IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received March 15, 2018, accepted April 17, 2018, date of publication April 23, 2018, date of current version May 16, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2828979

Enhanced CSI Acquisition for FDD Multi-User Massive MIMO Systems

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ABSTRACT Massive multiple-input multiple-output (MIMO) is envisioned to meet the growing spectral efficiency (SE) requirement in next generation cellular systems. However, it has been recognized that the unaffordable channel state information reference signal (CSI-RS) overhead required for acquiring CSI is a major challenge in frequency division duplexing (FDD) massive MIMO systems. To tackle the challenge of this CSI-RS overhead limitation, certain attempts, which have been designed for the scenarios with dispersive locations of users and sparse nature of channels, suffer from inaccurate channel estimation when the nature of channels for different users becomes highly correlated and rich. In this paper, we propose an enhanced CSI acquisition scheme for FDD multi-user massive MIMO systems, which exploits beamformed CSI-RS transmission mechanism to reduce the CSI-RS overhead. We present two limited feedback algorithms which provide different tradeoffs between system performance and CSI feedback overhead, where the multistage CSI acquisition strategy is adopted to avoid prohibitive computational complexity and amount of feedback requirement. The simulation results show that our CSI acquisition scheme, without additional CSI-RS overhead and enormous CSI feedback overhead, achieves higher SE performance as compared to conventional scheme.

INDEX TERMS Massive MIMO, CSI-RS, feedback, SE.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) technology has been demonstrated to be effective in improving system capacity and link reliability in wireless networks [1]. Recently, research trends are moving toward massive MIMO systems, where the base station (BS) is equipped with a large number of antennas [2]. Since the advantages in increasing the spectral efficiency (SE) and energy efficiency as well as simplifying signal processing, massive MIMO is considered as a promising technology for next generation wireless systems [3].

Achieving the aforementioned potential gains of massive MIMO in practical systems hinges on the sufficient accuracy of channel state information (CSI) at the BS. In time division duplexing (TDD) massive MIMO systems, the uplink training enables CSI acquisition by exploiting channel reciprocity [4]–[6]. Nevertheless, with the growth of users number, TDD mode incurs a serious problem, referred to as pilot contamination induced by the reuse of uplink training signals, which leads to severe multi-user interference causing degraded system performance [7], [8]. A straightforward way to circumvent this difficult is by adopting the frequency division duplexing (FDD) mode. In FDD systems, since channel reciprocity is unavailable between uplink channel and downlink channel, the CSI acquisition consists of two stages, including downlink channel estimation and uplink CSI feedback. First, the CSI reference signals (CSI-RSs) are transmitted by BS, and each user estimates its own channel based on the CSI-RS observation. Then, each user sends the estimated CSI to BS through a feedback link [9], [10]. However, as the number of antennas at the BS increases, the CSI-RS overhead for direct estimation of downlink channel becomes overwhelming, since which is proportional to the number of antennas at the BS. In addition, the overhead of CSI feedback is prohibitive for the feedback link due to the same reason. Such overly high CSI-RS overhead and CSI feedback overhead leads to difficult implementation of massive MIMO in FDD mode, there is thus the need for the design of efficient CSI acquisition scheme, with limited CSI-RS overhead and CSI feedback overhead, for multi-user massive MIMO systems operating on FDD mode.

Several research works have attempted to address such challenges in massive MIMO scenarios. In view of the fact that the deployment of a uniform planar array (UPA) with a large number of antennas at the BS typically leads to spatially correlated channel, an approach based on a non-beamformed CSI-RS transmission mechanism is proposed to reduce both the CSI-RS overhead and CSI feedback overhead in [11], two sets of CSI-RSs are transmitted from one column and one row of antennas, respectively, where each CSI-RS port is mapped to one antenna. Nevertheless, the system performance degrades significantly due to the inaccurate channel estimation. In [12], enabled by the beamformed CSI-RS transmission mechanism, a set of CSI-RSs is transmitted on the whole antenna array, in which each CSI-RS port is mapped to one column of antennas and the CSI-RSs transmitted on different columns of antennas are precoded with different beamforming vectors in a predefined codebook, which leads to significant reduction in the CSI-RS overhead since the CSI-RS overhead becomes proportional to the number of beamforming vectors instead of the BS antenna array size. In [13], Liu *et al.* develop a sophisticated beamformed CSI-RS transmission mechanism which transmits multiple sets of CSI-RSs on whole antenna array, where each CSI-RS port is mapped to one column of antennas, and the CSI-RSs in different sets, transmitted on same column, are precoded with different beamforming vectors in a predefined codebook such that multiple beam indexes corresponding to different columns are needed to be fed back to BS. Hence, the problem of uplink CSI feedback becomes even more challenging due to the large amount of feedback requirements. Motivated by this, in [14], a simplified CSI acquisition scheme is proposed to reduce the CSI feedback overhead, where each CSI-RS port is mapped to one column of antennas, and different sets of CSI-RSs are precoded with different beamforming vectors in a predefined codebook while the CSI-RSs in each set transmitted on different columns of antennas are precoded with same beamforming vector. With the feedback of only one beam index for vertical dimension, it will be shown a considerable reduction in CSI feedback overhead can be achieved.

A. MOTIVATION AND CONTRIBUTIONS

Nonetheless, the conventional CSI acquisition scheme described in [14], which has been designed through beam selection, works well under the assumption of dispersive location of users and sparse nature of channels. However, in practical scenarios, the conventional CSI acquisition scheme encounters a serious problem when the channels of several users are highly correlated, due to the fact that same beamforming vector can be selected to serve those users. This eventually causes severe multi-user interference and hence degrades the system performance. Furthermore, in the propagation environment with rich scattering channels, in view of fact that the propagation characteristic of rich scattering channel cannot be effectively captured by the selected one beamforming vector, significant performance improvement would not be achieved when the size of predefined codebook increases beyond a certain value.

