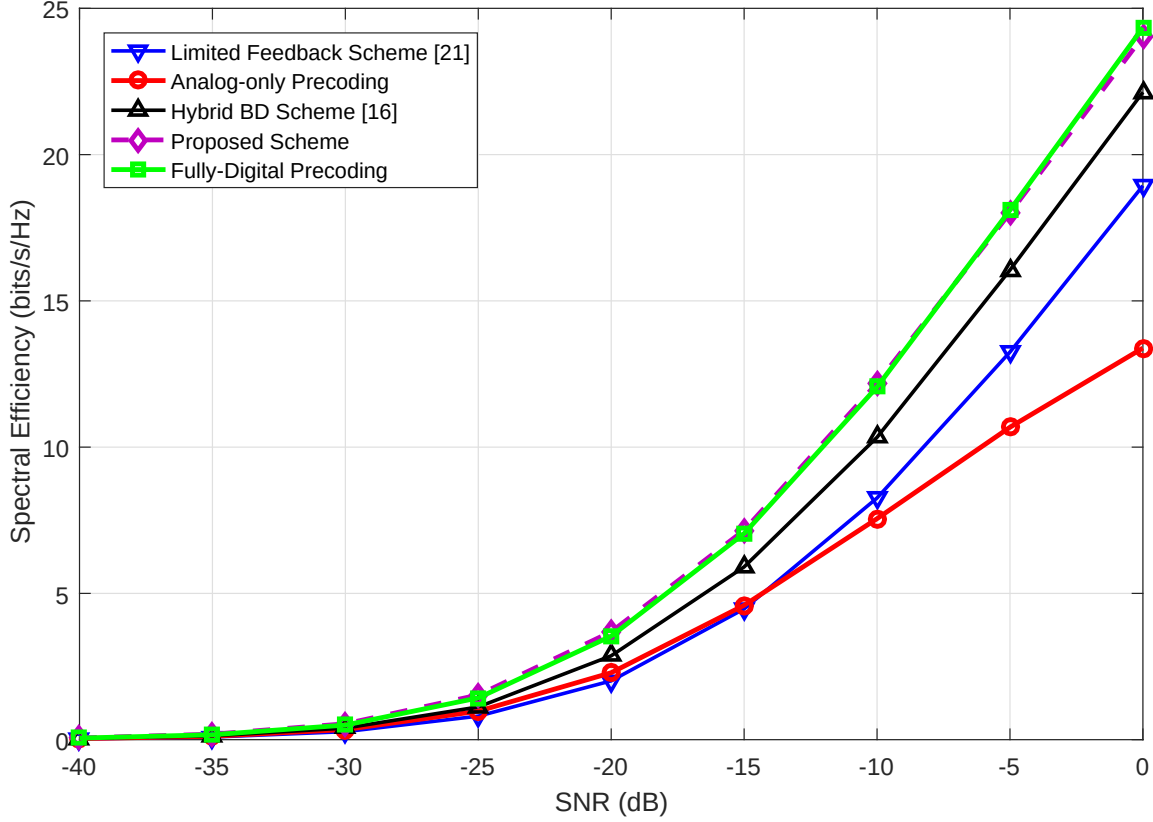


Fig. 2: The average achievable capacity of uplink versus the transmit power on the condition $N_b = 128$, $N_r = 24$, $N_u = 10$, $b_u = 3$ bit.

We can also see that though the spectral efficiency of all the hybrid precoding is decreasing with the increase path number, the decreasing rate of our proposed scheme is the slowest one. Hence, our proposed hybrid precoding scheme can be applicable to both sparse and dense scatter scenarios.

V. CONCLUSION

We have proposed a hybrid precoding scheme for massive MIMO systems with multiple users based on the concept of equivalent channel in this paper. The design of analog phase-shifters at the transmitter and the receiver are combined jointly to maximize the achievable spectral efficiency individually for each user. Then, the baseband digital precoding in the block diagonalization method is used to suppress the interference among users. Hybrid precoding for multi-user massive MIMO systems are implemented with superior performance in spectral efficiency. The simulation results show that the proposed scheme outperforms other existing strategies in spectral efficiency.

