Research Article

Multiple Beam Selection for Combing M2M Communication Networks and Cellular Networks with Limited Feedback

Xiaoning Zhang,1 Lin Bai,2 and Wenyang Guan1

1 State Key Laboratory of Advanced Optical Communication Systems and Networks, Peking University, Beijing 100871, China
2 School of Electronic and Information Engineering, Beihang University, Beijing 100191, China

Correspondence should be addressed to Lin Bai; l.bai@buaa.edu.cn and Wenyang Guan; guanwenyang@pku.edu.cn

Received 18 August 2013; Accepted 19 October 2013

Academic Editor: Jianhua He

Copyright © 2013 Xiaoning Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

We study the scenario in which a large number of machine-type communication devices (MTCDs) communicate with each other by utilizing the help of the base station (BS) through some MTCD gateways. We consider an overlay mode of an orthogonal frequency division multiple access (OFDMA) based cellular system using orthogonal beamforming to provide broadband wireless access for the MTCD gateways. In order to avoid the interference with mobile users, the beamforming vectors to the MTCD gateways have to be orthogonal to the channel vectors of mobile users, which become a constraint in finding the beamforming vectors for the MTCD gateways. However, with limited feedback of channel state information (CSI) at a BS, the orthogonal beamforming constraints may not be achieved. In such a practical case, conventional feedback schemes are feasible but not efficient due to the orthogonality constraints. In this paper, we propose a novel multiple beam selection (MBS) approach with limited feedback for MTCD gateways by taking into account the previous orthogonality constraints. Simulation results show that the performance improvement of the proposed approach over the conventional ones is generally about 10% when a BS is equipped with an array of 6 elements.

1. Introduction

Machine-to-machine (M2M) communication networks have been proposed to connect machines without the intervention from human beings. In recent years, the research of combing M2M networks and mobile cellular networks draws much attention [1, 2]. In an M2M network, there are lots of machine-type communication devices (MTCDs). These MTCDs access a cellular network by some MTCD gateways [3], which are assumed as secondary users in the cellular network. There are hundreds of MTCDs connecting to one MTCD gateway. In the combined M2M cellular networks, the MTCD gateway may need to communicate with the BS at a high data rate.

As the mobile users in a cellular system have a higher priority than the MTCD gateways, the beamforming vectors for the mobile users are designed to maximize the beamforming gains. In the overlay mode, since the signals transmitted to the MTCD gateways should not interfere with the mobile users [4], the beamforming vectors have to be orthogonal to the channel vectors of the mobile users, which become a constraint in finding the beamforming vectors for the MTCD gateways. The throughput performance can be improved when the orthogonal beamforming is combined with multiuser scheduling over multiple subcarriers, where the users with good channel conditions are selected for each transmission. Channel state information (CSI) is required in both beamforming and multiuser scheduling. However, unfortunately, in a practical system, the CSI available at the BS is imperfect due to specific system configurations. Therefore, it is worthwhile to design orthogonal beamforming using imperfect CSI for this kind of hybrid network.

1.1. Related Work. There are mainly two ways for the BS to get information from each user, that is, channel reciprocity and feedback channel. In a time division duplexing (TDD) system, it is possible to use the channel reciprocity at the BS, which refers to estimating the downlink channel from the uplink signal. However, the channel reciprocity requires calibration of the radio devices of both the receiver and the transmitter, for example, A/D converters, mixers, filters, and antennas. This requires extra special hardware as well as special protocols to facilitate the channel measurement and calibration [5, 6]. Therefore, most of the research papers
assume that a feedback channel exists from each user to the BS for carrying feedback information as those in [7–9]. It is generally assumed that the feedback channel from each user to the BS is not perfect. In [10–12], the delayed feedback channel is considered. The effects of outdated CSI at the BS are analyzed by means of Markov model of the channel temporal correlation in [11, 12]. The effects of the noisy feedback channel are considered in [13–15], where the feedback channel is assumed as a discrete symmetric channel. Plenty of the pieces of literature focus on the feedback channel with finite rate (see, e.g., [16] and the references therein), which is referred to as limited feedback channel.

