Limited feedback scheme based on Zero-forcing Precoding for Multiuser MIMO-OFDM Downlink Systems

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***Abstract*—Conventional zero-forcing precoding was well investigated, but it hadn't considered the channel quality indicator (CQI) mismatch for practical system with limited feedback. This paper studies a novel zero-forcing precoding with channel quality indicator (CQI) estimation and adjusting, channel directional information(CDI) quantization, user scheduling and link adaptation and then proposes a CQI estimation algorithm for multiuser multiple input multiple output antenna (MU-MIMO) downlink systems with limited feedback. Simulation with 3GPP long term evolution system demonstrates that the scheme with proposed method can significantly improve system performance, compared with conventional zero-forcing precoding and single user MIMO systems.**

***Index Terms*—Zero-forcing precoding, CQI, CDI, MMSE, MU-MIMO.**

I. Introduction

Multiuser multiple input multiple output antenna (MU-MIMO) downlink system is considered as a promising technology to improve the system capacity with benefit from both multiuser diversity and spatial diversity [1]-[2]. It has been proven in theory that MU-MIMO can provide larger throughput than single user (SU) MIMO when downlink channel state information (CSI) is available at the transmitter [2]-[3].

In previous, many of researches on MU-MIMO downlink system consider that transmitter knows the full CSI. In [4]-[6], zero-forcing (ZF) precoding is well investigated which is used to cancel the multiuser interference; in [7]-[8], they derive the user selection strategies for MU-MIMO based on full CSI. These methods have been demonstrated to perform well with full CSI knowledge at transmitter. Unfortunately, obtaining full CSI at transmitter is unrealistic in practical system. Thus, how to obtain channel information at transmitter is of great interesting for MU-MIMO.

In general, the CSI is composed of two aspects: channel directional information (CDI) and channel quality indicator (CQI). In practical system, such as 3GPP long term evolution(LTE) systems and IEEE 802.16m systems, the CDI can be provided to transmitter with a codebook-based feedback strategy, known as limited feedback where the receiver quantizes the CDI from a set of codeword, i.e. codebook, and the index of the selected codeword is fed back to the transmitter. Meanwhile, due to the requirement of link adaptation and user selection, transmitter also need the user to feedback the CQI. Usually, the signal-to-interference plus-noise ratio (SINR) is used as CQI and is estimated by each user without prior knowledge of the other user's precoding vector in the practical system which will lead to a mismatch between the estimated CQI and actual CQI.

Some researches on imperfect CSI can be found in [9]-[14]. These researches take a step further and actually quantize the CSI at user where they derive the lower-bound approximation of the expected value of the SINR by taking the expectation of instant SINR and feedback the approximated SINR to transmitter as CQI. Taking practical system into account, transmitter needs to select the modulation and coding scheme (MCS) for the users adaptively according to the CQI during link adaptation. Due to the mismatch between approximated SINR and actual CQI, there is a question that whether the approximated CQI feedback is robust enough for link adaptation. Another concern on the approximated SINR is that if it's suitable for different receiver detections like MMSE-based detection which is testing baseline in WiMAX system [18]. However, these researches didn't consider these concerns and just presented the capacity-based sum-rate performance which is regardless of the CQI mismatch and receiver detections.

In this paper, with the purpose of investigating the performance for practical system, we develop a feasible MU-MIMO zero-forcing precoding scheme to cover CQI calculation, CDI quantization, user selection and link adaptation where we proposed an alternative CQI estimation method especially for minimum mean square error (MMSE) detector and OFDM system to improve the performance.

The rest of the paper is organized as follows. The MU-MIMO OFDM downlink system model is discussed in Section . In section III, we describe the zero-forcing precoding scheme in detail. The simulation results are given in section IV and conclusions are drawn in Section V.