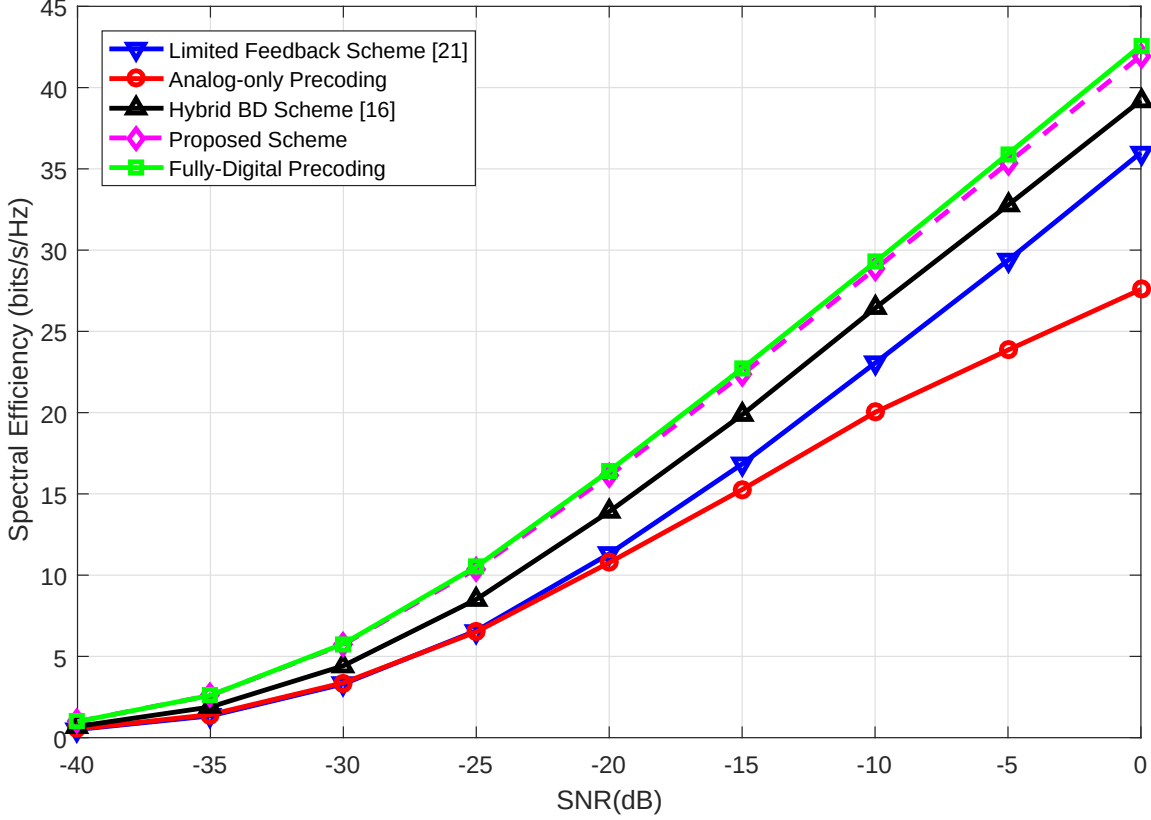


Fig. 3: The average achievable capacity of uplink versus the transmit power on the condition $N_b = 128$, $N_r = 24$, $N_u = 10$, $b_u = 3$ bit.

VI. DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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VII. DECLARATIONS

This work was supported in part by the National Natural Science Foundation of China (61771414), the Natural Science Foundation of Hunan Province of China (2021JJ30737, 2021JJ50126) and the key project of education bureau of Hunan province (20A016, 21A0083).

We declare that we do not have any commercial or associative interest conflict with it.