From the limited feedback channel, each user is allowed to send a small number of information bits back to the BS. Most of the conventional feedback schemes focus on the quantization of the channel direction information (CDI) [9] using some vector quantization algorithms [17]. In [8], a codebook of orthogonal beamforming matrices is used for the quantization. Each user quantizes the channel directions according to a beamforming codebook with a priori knowledge by both the BS and the users. Possible ways of reducing the number of feedback bits have been proposed in [18, 19], where only the mean or covariance of CSI is sent back to the BS.

As for the overlay mode based on the orthogonal beamforming that we consider in this paper, the conventional feedback strategies are no longer suitable; using conventional feedback schemes, the BS acquires an approximation of each users’ channel directions the resulting beamforming vectors designed according to this approximation will not be best aligned with the MTCD gateways’ channel direction. Besides, due to the orthogonality constraint, the conventional feedback strategies become inefficient. That is, the codebook used and designed in [8] is uniformly distributed in the whole space, while the actual beamforming vector lies in a subspace due to the orthogonality constraint. Thus, the vectors in the codebook that lie out of the subspace provide redundant information and result in excessive feedback. Therefore, a new feedback strategy is needed in the overlay mode for MTCD gateways.

In this study, we propose a new multiple beam selection (MBS) strategy with limited feedback of CSI. A (downlink) broadcasting channel is used to inform MTCD gateways with all the available beams. Each user chooses the best one out of the available beams and sends the index of the chosen beam back to the BS. As the beams are dynamically generated at the BS according to the interference pattern of the users, the orthogonality is guaranteed and the CSI can be fed back through the feedback channel to the BS more efficiently.

This paper addresses joint beamforming, scheduling, and feedback for broadband wireless access to provide high throughput for MTCD gateways. The design of beamforming vectors and limited feedback from each user are closely connected due to the orthogonal constraint for MTCD gateways. In conventional feedback schemes, the beamforming vectors are calculated after receiving the feedback information from each user. However, in the proposed MBS scheme, the beamforming vectors are calculated in advance, awaiting for each user’s choice. A similar thought has been applied to opportunistic space division multiple access (OSDMA) in [20, 21].

1.2. Organization and Notations. The remainder of this paper is organized as follows. The system model is given in Section 2. In Section 3, a detailed study on the limited feedback for MTCD gateways is presented and the MBS strategy is proposed. The performance analysis is given in Section 4 followed by a comprehensive evaluation of the proposed MBS strategy using Monte Carlo simulation in Section 5. We conclude the paper with some remarks in Section 6.

The superscripts $T$ and $H$ stand for the transpose and Hermitian transpose, respectively. Upper and lower bold-faced letters are used for matrices and column vectors, respectively. Denote by $|x|$ the absolute value of a scalar $x$ or cardinality of $x$ if $x$ is a set, $\|x\|$ the 2-norm of vector $x$, $\perp$ perpendicularity, and $I$ the identity matrix of a certain size implicitly given by the context. We denote by $[w_1, w_2, \ldots, w_N]$ the concatenation of $N$ column vectors and by $[\mathbf{W}, \mathbf{c}]$ the concatenation of a matrix $\mathbf{W}$ and a vector $\mathbf{c}$ of the same column size. Elements of a set are enumerated as $[a_1, \ldots, a_N]$. $E[\cdot]$ denotes the statistical expectation. $\mathcal{C}(a, \mathbf{R})$ represents the distribution of circularly symmetric complex Gaussian (CSCG) random vectors with mean vector $a$ and covariance matrix $\mathbf{R}$, and $\mathcal{C}^n(a)$ denotes $n$-dimensional complex space. We denote the probability of an event $X$ by $Pr(X)$. $\log$ and $\log_2$ represent the natural logarithm and binary logarithm, respectively.

2. System Model

As in [22], in this paper, we consider downlink beamforming for MTCD gateways. Suppose that a BS in a cellular network is equipped with an antenna array of $L$ elements. For downlink channels, there are $M$ orthogonal subcarriers. The BS can support two different groups of users. One group has ordinary mobile users, which is called Group I. The other group consists of MTCD gateways, which is called Group II. The users in Group II want to have high data rate services. It is assumed that the users in Group I have higher priority than those in Group II. In the overlay mode, the downlink transmissions to the users in Group II should not affect the users in Group I.