Motivated by these observations, in this paper, we propose an enhanced CSI acquisition scheme, aiming to handle the multi-user interference and capture the propagation characteristic of the rich scattering channel. Main contributions are summarized as follows:

1) We propose a separated design of vertical and horizontal processing framework that enables a reduced computational complexity.
2) We present two limited feedback algorithms that provide different trade-offs between system performance and CSI feedback overhead, in which the processes of the two presented algorithms are divided into multiple stages, including multiple wideband beamforming vectors selection and subband combination coefficients calculation, to achieve significant system SE improvement and avoid prohibitive amount of feedback requirement.
3) We analyze the cell average SE of two presented algorithms based on simulation results, and compare them with the conventional CSI acquisition scheme.

B. ORGANIZATION

The rest of this paper is organized as follows. Section II introduces the system model. In Section III, the problem statement of the multi-cell multi-user system and motivation for the proposed scheme are described. Section IV proposes the enhanced CSI acquisition scheme, and presents two limited feedback algorithms based on multi-stage strategy. The simulation results are given in Section V. Finally, Section VI concludes this paper.

Notation: We use the following notation throughout this paper. $\boldsymbol{A}$ is a matrix, $\boldsymbol{a}$ is a column vector, a is a scalar, and $\mathcal{A}$ is a set. The superscripts $(\cdot)^T$ and $(\cdot)^H$ are the transpose and conjugate transpose operations, respectively. $\|\boldsymbol{A}\|_F$ is the Frobenious norm of $\boldsymbol{A}$, $\|\boldsymbol{a}\|_2$ is the 2-norm of $\boldsymbol{a}$, and $[\boldsymbol{a}]_i$ is the ith entry of $\boldsymbol{a}$. $\lceil\cdot\rceil$ is the round up integer operation. $\mathbb{C}$ is the field of complex numbers. $\otimes$ and $E\{\cdot\}$ denote the Kronecker product and expectation operations, respectively. Finally, $\boldsymbol{0}_{M\times N}$ and $\boldsymbol{I}_M$ are an $M \times N$ matrix composed of all-zeros and an $M \times M$ identity matrix, respectively.

II. SYSTEM MODEL

Consider a multi-cell multi-user massive MIMO system with L cells, each of which consists of three sectors, and the orthogonal frequency division multiplexing with N_W subcarriers is utilized. In each sector, a BS equipped with dual-polarized UPA of M antennas, which has M_H antennas in horizontal dimension with same polarization and M_V antennas in vertical dimension, is employed to serve K users, each of which processes single data stream with N antennas, as illustrated in Fig. 1. For the user k served by the BS l, the received signal on the ith subcarrier can be

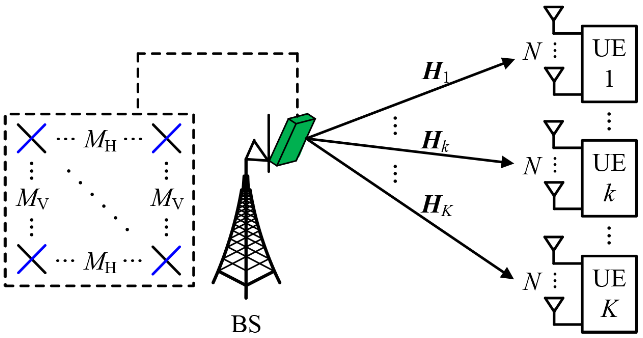

FIGURE 1. System model of a multi-user massive MIMO system.

written as

$$y_{l,k}[i] = H_{l,k}[i]W_l[i]x_l[i] + \sum_{l'=1,l'\neq l}^{3L} H_{l',k}[i]W_{l'}[i]x_{l'}[i] + n_{l,k}[i], \quad (1)$$

where $H_{l,k}[i]$ of size $N \times M$ is the channel matrix between the BS l and the user k on the ith subcarrier, $W_l[i] = [w_{l,1}[i], w_{l,2}[i], \ldots, w_{l,K}[i]]$ is the $M \times K$ beamforming matrix for K users served by the BS l on the ith subcarrier, $x_l[i] = [x_{l,1}[i], x_{l,2}[i], \ldots, x_{l,K}[i]]^T \in \mathbb{C}^{K\times 1}$ is the transmitted signal vector at the BS l on the ith subcarrier with $E\{x_l[i]x_l^H[i]\} = (P_T/KN_W)I_K$, where P_T is the transmit power at the BS, and $n_{l,k}[i] \in \mathbb{C}^{N\times 1}$ is the additive white Gaussian noise vector on the ith subcarrier with $E\{n_{l,k}[i]n_{l,k}^H[i]\} = \sigma^2 I_N$.

III. PROBLEM STATEMENT AND MOTIVATION

The objective of this paper is to design the beamforming vectors to maximize the cell average SE of the system. This problem can be formulated as

$$\left\{\left\{\left\{w_{l,k}^*[i]\right\}_{k=1}^{K}\right\}_{l=1}^{3L}\right\}_{i=1}^{N_W} = \arg\max \sum_{i=1}^{N_W}\sum_{l=1}^{3L}\sum_{k=1}^{K} \log_2\left(1+\gamma_{l,k}[i]\right),$$
$$s.t.\ \left\|w_{l,k}[i]\right\|_2^2 = 1, \quad (2)$$

where $\gamma_{l,k}[i]$ is the received signal-to-interference-plus-noise-ratio (SINR) at the user k served by the BS l on the ith subcarrier defined as (3), at the bottom of this page, where $a_{l,k}[i]$ is the linear combiner at the user k served by the BS l on the ith subcarrier.

Direct estimation of the downlink channel will not only entail excessive CSI-RS overhead but also be computationally demanding. With a large number of antennas packed in a small physical space, the spatial channel tends to be correlated [5]. In addition, considering the antenna architecture, the spatially correlated channel can be divided into two dimensions, including vertical and horizontal dimensions. According to [15], the spatial correlation matrix of such antenna deployment can be obtained through the Kronecker product of the spatial correlation matrices in horizontal and vertical dimensions. Mathematically, let $R_{l,k}[i] = H_{l,k}^H[i]H_{l,k}[i]$ represent the correlation matrix of the user k served by the BS l on the ith subcarrier, which can be expressed as

$$R_{l,k}[i] = R_{l,k,H}[i] \otimes R_{l,k,V}[i], \quad (4)$$

where $R_{l,k,H}[i]$ and $R_{l,k,V}[i]$ denote the horizontal and vertical correlation matrices of the user k served by the BS l on the ith subcarrier, respectively.