II. MU-MIMO OFDM Downlink System Model

The MU-MIMO OFDM downlink systems model is described in Fig.1. Without loss of generality, we assume the transmitter has N_t transmit antennas and selects M users to

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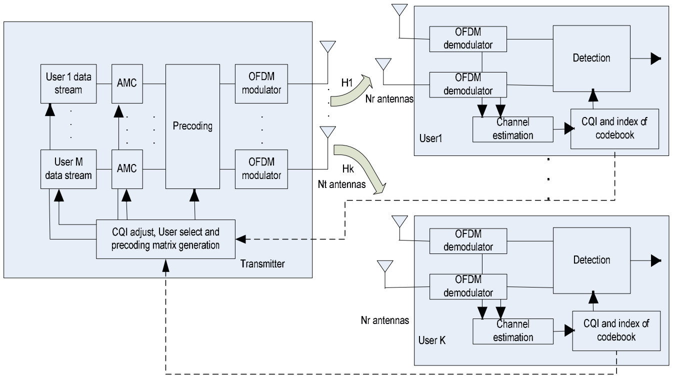

Fig. 1. MU-MIMO OFDMA downlink system

transmit from K users $(K \geq M)$ at one time. We denote that S is the set of selected users, so M is cardinality S. All users have N_r receive antennas and the channel is assumed to be flat fading channel.

In addition, the basic scheduling unit is chunk in OFDM system (e.g., 3GPP LTE [18]). In space domain, the number of users to be simultaneously transmitted in a chunk by using precoding can be up to N_t and accordingly the maximal number of data stream is N_t in one chunk. Although it can be assumed, that any number of data streams could be sent to any user, we restrict ourselves to one stream per user in this paper.

With this system model as in Fig.1, the received signal vector for the i-th user $(i \in S)$ can be expressed as follows

$$\begin{aligned} \mathbf{y}_i &= \sum_{j \in S} \mathbf{H}_i \mathbf{p}_j x_j + \mathbf{n}_i \\ &= \underbrace{\mathbf{H}_i \mathbf{p}_i x_i}_{signal} + \underbrace{\sum_{\substack{j \in S \\ j \neq i}} \mathbf{H}_i \mathbf{p}_j x_j}_{interference} + \underbrace{\mathbf{n}_i}_{noise} \end{aligned} \tag{1}$$

where $\mathbf{y}_i$ denotes the i-th user's received signal vector; $\mathbf{H}_i$ is the $N_r \times N_t$ channel matrix from the transmitter to the i-th user; $\mathbf{p}_i$ represents the precoding vector for the i-th user for one chunk, which is the same in a subcarrier for a user within one chunk; x_i is the data symbol for the i-th user; $\mathbf{n}_i$ represents the noise vector for the i-th user at the receiver, which element is zero mean Gaussian random variables with variance σ^2. Without loss of generality, we assume the data symbol x_i has statistical power $\mathbf{E}[|x_i|] = 1$.

Hence, the precoding matrix $\mathbf{P}$ can be written as

$$\mathbf{P} = [\mathbf{p}_1^T \quad \mathbf{p}_2^T \cdots \mathbf{p}_M^T] \tag{2}$$

where $\mathbf{p}_i$ is an $N_t \times 1$ matrix according to that each user only gets a single stream transmission.

In this paper, we consider the practical frequency-division duplexing (FDD) system. In this case, the transmitter must rely on uplink feedback from the user to obtain partial CSI and each user only knows its own channel matrix $\mathbf{H}_i$. Based on (1), the i-th user cannot know $\mathbf{p}_j (j \neq i)$ accordingly and hence cannot calculate the accurate SINR. In the next section, a complete zero forcing solution is developed corresponding in this situation.

III. ZERO-FORCING PRECODING SCHEME

A. CDI quantization

In cellular systems, limited uplink bandwidth allows only a few bits of feedback during each interval, resulting in limited, nonideal CSI. For the purpose to reduce the feedback overheads, each user only feeds back one CDI to represent a chunk and the CDI in the chunk is generated by doing singular value decomposition (SVD) for the channel matrix $\mathbf{H}_i$ as following

$$\mathbf{H}_i = \mathbf{U}_i \mathbf{D}_i \mathbf{V}_i^H, \quad i \in K \tag{3}$$