It is assumed that there are $K$ users in Group I, and $Q$ users out of $K$ are chosen for data transmissions in each subcarrier. These are called active users in Group I. The number of users in Group II is denoted by $U$. Only one of these users is selected for transmission through each subcarrier. In general, $Q$ is small (usually $Q = 1$ if no spatial multiplexing is considered and $U$ is also small as the number of active fixed subscribers at a time would be limited, especially in a rural area where there are not so many mobile users).

The transmitted signal vectors from the antenna array to users in Groups I and II through subcarrier $m$, denoted by $s_{lm}$ and $s_{lIIm}$, are given by

$$s_{lm} = \sum_{q=1}^{Q} w_{lmq} a_{m,q}, \quad s_{lIIm} = w_{lIIm} b_m, \quad (1)$$
where $a_{m\ell}$ and $b_{m}$ are independent data symbols for users in Groups I and II, respectively, and $w_{m\ell,\ell}$ and $w_{m\ell}$ are the corresponding beamforming weight vectors. Throughout the paper, we assume that the beamforming vectors are normalized; that is, $\|w_{m\ell,\ell}\| = \|w_{m\ell}\| = 1$ for all $m$. Denote $P_{\ell} = \mathbb{E}[|a_{m\ell}|^2]$ and $P_{II} = \mathbb{E}[|b_{m}|^2]$ as the transmitted powers for Groups I and II, respectively.

We denote by $k_{\ell}$ the index of a user in Group I who receives the signal through subcarrier $m$. The received signal at this user is given by

$$x_{m,k_{\ell}} = h_{m,k_{\ell}}^H(s_{m,\ell} + s_{m,II}) + v_{m,k_{\ell}},$$

where $h_{m,k_{\ell}}$ is the $1 \times L$ downlink channel vector of subcarrier $m$ from the transmit antenna array to the $k_{\ell}$th user in Group I and $v_{m,k_{\ell}} \sim \mathcal{CN}(0, \sigma^2)$ is an independent background noise.

If a user in Group II also receives a signal through subcarrier $m$ whose index is denoted by $u_{m}$, the received signal at this user is given by

$$y_{m,u_{m}} = \frac{h_{m,k_{\ell}}^H(s_{m,\ell} + s_{m,II}) + v_{m,u_{m}}}{\|h_{m,k_{\ell}}\|^2 + \|h_{m,k_{\ell}}\|^2},$$

where $g_{m,u_{m}}$ is the $1 \times L$ downlink channel vector of subcarrier $m$ from the transmit antenna array to the $u_{m}$th user in Group II and $v_{m,u_{m}} \sim \mathcal{CN}(0, \sigma^2)$ is also an independent background noise.

Note that the characteristics of the channel vectors to users in Groups I and II are different. In general, $g_{m,u_{m}}$ is not varying rapidly, while $h_{m,k_{\ell}}$ is time varying as Group I users are mobile. The beamforming weight vectors $w_{m\ell,\ell}$ and $w_{m\ell}$ are decided by the BS according to the information sent back by each user. If the feedback channel is perfect, the CSI of each user, that is, $h_{m,k_{\ell}}$ and $g_{m,u_{m}}$, is known by the BS.

Throughout the paper, we focus on the data transmissions of the MTCD gateways. Generally we assume that the $h_{m,k_{\ell}}$’s are available at the BS for beamforming and discuss the impact of limited feedback with $g_{m,u_{m}}$. Note that the impact of imperfect $h_{m,k_{\ell}}$ is considered in [8, 9]. We do not consider this issue in detail.

### 3. Beamforming with Limited Feedback

In this section, the beamforming algorithms for MTCD gateways are proposed. First, the algorithms with perfect CSI of the Group II users are briefly described in Section 3.1. The motivations for the new feedback scheme are given in Section 3.2. In Section 3.3, the beamforming algorithms with limited feedback CSI of the MTCD gateways are proposed.