Thus, the problem in (2) can be equivalently written as

$$\left\{\left\{\left\{b_{l,k}^*[i], f_{l,k}^*[i]\right\}_{k=1}^{K}\right\}_{l=1}^{3L}\right\}_{i=1}^{N_W} = \arg\max \sum_{i=1}^{N_W}\sum_{l=1}^{3L}\sum_{k=1}^{K} \log_2\left(1+\gamma_{l,k}[i]\right),$$
$$s.t.\ \left\|b_{l,k}[i] \otimes f_{l,k}[i]\right\|_F^2 = 1, \quad (5)$$

where $b_{l,k}[i]$ and $f_{l,k}[i]$ denote the horizontal and vertical beamforming vectors for the user k served by the BS l on the ith subcarrier, respectively.

The problem of SE maximization in (5) involves joint optimization over the horizontal and vertical beamforming vectors, however, with prohibitively high computational complexity. Therefore, this paper considers the separated design of vertical and horizontal processing instead, which achieves satisfying improvement in the system performance without involving a large number of iterative procedures. First, we focus on the vertical beamforming vector design, regardless of the value of horizontal beamforming vector. Then, we seek to design the horizontal beamforming vector based on the already designed vertical beamforming vector accordingly.

The additional challenge in solving (5) is to enable the efficient operation of the limited feedback. The codebook-based feedback is utilized for the separated beamforming vectors design, each with different constraints. In [14], one discrete Fourier transform codebook $\mathcal{F}$ is adopted for the vertical dimension, while for the horizontal dimension, a codebook $\mathcal{B}$ described in [16] is used. As a result, the conventional CSI

$$\gamma_{l,k}[i] = \frac{\left\|a_{l,k}^H[i]H_{l,k}[i]w_{l,k}[i]\right\|_2^2}{\sum_{k'\neq k}\left\|a_{l,k}^H[i]H_{l,k}[i]w_{l,k'}[i]\right\|_2^2 + \sum_{l'\neq l}\left\|a_{l,k}^H[i]H_{l',k}[i]W_{l'}[i]\right\|_F^2 + \frac{KN_W\sigma^2}{P_T}\left\|a_{l,k}[i]\right\|_2^2}, \quad (3)$$

acquisition scheme simplifies the problem in (5) by selecting two beamforming vectors from the predefined codebook $\mathcal{F}$ and $\mathcal{B}$, respectively, and neglecting the multipath effect, which can be formulated as

$$\left\{\left\{\{\boldsymbol{b}^*_{l,k}[i], \boldsymbol{f}^*_{l,k}[i]\}_{k=1}^{K}\right\}_{l=1}^{3L}\right\}_{i=1}^{N_W} = \arg\max \sum_{i=1}^{N_W}\sum_{l=1}^{3L}\sum_{k=1}^{K} \log_2\left(1+\gamma_{l,k}[i]\right), \quad s.t.\ \boldsymbol{f}_{l,k}[i] \in \mathcal{F}, \quad \boldsymbol{b}_{l,k}[i] \in \mathcal{B}. \tag{6}$$

Although the conventional CSI acquisition scheme is capable of capturing the dominant paths in the spatial channels, it fails to mitigate the multi-user interference and increase considerable received power of several users when the propagation paths of those users are highly correlated in rich scattering environment, since the same beamforming vector may be selected to serve those users and propagation characteristic of the reflection paths is neglected by the selected beamforming vector.

IV. PROPOSED SCHEME

Given the spatial channel in [17], downlink channel estimation is equivalent to estimating the different parameters of propagation paths, namely the angle of arrival, angle of departure and gain of each path. Our enhanced CSI acquisition scheme expands the selected beamforming vectors of each user to the light-of-sight path and the reflection paths, which leads to significant system SE improvement.

It has been recognized that the number of CSI-RSs grows with the number of antennas at the BS such that CSI-RS overhead becomes overwhelming for massive MIMO systems, which motivates the design of CSI acquisition scheme with high channel estimation accuracy and limited CSI-RS overhead. Inspired by the beamformed CSI-RS transmission mechanism which maps to one CSI-RS port to antennas in one column [14], we develop the methodology that acquires accurate CSI and maintains acceptable CSI feedback overhead for multi-user massive MIMO systems.

The procedure of the proposed CSI acquisition scheme is described in Fig. 2. For the downlink channel estimation, multiple sets of cell-specific beamformed CSI-RSs are first transmitted from BS, where different sets of CSI-RSs are precoded with different beamforming vectors in the predefined codebook $\mathcal{F}$ with size N_V. In each set of CSI-RSs, each column of antennas is assigned to one CSI-RS port by precoding different columns of antennas with same beamforming vector. Mathematically, in the nth set of CSI-RSs, the equivalent horizontal channel matrix between $2M_H$ CSI-RS ports at the BS l and the user k on the ith subcarrier can be written as

$$\bar{\boldsymbol{H}}^n_{l,k}[i] = \left[\boldsymbol{H}^1_{l,k}[i]\boldsymbol{f}_n, \boldsymbol{H}^2_{l,k}[i]\boldsymbol{f}_n, \ldots, \boldsymbol{H}^{2M_H}_{l,k}[i]\boldsymbol{f}_n\right] = \boldsymbol{H}_{l,k}[i]\left[\boldsymbol{I}_{2M_H} \otimes \boldsymbol{f}_n\right], \tag{7}$$

where $\boldsymbol{H}^m_{l,k}[i]$ of size $N \times M_V$ denotes the channel matrix between the antennas in mth column of BS l and the user k on the ith subcarrier, and $\boldsymbol{f}_n$ is the nth beamforming vector in the predefined codebook $\mathcal{F}$, given by

$$\boldsymbol{f}_n = \frac{1}{\sqrt{M_V}}[1, e^{j2\pi n/N_V}, \ldots, e^{j2\pi(M_V-1)n/N_V}]^T. \tag{8}$$