where $\mathbf{U}_i$ is $N_r \times N_r$ unitary matrix; $\mathbf{D}_i$ is $N_r \times N_t$ diagonal matrix with descended singular values of $\mathbf{H}_i$ and $\mathbf{V}_i$ is $N_t \times N_t$ unitary matrix. Since only one data stream within one chunk is transmitted for a user, each user takes the first right singular vector $\mathbf{V}_i(:,1)$, that's say the first column of $\mathbf{V}_i$, as the CDI since it is corresponding to the highest singular value of $\mathbf{H}_i$, which means it contains the higher information of $\mathbf{H}_i$ than other right singular vectors. The singular-vector-based CDI will reduce the overhead greatly when the user is equipped with multiple antennas since the user doesn't need to feedback the channel matrix.

According to the minimum Euclidean distance criterion, the i-th user $(i \in K)$ quantizes $\mathbf{V}_i(:,1)$ and chooses a quantization vector, denoted as $\mathbf{v}_i$ from a given set of codeword, i.e. codebook.

$$\mathbf{v}_i = \mathbf{c}_n, \quad n = \underset{q=1,\cdots,Q}{\arg\max} \left| \mathbf{V}_i(:,1)^H \mathbf{c}_q \right| \tag{4}$$

where $\mathbf{c}_q$ is the q-th codeword corresponding to q-th column of the codebook $\mathbf{C}$ and $\mathbf{Q}$ is the size of this codebook.

Each user shares the knowledge of codebook with the transmitter, and sends the index of selected codeword to the transmitter, which just requires $log_2 Q$ bits per user.

B. CQI estimation

Since a user cannot know other user's precoding vector prior, the interference came from other user hasn't been calculated accurately in a user. In this paper, we propose an alternative method to estimate the CQI based on MMSE receiver, in order to reduce the CQI mismatch between UE feedback and downlink channel when the transmitter schedule multiple UEs in the same time-frequency resource.

In this method, the i-th user assumes its precoding vector is $\mathbf{v}_i$ as in (4) and the precoding matrix used by the transmitter is unitary. Based on the assumption, the user generates the precoding matrix by using the $\mathbf{v}_i$ as follow

$$\bar{\mathbf{V}}_{\mathbf{i}} = [\mathbf{v}_i, \mathrm{null}(\mathbf{v}_i)] \tag{5}$$

where $null(\mathbf{v}_i)$ denotes the null space of $\mathbf{v}_i$. Then the SINR of i-th user at l-th subcarrier within one chunk can be calculated

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based on MMSE receiver with the precoding matrix. Firstly the MMSE weight is specified as

$$\mathbf{r}_i = \left((\mathbf{H}_i\bar{\mathbf{V}}_i)^H(\mathbf{H}_i\bar{\mathbf{V}}_i) + \mathbf{I}\cdot\sigma^2\right)^{-1}\cdot(\mathbf{H}_i\bar{\mathbf{V}}_i)^H \quad (6)$$

Then the SINR is thus given as

$$\begin{aligned} \bar{\mathbf{H}}_i &= \mathbf{r}_i(\mathbf{H}_i\bar{\mathbf{V}}_i) \\ \mathbf{D}_i &= diag[diag[\bar{\mathbf{H}}_i]] \\ \mathbf{\Phi} &= \bar{\mathbf{H}}_i - \mathbf{D}_i \\ SINR_{i,j}^{pro} &= \left.\frac{diag[\mathbf{D}_i\mathbf{D}_i^H]}{diag[\sigma^2\mathbf{r}_i\mathbf{r}_i^H + \mathbf{\Phi}\mathbf{\Phi}^H]}\right|_{j,j} \end{aligned} \quad (7)$$

where $\mathbf{I}$ is the $N_r \times N_r$ identical matrix and $diag[\mathbf{A}]$ returns a square matrix with elements of $\mathbf{A}$ on the diagonal when $\mathbf{A}$ is a vector or return a vector which elements are the diagonal of $\mathbf{A}$ when $\mathbf{A}$ is a matrix. The $SINR_{i,j}^{pro}$ denotes the j-th stream SINR of the i-th user.