#### 3.1. Orthogonal Beamforming with Perfect CSI

As users in Group I have a higher priority than those in Group II, the signals to users in Group II should not interfere with the signals to users in Group I. For broadband access, it is required that the data rate to users in Group II from the BS is sufficiently high, while the number of users in Group II would not be large. In order to deal with these issues, we consider orthogonal beamforming. Using orthogonal beamforming, space division multiple access (SDMA) [23] can be implemented for downlink transmission to users in Groups I and II. The main difference of the orthogonal beamforming approach in this paper from that for the conventional SDMA is that the overlay mode based beamforming approach should take into account the priority between users in Groups I and II and maximize the data rate to users in Group II.

Note that a user scheduling problem exists in Group I as $Q < K$. When $Q > 1$, this selection problem cannot be solved by simply choosing the users with the best signal-to-interference-plus-noise ratio (SINR) or signal-to-noise ratio (SNR). Fortunately, there is an existing approach in [24].

In [24], the semiorthogonal user selection (SUS) algorithm is used for scheduling $Q$ active users out of $K$ users through each subcarrier. The SUS algorithm results in a group of users with channel vectors $h_{m,k_{\ell}}$, $q = 1, \ldots, Q$, and

$$1 - \frac{|h_{m,k_{\ell}}^H h_{m,k_{\ell}}^H|^2}{|h_{m,k_{\ell}}^H h_{m,k_{\ell}}^H|^2} > 1 - \epsilon,$$

where $\epsilon$ is a small positive constant. Note that $\epsilon$ is a parameter related to the number of users $K$ similar to $\alpha$ in [24], which is used to find semiorthogonal users. The SUS algorithm chooses the users with semiorthogonal channel directions. Thus, hereafter, we assume that the chosen users in Group I have orthogonal channel directions; that is,

$$h_{m,k_{\ell}} \perp h_{m,k_{\ell}}, \forall m = 1, \ldots, M,

i, j = 1, \ldots, Q, i \neq j.$$  

This becomes true when the number of users $K$ is sufficiently large [24]. We denote by $\mathcal{Q}_{m}$ the set of the Group I active users in each subcarrier $m$. From (5), the beamforming vectors for the $Q$ selected users are simply represented by

$$w_{m,i} = \frac{h_{m,k_{\ell}}}{\|h_{m,k_{\ell}}\|}, i = 1, \ldots, Q.$$  

At a user in Group II, the SINR is given by

$$\text{SINR}_{II,m,u_{m}} = \frac{|g_{m,u_{m}}^H w_{II,m}|^2 P_{II}}{\sum_{i=1}^{Q} |g_{m,u_{m}}^H w_{II,i}|^2 P_{I} + \sigma^2}.$$  

Since $w_{m,i}$ is decided, this SINR can be maximized by maximizing the numerator. That is,

$$\text{maximize} |g_{m,u_{m}}^H w_{II,m}|,$$

subject to $w_{II,m} = h_{m,k_{\ell}}, \forall i = 1, \ldots, Q.$

The optimal beamforming vector is given by

$$w_{II,m} = \frac{1}{\|w_{II,m}\|} \bar{w}_{II,m},$$

where

$$\bar{w}_{II,m} = \left(1 - \sum_{i=1}^{Q} \frac{h_{m,k_{\ell}}^H h_{m,k_{\ell}}^H}{\|h_{m,k_{\ell}}^H h_{m,k_{\ell}}^H\|^2} g_{m,u_{m}}ight).$$
International Journal of Distributed Sensor Networks

\[ (I - \sum_{j=1}^{Q} w_{lm,k}^{H} W_{lm,k}^{H}) g_{m,u} = (I - W_{lm} W_{lm}^{H}) g_{m,u} \]  

(11)

Here \( W_{lm} = [w_{lm,1}, w_{lm,2}, \ldots, w_{lm,Q}] \).

3.2. Motivations for the New Feedback Scheme. With perfect CSI, the optimal beamforming vectors for users in Group II are designed subject to the orthogonal constraints (9). The resulting beamforming vector (11) lies in the null space formed by the column vectors of \( W_{lm} \) and is best aligned to the channel vector \( g_{m,u} \). However, with limited feedback, the exact value of \( g_{m,u} \) is not available at the BS.

In the conventional feedback scheme in [8], each \( g_{m,u} \) is decomposed into two components, that is, the gain and the direction, as follows:

\[ g_{m,u} = \|g_{m,u}\| \hat{g}_{m,u}, \]  

(12)

where \( \hat{g}_{m,u} = g_{m,u}/\|g_{m,u}\| \) is the channel direction. The user computes the SINR and the channel direction, quantizes them according to a codebook and sends them back to the BS.