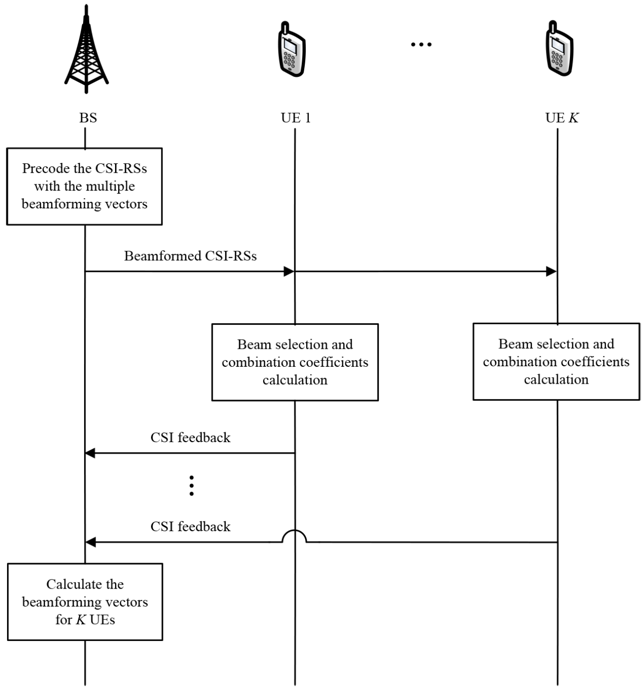

FIGURE 2. Procedure of the proposed CSI acquisition scheme.

Due to the prohibitive amount of feedback requirement and computational complexity, the multi-stage CSI acquisition strategy is adopted. We first select multiple beamforming vectors from the predefined codebook, and wideband feedback is assumed to enable the efficient operation of limited CSI feedback, then calculate the subband combination coefficients based on the selected beamforming vectors. In the following subsections, we present two limited CSI feedback algorithms that provide different trade-offs between CSI feedback overhead and system performance. For the sake of simplicity, we omit the indexes of BS and user for the selected beamforming vector.

A. ALGORITHM 1

The process of algorithm 1 could be divided into five stages, i.e.,

1) Multiple wideband vertical beamforming vectors selection.
2) Subband vertical combination coefficients calculation.
3) Equivalent horizontal channel estimation for the reported vertical beamforming vector.
4) Multiple wideband horizontal beamforming vectors selection based on the equivalent horizontal channel.
5) Subband horizontal combination coefficients calculation.

1) STAGE 1

Based on the transmitted N_V sets of CSI-RSs, each user estimates the corresponding equivalent horizontal channel matrices and selects the optimal vertical beamforming vector that maximizes the received signal power on N_W subcarriers, which can be formulated as

$$f_1 = \arg\max_{n\in\{1,2,\ldots,N_V\}} \sum_{i=1}^{N_W}\sum_{m=1}^{2M_H} \left\|\boldsymbol{H}_{l,k}^{m}[i]\boldsymbol{f}_n\right\|_2. \quad (9)$$

Then, the similar beam selection method described above can be reused to select other $Q_V - 1$ vertical beamforming vectors. Consequently, for the user k served by the BS l, all selected vertical beamforming vectors can be formed as

$$\boldsymbol{F}_{l,k} = \left[\boldsymbol{f}_{f_1}, \boldsymbol{f}_{f_2}, \ldots, \boldsymbol{f}_{f_{Q_V}}\right]. \quad (10)$$

2) STAGE 2

Each user groups the estimated equivalent horizontal channel matrices for all selected Q_V vertical beamforming vectors together, and calculates the vertical combination vectors on the different subbands with N_S subcarriers per subband using eigenvalue decomposition. Let $\bar{\boldsymbol{R}}_{l,k}[j] = E\{\left(\boldsymbol{H}_{l,k}^{m}[i]\boldsymbol{F}_{l,k}\right)^H \boldsymbol{H}_{l,k}^{m}[i]\boldsymbol{F}_{l,k}\}$ for $1 \le m \le 2M_H$ and $(j-1)N_S + 1 \le i \le \min\{jN_S, N_W\}$ denote the vertical correlation matrix of the user k served by the BS l on $2M_H$ CSI-RS ports and the jth subband, which can be decomposed as

$$\bar{\boldsymbol{R}}_{l,k}[j] = \bar{\boldsymbol{U}}_{l,k}[j]\bar{\boldsymbol{A}}_{l,k}[j]\bar{\boldsymbol{U}}_{l,k}^{H}[j], \quad 1 \le j \le \left\lceil \frac{N_W}{N_S} \right\rceil, \quad (11)$$

where $\bar{\boldsymbol{U}}_{l,k}[j] = [\bar{\boldsymbol{u}}_{l,k,1}[j], \bar{\boldsymbol{u}}_{l,k,2}[j], \ldots, \bar{\boldsymbol{u}}_{l,k,Q_V}[j]] \in \mathbb{C}^{Q_V\times Q_V}$ and $\bar{\boldsymbol{A}}_{l,k}[j] = diag\left\{\bar{\lambda}_{l,k}^{1}[j], \bar{\lambda}_{l,k}^{2}[j], \ldots, \bar{\lambda}_{l,k}^{Q_V}[j]\right\}$ is composed of the eigenvalues of $\bar{\boldsymbol{R}}_{l,k}[j]$ in descending order. Thus, for the user k served by the BS l, the vertical combination vector on the jth subband can be expressed as

$$\boldsymbol{c}_{l,k,V}[j] = \frac{\bar{\boldsymbol{u}}_{l,k,1}[j]}{\left[\bar{\boldsymbol{u}}_{l,k,1}[j]\right]_1}, \quad 1 \le j \le \left\lceil \frac{N_W}{N_S} \right\rceil. \quad (12)$$

Then, other $Q_V - 1$ entries of $c_{l,k,V}[j]$ are quantized utilizing N_Q bits for each entry.