The first element of the $SINR_i^{eff}$ is considered as the CQI.

$$CQI_i = SINR_i^{eff}(1) \quad (8)$$

and the users send the CQI to transmitter for user selection and link adaptation.

C. Precoding and CQI adjusting

After obtaining the CQI and CDI from all the users, transmitter combines CDI for all possible user sets S^*, as $g = 1, \cdots S^*$, as follows

$$\hat{\mathbf{W}}_g = [\mathbf{v}_{g1}, \cdots, \mathbf{v}_{gM}]^H, g = 1, \cdots S^* \quad (9)$$

where g_i denotes the i-th user $i \in M$ in g subset.

The precoding matrix for a given g subset is generated based on zero forcing algorithms by the following pseudo-inverse expression:

$$\bar{\mathbf{W}}_g = \hat{\mathbf{W}}_g^H(\hat{\mathbf{W}}_g\hat{\mathbf{W}}_g^H)^{-1} \quad (10)$$

In general, a drawback of the zero forcing precoding by means of the pseudo-inverse is the increase of the transmit power and the precoded signal prior to transmission has to be scaled to meet the power limitation where the scaled factor need to be known at users which will lead to difficulty in practical system[19].

One straightforward solution is to normalize the precoding vector instead of normalizing the precoded signal, that's say, the actual transmit precoding matrix for the given g subset is $\mathbf{W}_g$, where the column of $\mathbf{W}_g$ is got by normalizing the corresponding column of $\bar{\mathbf{W}}_g$. According to (8)-(10), the users estimate the CQI without normalization of the precoding vectors, therefore transmitter need to adjust the feedback CQI to account for this effect as following.

For a given g subset, let's denote the i-th column of $\mathbf{W}_g$ and $\bar{\mathbf{W}}_g$ as $\mathbf{w}_{gi}$ and $\bar{\mathbf{w}}_{gi}$. So $\mathbf{w}_{gi}$=$\bar{\mathbf{w}}_{gi}/\| \bar{\mathbf{w}}_{gi} \|$. Assuming the feedback CQI from the i-th user in g subset is CQI_{gi} , then transmitter adjusts the CQI of the g subset as

$$\begin{aligned} CQI_g^{eff} &= [CQI_{g1}^{eff}, ..., CQI_{gM}^{eff}] \\ &= [\frac{CQI_{g1}}{\|\bar{\mathbf{w}}_{g1}\|}, ..., \frac{CQI_{gM}}{\|\bar{\mathbf{w}}_{gM}\|}] \end{aligned} \quad (11)$$

D. User selection

In each chunk, transmitter makes a decision to allocate the user set. For a given g subset, transmitter computes the sum rate according to the CQI and precoding matrix as follows

$$R^g = \log(\det(\mathbf{I} + \mathbf{W}_g^H\mathbf{\Psi}_g\mathbf{W}_g)) \quad (12)$$

where $\mathbf{\Psi}_g$ is diagonal matrix as

$$\mathbf{\Psi}_g = diag([CQI_{g1}^{eff}, ..., CQI_{gM}^{eff}])$$

In order to achieve maximal capacity, transmitter needs to select S from S^* set according to

$$R^S = \max_{g=1\cdots S^*} R^g \quad (13)$$

In general, solving (15) requires a brute force search over all subset S^*. The number of computing of this search is $\frac{K!}{M!(K-M)!}$, so the complexity of this search becomes unacceptably high for large number of users. An alternative greedy algorithm to be used to greatly reduce the computing complexity is as follows:

$Initialization$: $S = \emptyset$ as null set and $R^S = 0$
$While$ (the cardinality S is less than or equal to M)
  $Find\ k^* = \arg\max_{k \notin S} R^{S\cup\{k\}}$
  $If \quad R^{S\cup\{k^*\}} > R^S$
    $Update \quad S = S \cup \{k^*\}$
  $Else$
    $Exit$