In conventional feedback schemes, a codebook-based quantizer with a codebook comprised of multiple sets of orthonormal vectors in \( \mathbb{C}^{d} \) is used to quantize the channel direction \( g_{m,u}/\|g_{m,u}\| \). Denote the codebook by \( \mathcal{F} \),

\[ \mathcal{F} = \bigcup_{b=1}^{B} \mathcal{F}^{(b)}, \]  

(13)

where \( \mathcal{F}^{(b)} \) is the \( b \)th orthonormal set in the codebook \( \mathcal{F} \). There are \( L \) mutually orthogonal vectors in each \( \mathcal{F}^{(b)} \), \( b = 1, \ldots, B \). Thus, the codebook size can be denoted by \( |\mathcal{F}| = BL \). For each weight vector \( v \) in the codebook \( \mathcal{F} \), a distortion function \( d(v, \hat{g}_{m,u}) \) is defined as

\[ d(v, \hat{g}_{m,u}) = 1 - \|v^{H} \hat{g}_{m,u}\|^2. \]  

(14)

For the quantization of the channel direction, the member of \( \mathcal{F} \) that has the smallest distortion is chosen as the feedback channel direction; that is,

\[ \hat{g}_{m,u} = \arg \min_{v \in \mathcal{F}} d(v, \hat{g}_{m,u}). \]  

(15)

For the quantization of the SINR, \( G \) bits are used to quantize this scalar value. For analysis convenience, the SINR is always assumed to be known perfectly by the BS. This assumption will be justified in Section 5 where the simulation results show that the throughput loss due to limited SINR feedback is marginal compared with the case in which perfect SINR feedback is available.

In the orthogonal beamforming for users in Group II, the optimal beamforming vectors are designed subject to orthogonal constraints which is illustrated in Figure 1. If \( w_{lm} \) and \( g_{m,u} \) are given, the beamforming vector for \( g_{m,u} \) should lie in the null space of \( h_{m,k} \), that is, the disk perpendicular to \( W_{lm} \). The best beam for \( u_{m} \) is \( w_{lm} \) in Figure 1.

With limited feedback, if we can quantize \( g_{m,u} \) to the vector \( w_{lm} \) as depicted in Figure 1, the BS obtains sufficient information to determine the beamforming vector. It is equivalent to say that if the quantization codebook \( \mathcal{F} \) lies in the null space formed by the column vectors of \( W_{lm} \), we are more likely to get a quantized version of \( g_{m,u} \) as close to \( w_{lm} \) as possible.

In conventional feedback schemes, the codebook is pre-designed and known at both the BS and each user. The vectors in \( \mathcal{F} \) that lie out of null space of \( W_{lm} \) provide redundant information and result in excessive feedback bits. Meanwhile it is not possible to change \( \mathcal{F} \) flexibly according to a given \( W_{lm} \). A new feedback scheme is needed in orthogonal beamforming for MTCG gateways.

3.3. Orthogonal Beamforming with Limited Feedback. We propose a new MBS strategy where a group of beamforming vectors for the MTCG gateway is generated by the BS and broadcasted through the downlink channel.

Suppose that the \( Q \) active users in Group I have been chosen and the beamforming matrix is denoted by \( W_{lm} \). The
size of $W_{lm}$ is $L \times Q$. For an extra user from Group II, we generate $N$ new candidate beamforming vectors as follows:

$$C_{II,m} = \frac{\overline{C}_{II,m}}{\overline{\|C_{II,m}\|}},$$

$$C_{II,m} = (1 - W_{lm} W_{lm}^H) U_m,$$

where $U_m$ is a random matrix of size $L \times N$. Each column vector of $C_{II,m}$ is a normalized weight vector. The set of the column vectors of $C_{II,m}$ is denoted by $\{c_{m,1}, \ldots, c_{m,N}\}$.