3) STAGE 3

According to (10) and (12), the reported vertical beamforming vector on the ith subcarrier can be written as

$$\hat{\boldsymbol{f}}_{l,k}[i] = \boldsymbol{F}_{l,k}\hat{\boldsymbol{c}}_{l,k,V}[j], \quad 1 \le j \le \left\lceil \frac{N_W}{N_S} \right\rceil,$$
$$(j-1)N_S + 1 \le i \le \min\{jN_S, N_W\}, \quad (13)$$

where $\hat{\boldsymbol{c}}_{l,k,V}[j]$ is the quantized vertical combination vector for the user k served by the BS l on the jth subband. However, there is a mismatch between the reported vertical beamforming vector and the selected vertical beamforming vectors in the stage 1, which leads to significant difference between the equivalent horizontal channel for the reported vertical beamforming vector and the equivalent horizontal channels estimated by the selected vertical beamforming vectors. In this case, we derive a property of algorithm 1.

Proposition 1: The equivalent horizontal channel for the reported vertical beamforming vector can be obtained by combining the equivalent horizontal channels estimated by the selected vertical beamforming vectors.

Proof: From (7) and (13), and defining $\hat{\boldsymbol{H}}_{l,k}[i]$ as the equivalent horizontal channel matrix for $\hat{\boldsymbol{f}}_{l,k}[i]$, we have

$$\begin{aligned}
&\hat{\boldsymbol{H}}_{l,k}[i] \\
&= \left[\boldsymbol{H}_{l,k}^{1}[i]\hat{\boldsymbol{f}}_{l,k}[i], \boldsymbol{H}_{l,k}^{2}[i]\hat{\boldsymbol{f}}_{l,k}[i], \ldots, \boldsymbol{H}_{l,k}^{2M_H}[i]\hat{\boldsymbol{f}}_{l,k}[i]\right] \\
&= \left[\boldsymbol{H}_{l,k}^{1}[i]\boldsymbol{F}_{l,k}\hat{\boldsymbol{c}}_{l,k,V}[j], \boldsymbol{H}_{l,k}^{2}[i]\boldsymbol{F}_{l,k}\hat{\boldsymbol{c}}_{l,k,V}[j], \ldots, \boldsymbol{H}_{l,k}^{2M_H}[i]\right. \\
&\quad \left.\boldsymbol{F}_{l,k}\hat{\boldsymbol{c}}_{l,k,V}[j]\right] \\
&= \bar{\boldsymbol{H}}_{l,k}^{f_1}[i] + \left[\hat{\boldsymbol{c}}_{l,k,V}[j]\right]_2 \bar{\boldsymbol{H}}_{l,k}^{f_2}[i] + \ldots + \left[\hat{\boldsymbol{c}}_{l,k,V}[j]\right]_{Q_V} \bar{\boldsymbol{H}}_{l,k}^{f_{Q_V}}[i].
\end{aligned} \quad (14)$$

Accordingly, the presented algorithm 1 would not transmit an additional set of CSI-RSs precoded by the reported vertical beamforming vector such that the increase of CSI-RS overhead is avoidable.

4) STAGE 4

Considering the dual-polarized antenna architecture, (14) can be rewritten as

$$\hat{\boldsymbol{H}}_{l,k}[i] = [\hat{\boldsymbol{H}}_{l,k}^{1}[i], \hat{\boldsymbol{H}}_{l,k}^{2}[i]], \quad (15)$$

where $\hat{\boldsymbol{H}}_{l,k}^{1}[i]$ and $\hat{\boldsymbol{H}}_{l,k}^{2}[i]$ are the $N \times M_H$ equivalent horizontal channel matrices in the first and second polarizations for the user k served by the BS l on the ith subcarrier, respectively. Here, a predefined codebook $\mathcal{D}$ with size $M_H O_H$ is adopted for the single-polarized uniform linear array, where O_H is the oversampling factor. Let $\boldsymbol{d}_m$ denote the mth beamforming vector in the predefined codebook $\mathcal{D}$, given by

$$\boldsymbol{d}_m = \frac{1}{\sqrt{M_H}}[1, e^{j2\pi m/M_H O_H}, \ldots, e^{j2\pi(M_H-1)m/M_H O_H}]^T. \quad (16)$$

First, each user scans all beamforming vectors in the predefined codebook $\mathcal{D}$ and selects the optimal one that maximizes the received signal power on N_W subcarriers. Meanwhile, same horizontal beamforming vector is selected for another polarization to further reduce CSI feedback overhead, which can be formulated as

$$d_1 = \arg\max_{m\in\{1,2,\ldots,M_H O_H\}} \sum_{i=1}^{N_W} \left(\left\|\hat{\boldsymbol{H}}_{l,k}^{1}[i]\boldsymbol{d}_m\right\|_2 + \left\|\hat{\boldsymbol{H}}_{l,k}^{2}[i]\boldsymbol{d}_m\right\|_2\right). \quad (17)$$

Afterwards, we restrict the searching space with size $M_H - 1$, where each beamforming vector in the restricted searching space is orthogonal to the $\boldsymbol{d}_{d_1}$. Then, the similar beam selection method described above can be reused to select other $Q_H - 1$ horizontal beamforming vectors. Consequently, for the user k served by the BS l, all selected horizontal beamforming vectors can be formed as

$$\boldsymbol{D}_{l,k} = \boldsymbol{I}_2 \otimes \left[\boldsymbol{d}_{d_1}, \boldsymbol{d}_{d_2}, \ldots, \boldsymbol{d}_{d_{Q_H}}\right]. \tag{18}$$

5) STAGE 5

Each user calculates the horizontal combination vectors on the different subbands using eigenvalue decomposition. Let $\hat{\boldsymbol{R}}_{l,k}[j] = E\left\{\hat{\boldsymbol{H}}^H_{l,k}[i]\hat{\boldsymbol{H}}_{l,k}[i]\right\}$ for $(j-1)N_S + 1 \leq i \leq \min\{jN_S, N_W\}$ denote the equivalent horizontal correlation matrix of the user k served by the BS l on the jth subband, which can be decomposed as

$$\hat{\boldsymbol{R}}_{l,k}[j] = \hat{\boldsymbol{U}}_{l,k}[j]\hat{\boldsymbol{\Lambda}}_{l,k}[j]\hat{\boldsymbol{U}}^H_{l,k}[j], \quad 1 \leq j \leq \left\lceil \frac{N_W}{N_S} \right\rceil, \tag{19}$$