E. Link adaptation

With link adaptation, the modulation and code rate are adaptively changed according to the channel state information. If the channel quality of selected user is relatively strong, a transmission scheme with higher spectral efficiency may be selected via link adaptation. Without loss of generality, we assume the CQI of the i-th user of the selected set S is CQI_{si}^{eff} as in (13), transmitter can predict the user's throughput for

$$\begin{aligned} Throughput &= (1 - \mathrm{P}(CQI_{si}^{eff})) \times r \times \sqrt{\Gamma}, \\ \text{s.t.} \quad & \mathrm{P}(CQI_{si}^{eff}) \le target\_PER \end{aligned} \quad (14)$$

where r is the channel coding rate and Γ is the modulation order, i.e. 4, 16 and 64 for QPSK, 16QAM and 64QAM respectively; $\mathrm{P}(CQI_{si}^{eff})$ is the function that converts the SINR information into packet error rate (PER) information for each MCS. The received bit mutual information rate (RBIR) rule is considered as this function in [18].

Based on $target\_PER$, transmitter selects the modulation coding scheme (MCS) for the user that yields the largest throughput while remaining within the PER target bound.

It's noted that the predicted throughput in (16) is just used to select MCS for the selected users and after the selected users detect the received signal, the actual throughput is collected to evaluate the system performance.

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TABLE I
SIMULATION PARAMETERS

Channel model	ITU Pedestrian B
User speed	3km/h
Antenna configuration	2x2 case
OFDM structure	7 OFDM symbols /sub-frame IFFT size: 1024 Used subcarriers: 600
Chunk	25 subcarriers in frequency domain and 7 OFDM symbols in time domain
Sub-frame duration	0.5 ms
Receiver detection	MMSE
Feedback delay	1 ms
Channel estimation	ideal
Total user number	20
Scheduling method	Max C/I
Link adaptation	RBIR
MCS	QPSK, 16QAM and 64QAM with 1/3, 2/5, 1/2, 3/5, 2/3,3/4, 4/5, and 7/8
Target PER	0.1
Channel coding	Convolution turbo coding

IV. SIMULATION COMPARISON AND RESULTS

A. Simulation Comparison

In this section, we compare the achievable throughput of the proposed zero forcing precoding scheme with the conventional zero forcing MU-MIMO [9]-[14] and single user closed loop MIMO [20].

(1) Conventional zero-forcing MU-MIMO: In [9]-[14], a method for SINR estimation is introduced, where user approximates the SINR as CQI, which we call approximated CQI here. Let us define $\cos\theta_i = \left|\mathbf{V}_i(:,1)^H \mathbf{c}_n\right|$, the approximated SINR for i-th user is given by

$$SINR_i^{apr} = \frac{\|\mathbf{H}_i\mathbf{v}_i\|^2 cos^2\theta_i}{\sigma^2 + \|\mathbf{H}_i\mathbf{v}_i\|^2 \sin^2\theta_i} \quad (15)$$

where $\|\mathbf{A}\|$ means the Euclidean norm of a vector $\mathbf{A}$. The approximated SINR is derived as the lower-bound of the expectation of MRC-based received SINR. For MMSE detection, the close-form is hard to get the lower-bound approximation of the expectation of MMSE-based received SINR.

(2) Single user closed loop MIMO [20]: In SU-MIMO case, only one user is scheduled over the same chunk, which means that all the data streams at a chunk are assigned to the same user. As a result, there isn't CQI mismatch in this case, because the user can accurately estimate the interference. The precoding matrix is also obtained using SVD.

B. Simulation Results

Simulations are conducted by using the 3GPP long term evolution (LTE) system parameters shown in the Table I. In the simulation, 24 MCS are used including QPSK, 16QAM and 64QAM with code rate 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, and 7/8.