For the scheduling of a MTCD gateway, the BS should transmit $N$ pilot signals to let them choose the best beam among $N$ beams, $\{c_{m,1}, \ldots, c_{m,N}\}$. The resulting beam selection problem can be given by

$$\max_n \text{SINR}_{II,m,u,n},$$

where the SINR is given by

$$\text{SINR}_{II,m,u,n} = \frac{\|g_{m,n}^H c_{m,u}\|^2 P_{II}}{\sum_{q=1}^{Q} \|g_{m,n}^H W_{lm}^q\|^2 P_I + \sigma^2}.$$  \hspace{1cm} (18)

The SINR expressions in (17) and (18) are replaced by $\text{SINR}_{II,m,u,n}$ in order to emphasize their dependence on $n$ or $c_{m,n}$, the beamforming candidate. The detailed process is described as follows.

(1) The BS broadcasts $c_{m,1}, \ldots, c_{m,N}$ when choosing a user in Group II by employing a series of the beamforming matrices, $[W_{lm}, C_1], \ldots, [W_{lm}, C_N]$ for $N$ symbol durations. At the user $u_m$ in Group II, the received signal when the $n$th pilot signal is transmitted is given by

$$y_{m,u} = g_{m,n}^H \left( \sum_{q=1}^{Q} W_{lm,q} f_{m,q} + c_{m,n} b_{m,n} \right) + v_{m,u},$$

where $c_{m,q,n}$ and $b_{m,n}$ denote the $n$th pilot signals to the $q$th user in Group I and the user in Group II, respectively.

(2) After receiving all the $N$ pilot signals, each user in Group II estimates the local SINR, namely, $\text{SINR}_{II,m,u,n}$, with different beams, $n = 1, \ldots, N$. The $\text{SINR}_{II,m,u,n}$s are assumed to be known perfectly at each user $u_m$.

(3) The users choose the best beam among all the pilot beams according to (17) and sends the index of the best beam $n_{u,m}^*$ to the BS.

$$n_{u,m}^* = \arg \max_{n \in \{1, \ldots, N\}} \text{SINR}_{II,m,u,n}.$$  \hspace{1cm} (20)

If there are more than one beam that are equally the best, the user randomly chooses one of them and feeds the index back.

(4) At each user, the SINRs of the best beam through each subcarrier are quantized using $G$ bits as follows:

$$\text{SINR}_{II,m,u,n,u}^* \rightarrow \overline{\text{SINR}}_{II,m,u,n,u}^*.$$  \hspace{1cm} (21)

Through subcarrier $m$, only the quantized SINRs of the best beam at each user, namely, $\text{SINR}_{II,m,u,n,u}^*$, are sent back through the feedback channel.

In order to minimize the impact of the interference from the signals to users in Group I or maximize the throughput for users in Group II, the subcarrier allocation for Group II users can be carried out as follows:

$$u_m^* = \arg \max_{u \in \{1, \ldots, U\}} \log_2 \left( 1 + \overline{\text{SINR}}_{II,m,u,n,u}^* \right)$$

$$= \arg \max_{u \in \{1, \ldots, U\}} \text{SINR}_{II,m,u,n,u}^*,$$

and the corresponding beamforming vectors are selected as the final beam

$$n_{u,m}^*.$$  \hspace{1cm} (23)

That is, for each subcarrier, the user in Group II who maximizes the achievable rate, namely, $\log_2(1 + \text{SINR}_{II,m,u,n,u}^*)$, is to be selected. The set of subcarriers allocated to user $u$ is given by

$$M_u = \{m \mid u_m^* = u, m = 1, \ldots, M\}.$$  \hspace{1cm} (24)

Thus, the estimated throughput for user $u$ is given by

$$R_u = \sum_{m \in M_u} \log_2 \left( 1 + \overline{\text{SINR}}_{II,m,u,n,u}^* \right).$$  \hspace{1cm} (25)

4. Asymptotic Throughput Performance

In this section, we analyze the performance of the proposed MBS scheme asymptotically when $N \to \infty$. When $N \to \infty$, there is always a beam that is perfectly aligned to the channel direction of each user. From (11) and (16), if one column of $U_m$ is aligned with $g_{m,u,n}$, then $g_{m,u,n}$, the MBS scheme achieves the ideal performance with perfect CSI at the BS.