where $\hat{\boldsymbol{U}}_{l,k}[j] = [\hat{\boldsymbol{u}}^1_{l,k}[j], \hat{\boldsymbol{u}}^2_{l,k}[j], \cdots, \hat{\boldsymbol{u}}^{2M_H}_{l,k}[j]] \in \mathbb{C}^{2M_H \times 2M_H}$ and $\hat{\boldsymbol{\Lambda}}_{l,k}[j] = diag\left\{\hat{\lambda}^1_{l,k}[j], \hat{\lambda}^2_{l,k}[j], \ldots, \hat{\lambda}^{2M_H}_{l,k}[j]\right\}$ is composed of the eigenvalues of $\hat{\boldsymbol{R}}_{l,k}[j]$ in descending order. Thus, for the user k served by the BS l, the horizontal combination vector on the jth subband can be expressed as

$$\boldsymbol{c}_{l,k,H}[j] = \frac{\boldsymbol{D}^H_{l,k}\hat{\boldsymbol{u}}^1_{l,k}[j]}{\left[\boldsymbol{D}^H_{l,k}\hat{\boldsymbol{u}}^1_{l,k}[j]\right]_1}, \quad 1 \leq j \leq \left\lceil \frac{N_W}{N_S} \right\rceil. \tag{20}$$

Then, other $2Q_H - 1$ entries of $\boldsymbol{c}_{l,k,H}[j]$ are quantized utilizing N_Q bits for each entry.

B. ALGORITHM 2

The process of algorithm 2 could be divided into four stages, i.e.,

1) Multiple wideband vertical beamforming vectors selection.
2) Multiple wideband horizontal beamforming vectors selection based on equivalent horizontal channels estimated by the selected vertical beamforming vectors.
3) Subband horizontal combination coefficients calculation.
4) Subband whole combination coefficients calculation.

1) STAGE 1

Similar to stage 1 in algorithm 1, with the exception that Q_V is replaced by Q.

2) STAGE 2

Consists of Q iterations, each of which is similar to stage 4 in algorithm 1. In each iteration, only one horizontal beamforming vector is selected based on the equivalent horizontal channel estimated by the selected one vertical beamforming vector.

3) STAGE 3

Consists of Q iterations, each of which is similar to stage 5 in algorithm 1. In each iteration, the exception that Q_H is replaced by 1.

4) STAGE 4

Each user groups the equivalent channel matrices for all selected beamforming vectors together as

$$\tilde{\boldsymbol{R}}_{l,k}[j] = E\{\left(\boldsymbol{H}_{l,k}[i]\tilde{\boldsymbol{B}}_{l,k}[j]\right)^H \boldsymbol{H}_{l,k}[i]\tilde{\boldsymbol{B}}_{l,k}[j]\}, \quad 1 \leq j \leq \left\lceil \frac{N_W}{N_S} \right\rceil, \tag{21}$$

where $\tilde{\boldsymbol{B}}_{l,k}[j]$ of size $M \times Q$ is the beamforming matrix contains all selected beamforming vectors for the user k served by the BS l on the jth subband. Using eigenvalue decomposition, $\tilde{\boldsymbol{R}}_{l,k}[j]$ can be decomposed as

$$\tilde{\boldsymbol{R}}_{l,k}[j] = \tilde{\boldsymbol{U}}_{l,k}[j]\tilde{\boldsymbol{\Lambda}}_{l,k}[j]\tilde{\boldsymbol{U}}^H_{l,k}[j], \quad 1 \leq j \leq \left\lceil \frac{N_W}{N_S} \right\rceil, \tag{22}$$

where $\tilde{\boldsymbol{U}}_{l,k}[j] = [\tilde{\boldsymbol{u}}^1_{l,k}[j], \tilde{\boldsymbol{u}}^2_{l,k}[j], \ldots, \tilde{\boldsymbol{u}}^Q_{l,k}[j]] \in \mathbb{C}^{Q \times Q}$ and $\tilde{\boldsymbol{\Lambda}}_{l,k}[j] = diag\left\{\tilde{\lambda}^1_{l,k}[j], \tilde{\lambda}^2_{l,k}[j], \ldots, \tilde{\lambda}^Q_{l,k}[j]\right\}$ is composed of the eigenvalues of $\tilde{\boldsymbol{R}}_{l,k}[j]$ in descending order. Thus, for the user k served by the BS l, the whole combination vector on the jth subband can be expressed as

$$\boldsymbol{c}_{l,k}[j] = \frac{\tilde{\boldsymbol{u}}^1_{l,k}[j]}{\left[\tilde{\boldsymbol{u}}^1_{l,k}[j]\right]_1}, \quad 1 \leq j \leq \left\lceil \frac{N_W}{N_S} \right\rceil. \tag{23}$$

Then, other $Q - 1$ entries of $\boldsymbol{c}_{l,k}[j]$ are quantized utilizing N_Q bits for each entry.

Finally, the selected beam indexes and the quantized combination coefficients are sent to BS through a feedback link.

After receiving the reported CSI of K users, the BS first design the beamforming vector for each user by combining all the selected beamforming vectors with the quantized combination coefficients. Then, the BS groups the designed beamforming vectors of K users together, and utilizes zero-forcing algorithm that normalizes the beamforming vector of each user and mitigates multi-user interference to design the beamforming matrix for K users [18]. With the designed beamforming matrix, the BS is capable of performing downlink precoding for data communication.

C. CSI FEEDBACK OVERHEAD ANALYSIS

In this subsection, we analyze the CSI feedback overhead of the presented limited feedback algorithms. We focus on the number of feedback bits in entire bandwidth per user needed and only count the reported beam indexes and combination coefficients.

For algorithm 1, each user needs to feed back the wideband vertical and horizontal beam indexes, along with the subband vertical and horizontal combination coefficients. In the stage 1, each user requires to feed back $\left\lceil \log_2\binom{N_V}{1} \right\rceil + \left\lceil \log_2\binom{N_V-1}{Q_V-1} \right\rceil$ bits, while $N_Q(Q_V - 1)$ bits per subband in the stage 2. In the stage 4, the number of feedback bits is $\lceil \log_2 M_H O_H \rceil + \left\lceil \log_2\binom{M_H-1}{Q_H-1} \right\rceil$, while each user requires to feed back $N_Q(2Q_H - 1)$ bits per subband in the stage 5.