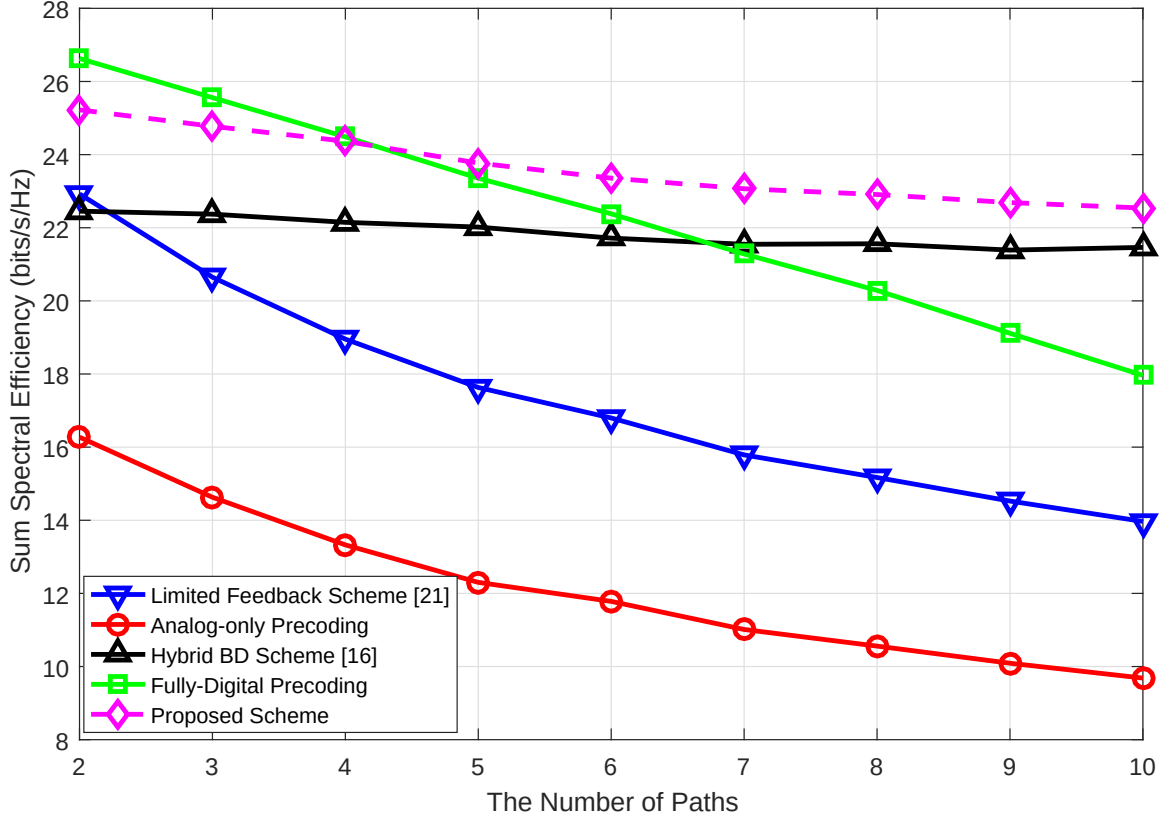


Fig. 4: The average achievable capacity of uplink versus the transmit power on the condition $N_b = 128$, $N_r = 24$, $N_u = 10$, $b_u = 3$ bit.

The data sets supporting the results of this article are included within the article.

No code is available in the state of the article being submitted.

The algorithm in this article is proposed and the article is written by Shiguo Wang and Yun Zhao. The simulation of the algorithm is implemented by Liang Wang and Yinshuang Ma. Prof. Peng Li is responsible for checking and modifying the article before it being submitted.

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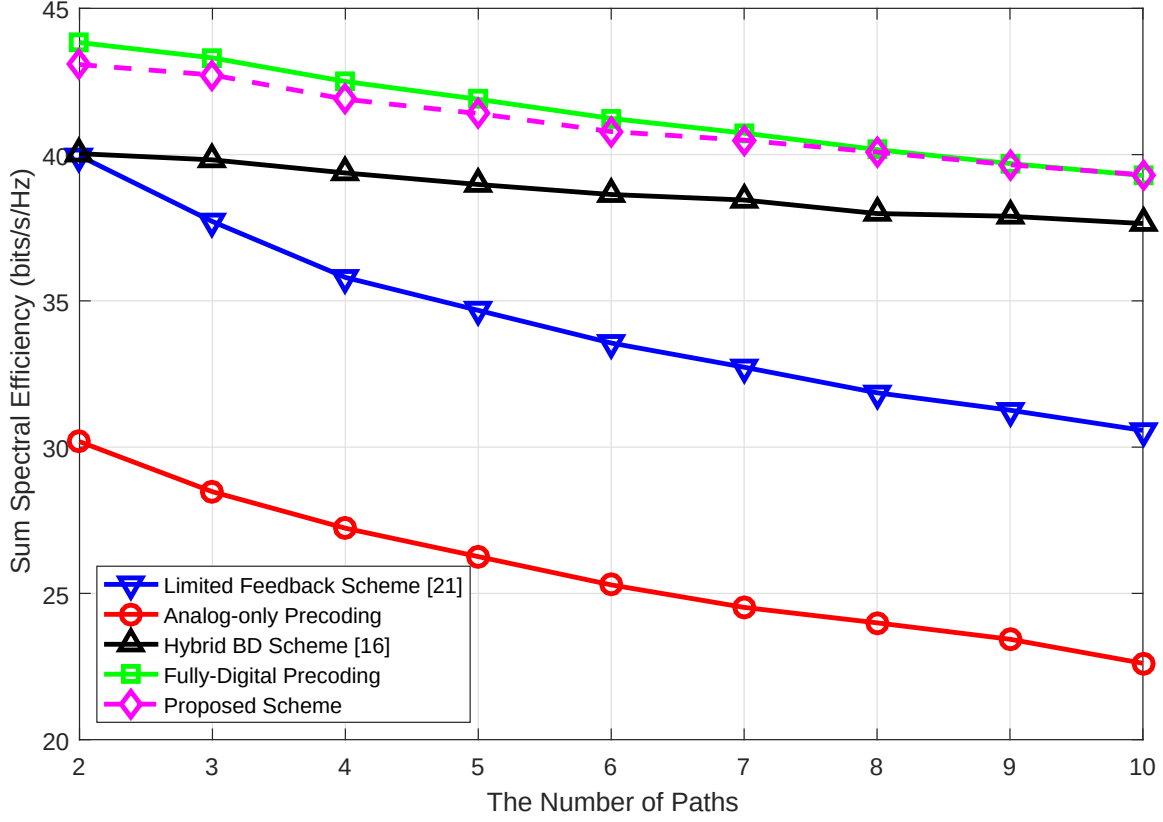


Fig. 5: The average achievable capacity of uplink versus the transmit power on the condition $N_b = 128$, $N_r = 24$, $N_u = 10$, $b_u = 3$ bit.

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