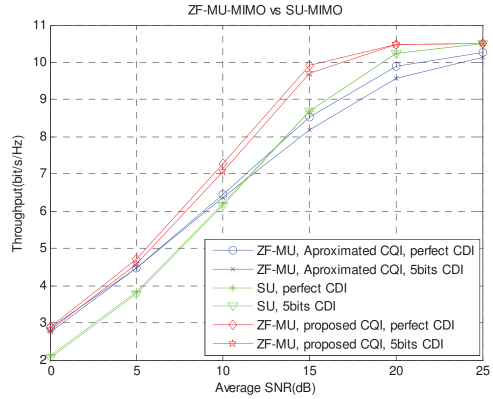

Fig. 2. Throughput vs. SNR plots for different cases in MU-MIMO OFDM downlink system

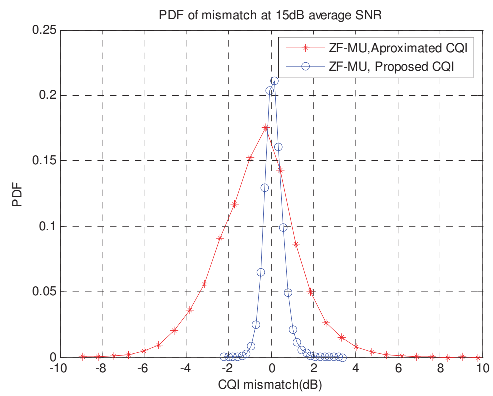

Fig. 3. PDF of CQI mismatch between estimated CQI and actual CQI

Different data streams can be transmitted with different MCS and the Householder-based codebook is used in the simulation [16]. We also assume MMSE receiver detection.

MU-MIMO with 2 antennas at transmitter and 20 users at the receiver are considered in the simulation, where each user is equipped 2 antennas. Thus, transmitter just selects 2 users from 20 users to be transmitted at a chunk. ITU Pedestrian B channel model is used with 3km/h user speed. In the simulation, we also consider feedback delay, which is 1 ms and equal to 2 sub-frame duration.

Fig.2 shows the performances of the precoding scheme. For zero-forcing MU-MIMO case, we tested the performance for both CQI estimations: one is approximated CQI in [9]-[14], the other is proposed CQI in this paper. The performances are tested with 5bits codebook size to quantize the CDI. The results show that zero-forcing MU-MIMO with proposed CQI always outperforms the SU-MIMO with 1bit/s/Hz gain and significant gain over MU-MIMO with approximated CQI at high averaged SNR range (>10 dB). In Fig.2, the performances with perfect CDI feedback are also validated and the results illustrate the similar trend as quantized CDI with codebook.

As the result of performance degradation, we also analyze the CQI mismatch between estimated CQI and actual CQI

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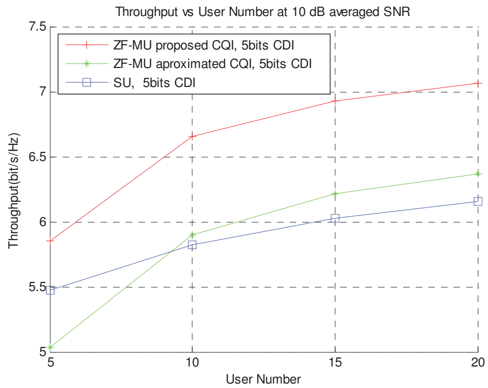

Fig. 4. Throughput vs. User number plots for different cases

from the simulation results. From the probability density function (PDF) of CQI mismatch shown in Fig 3, obviously, the approximated CQI has larger variance of CQI mismatch which lead to more performance degradation.

Fig 4 shows the throughput with different user number at averaged SNR of 10 dB. Even with few user number, the throughput of MU-MIMO with proposed CQI still better then SU-MIMO, but MU-MIMO with approximated CQI is worse than SU-MIMO with fewer user number. From Fig. 4, we can see MU-MIMO with proposed CQI is more robust to the variety of user number than that with approximated CQI.

V. Conclusion

This paper studies zero-forcing precoding with limited feedback for MIMO OFDM system and investigate the performance with CQI estimations, CDI quantization, user selection and link adaptation. In order to reduce the impact on the link adaptation from mismatch between estimated CQI and actual CQI, we proposed a CQI estimation method especially for MMSE detection and MU-MIMO OFDM system. Simulation with 3GPP LTE system evaluate the performance and the results show that the throughput of this proposed method is 1bit/s/Hz higher than that of SU-MIMO at all SNR range and has significant gain over the existing approximated CQI method at high averaged SNR range.

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