For algorithm 2, each user needs to feed back the wideband vertical and horizontal beam indexes, along with the subband horizontal combination coefficients and whole combination coefficients. In the stage 1, each user requires to feed back $\left\lceil \log_2 \binom{N_V}{1} \right\rceil + \left\lceil \log_2 \binom{N_V - 1}{Q-1} \right\rceil$ bits, while the number of feedback bits is $Q \left\lceil \log_2 M_H O_H \right\rceil$ in the stage 2. In the stage 3, the number of feedback bits per subband is $N_Q Q$, where each user requires to feed back $N_Q(Q-1)$ bits per subband in the stage 4.

TABLE 1. CSI feedback overhead comparison.

Scheme	Number of Feedback bits in entire bandwidth per user
Conventional Scheme	$\left(\left\lceil \log_2 \binom{N_V}{1} \right\rceil + \lceil \log_2 (M_H O_H/2) \rceil + 4\right) \left\lceil \frac{N_W}{N_S} \right\rceil$
Algorithm1	$\left\lceil \log_2 \binom{N_V}{1} \right\rceil + \left\lceil \log_2 \binom{N_V-1}{Q_V-1} \right\rceil + \lceil \log_2 M_H O_H \rceil + \left\lceil \log_2 \binom{M_H-1}{Q_H-1} \right\rceil + N_Q (Q_V + 2Q_H - 2) \left\lceil \frac{N_W}{N_S} \right\rceil$
Algorithm2	$\left\lceil \log_2 \binom{N_V}{1} \right\rceil + \left\lceil \log_2 \binom{N_V-1}{Q-1} \right\rceil + Q \lceil \log_2 M_H O_H \rceil + N_Q (2Q-1) \left\lceil \frac{N_W}{N_S} \right\rceil$

The CSI feedback overhead of two limited feedback algorithms are summarized in Table 1. We also compare them with the conventional CSI acquisition scheme described in [14]. It can be observed that the two presented algorithms would not increase excessive CSI feedback overhead in comparison to conventional CSI acquisition scheme when $\lceil N_W/N_S \rceil$ is larger, this is because that for the two presented algorithms, there is no subband feedback for reporting beam indexes.

V. SIMULATIONS RESULTS

In this section, we present numerical results to evaluate the performance of our proposed scheme for multi-user massive MIMO systems. We consider a traditional hexagonal layout of $L = 19$ cells and adopt wrap-around technology to avoid any border effects. Each cell is further divided into three sectors and 10 users are uniformly distributed in each sector. We assume that each user is equipped with dual-polarized antenna array of $N = 2$ antennas, the BS with $M = 64$ antennas is employed, in which $M_H = 4$ and $M_V = 8$ antennas, and the distances between two adjacent antennas in the vertical dimension and horizontal dimension are 0.8λ and 0.5λ, respectively, where λ is the carrier wavelength. We utilize an urban micro scenario and adopt the 3GPP channel model [17] to characterize the rich scattering feature of the spatial channel. In addition, the system is assumed to operate at 2GHz carrier frequency with a 10MHz bandwidth, where the number of subbands is $\lceil N_W/N_S \rceil = 9$. The number of bits for quantization is set $N_Q = 3$, where we use two-point uniform sampling in the range of [0, 1] and QPSK constellation to quantize amplitude and phase, respectively.

In Fig. 3, we compare the cell average SE of conventional CSI acquisition scheme with different vertical codebook sizes, i.e., different N_V, in which the oversampling factor is set as $O_H = 8$, and the maximum number of scheduled users is set as $K = 2, 4, 6, 8$ and 10. We can see that the

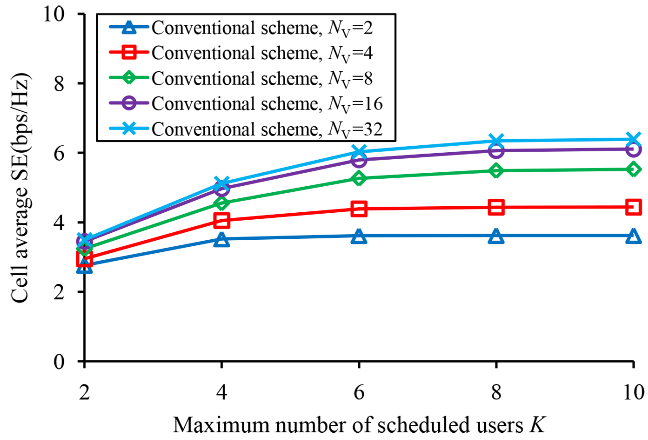

FIGURE 3. Cell average SE achieved by the conventional CSI acquisition scheme with different vertical codebook sizes.

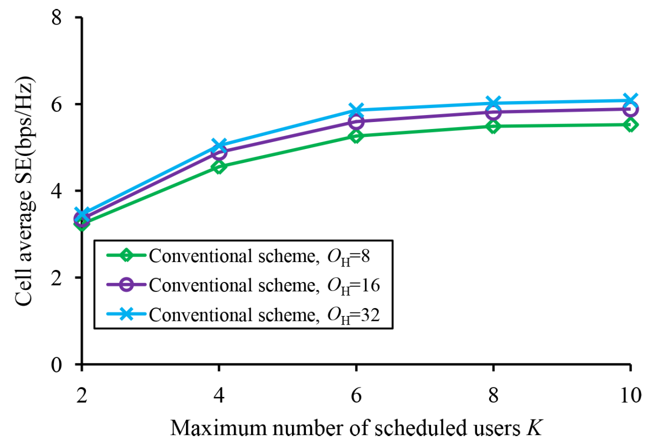

FIGURE 4. Cell average SE achieved by the conventional CSI acquisition scheme with different oversampling factors.

conventional CSI acquisition scheme approaches the optimal cell average SE at a certain K, this can be attributed to the fact that when K increases beyond the certain value, multi-user interference gradually becomes more severe and hence limits the system performance. It can also be observed that the achievable cell average SE of conventional CSI acquisition scheme improves with the growth of N_V, as an example, more than 51.6% performance gain can be achieved when N_V increases from 2 to 8 and K is set as 8, however, this performance gain increases slightly when N_V exceeds 8. In Fig. 4, we compare the cell average SE of conventional CSI acquisition scheme with different oversampling factors, i.e., different O_H, in which the size of vertical codebook is set as $N_V = 8$, and the maximum number of scheduled users is set as $K = 2, 4, 6, 8$ and 10. We can observe that slight performance gain would be achieved when O_H increases from 8 to 32. These are because that the conventional CSI acquisition scheme is designed based on beam selection principle, it cannot completely capture the propagation characteristic of the rich scattering channel even when N_V and O_H are relatively large.

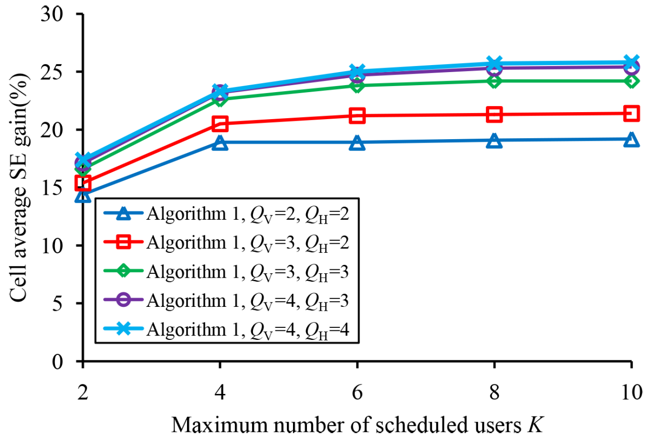

FIGURE 5. Cell average SE comparison between the conventional CSI acquisition scheme and the presented algorithm 1 with different number of beamforming vectors.

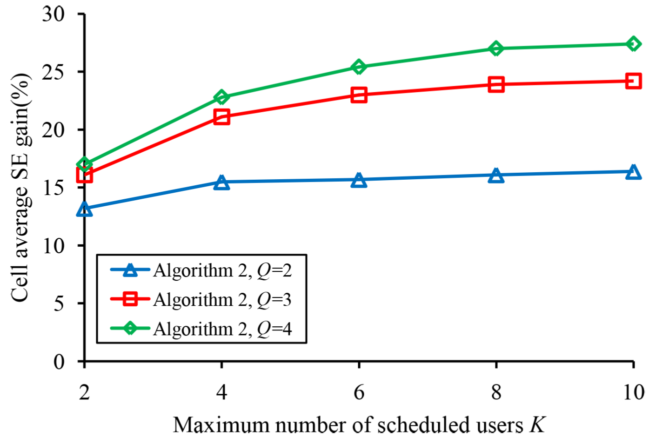

FIGURE 6. Cell average SE comparison between the conventional CSI acquisition scheme and the presented algorithm 2 with different number of beamforming vectors.

Fig. 5 shows the cell average SE comparison between the conventional CSI acquisition scheme and the presented algorithm 1 with different number of beamforming vectors, i.e., different Q_V and Q_H. In this simulation, the size of vertical codebook is set as $N_V = 8$, and the oversampling factor O_H is set as 8 for comparison. As can be seen, the presented algorithm 1 outperforms the conventional CSI acquisition scheme, and the gap between the former and the latter is enlarged as Q_V and Q_H increase, due to more beamforming vectors can be utilized to capture the propagation characteristic of the reflection paths and the effect of multi-user interference is mitigated. It can also be observed that the improvement becomes negligible when Q_V and Q_H are more than 4, respectively. This is because that the power of the channel is concentrated to its dominant path, which eventually leads to almost saturated performance when Q_V and Q_H increase to certain values, respectively. In addition, in the case of $Q_V = 2$ and $Q_H = 2$, the number of feedback bits in entire bandwidth per user for the presented algorithm 1 is 121, while that for conventional CSI acquisition scheme is 99.

Fig. 6 shows the cell average SE comparison between the conventional CSI acquisition scheme and the presented algorithm 2 with different number of beamforming vectors, i.e., different Q. In this simulation, the size of vertical codebook is set as $N_V = 8$, and the oversampling factor O_H is set as 8 for comparison. We can observe that the general trends of the cell average SE achieved by the presented algorithm 2 are consistent with the presented algorithm 1 in Fig. 5. In addition, in the case of $Q = 2$, the number of feedback bits in entire bandwidth per user for the presented algorithm 2 is 97, which is comparable to the conventional CSI acquisition scheme. From Fig. 5 and Fig. 6, we can see that the presented algorithm 2 outperforms the presented algorithm 1 in the case of approximate CSI feedback overhead, this can be attributed to the fact that the Stage 4 in the presented algorithm 1 is calculated based on the reported vertical beamforming vector, the quantization error limits the system performance.

In conclusion, the proposed scheme, with considerable performance improvement, consumes a small portion of uplink resource approaching that of the conventional CSI acquisition scheme, because the former can better process the multi-user interference and capture the propagation characteristic of the rich scattering channel than the latter.

VI. CONCLUSION

In this paper, we propose an enhanced CSI acquisition scheme for multi-user massive MIMO systems operating on FDD mode. Compared to the conventional CSI acquisition scheme that suffers from inaccurate channel estimation, the proposed scheme expands the selected beamforming vectors of each user to the reflection paths and the light-of-sight path, which effectively processes the multi-user interference and captures the propagation characteristic of the rich scattering channel. To enable low-overhead and spectral-efficient system implementation, we present two limited feedback algorithms that provide different trade-offs between the system performance and CSI feedback overhead by utilizing beamformed CSI-RS transmission mechanism, in which the processes of the two presented algorithms are divided into multiple stages, including multiple wideband beamforming vectors selection and subband combination coefficients calculation. The simulation results have been demonstrated that the proposed scheme achieves a significant improvement in system SE while avoiding prohibitive amount of feedback requirement.

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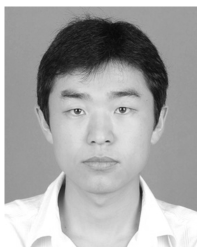

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