In this section the asymptotic throughput performance is first derived with perfect CSI feedback. In order to obtain a useful expression that characterizes the system performance with limited feedback, a lower bound on the asymptotic throughput performance is then derived.

Assumption 1. The elements of $h_{m,u,n}$ and $g_{m,u,n}$ are independent and identically distributed (i.i.d.) and CSCG random variables, $\mathcal{CN}(0, 1/L)$.

Hereafter, we consider performance analysis for users in Group II under the CSCG Assumption 1. For convenience, define the SNR at user $u_m$ in Group II as

$$\gamma_{II,m,u} = \frac{\|g_{m,u,n}\|^2 P_{II}}{\sigma^2}.$$  \hspace{1cm} (26)
Furthermore, define
\[ \xi_m (\theta_m, u_m) = 1 - \frac{\| H_{\theta_m} W_{L_m} \|^2}{\| H_{\theta_m} \|^2}. \] (27)

Then, we have
\[ \text{SINR}_m = \frac{\xi_m (\theta_m, u_m)}{1 - \xi_m (\theta_m, u_m)} \left( \frac{P_I}{P_{II}} + \frac{1}{\gamma_{\theta_m, u_m}} \right). \] (28)

In (28), \( \text{SINR}_m \), which is the SINR at user \( u_m \) in Group II, is replaced with \( \text{SINR}_{\theta_m, u_m} \). The proof of (28) is given in Appendix A.

Assumption 2. The distribution of \( 1 - \xi_m (\theta_m, u_m) \) can be approximated by a beta distribution with the parameters \( Q \) and \( L - 1 \). Note that the approximation becomes more accurate when \( L \to \infty \).

That is, we have
\[ 1 - \xi_m (\theta_m, u_m) \sim B (Q, L - 1) \] (30)
or
\[ \xi_m (\theta_m, u_m) \sim \frac{1}{B (a, b)} (1 - y)^{a-1} y^{b-1}, \quad 0 \leq y \leq 1, \] (31)
where \( B(a, b) \) is the beta function and \( a = Q, b = L - 1 \).

Now, we present numerical results to verify Assumption 2. In Figure 2, the number of users in Group I is set to \( Q = 4 \). Both the approximate and empirical distributions of \( 1 - \xi_m (\theta_m, u_m) \) are illustrated for different number of transmitter antennas \( L = 10, 20, 40 \). When \( L = 40 \), approximation (30) fits well with the empirical distribution. Figure 3 shows the results when the number of users in Group I is set to \( Q = 2 \). The same transmitter antenna arrays are considered as those in Figure 2. It is shown that the approximate distribution is reasonable especially when there are less users in Group I.

The probability density function (PDF) of \( z = \xi_m (\theta_m, u_m)/(1 - \xi_m (\theta_m, u_m)) \) is given by
\[ \frac{\xi_m (\theta_m, u_m)}{1 - \xi_m (\theta_m, u_m)} \sim f (z) = \frac{1}{B (a, b)} z^{a-1} (1 + z)^{b-1}, \quad 0 \leq z < \infty \] (32)
and the cumulative distribution function (CDF) by
\[ F (z) = \Pr \left( \frac{\xi_m (\theta_m, u_m)}{1 - \xi_m (\theta_m, u_m)} \leq z \right) = 1 - I_{1/(1+z)} (a, b), \] (33)

where \( I_x (a, b) \) is the incomplete beta function. The CDF of the maximum SINR among \( U \) independent users in Group II is
\[ F_{\max} (z) = \Pr \left( \max_u \frac{\xi_m (\theta_m, u)}{1 - \xi_m (\theta_m, u)} \leq z \right) = I_{z}^{U} (1 - I_{1/(1+z)} (a, b)) \] (34)

The outage probability of the maximum SINR is defined as
\[ P_{\text{out}} (\Gamma) = \Pr \left( \max_u \text{SINR}_m \leq \Gamma \right), \] (35)
where \( \Gamma \) is the target threshold SINR.
Using the upper bound in (29), a lower bound on the outage probability of the SINR can be found. Since

\[
\max_u \text{SINR}_{\text{II},m,u,\sigma_m} \\
\leq \max_u \min \left\{ \frac{\xi_m(\theta_m,u)}{1-\xi_m(\theta_m,u)} \frac{P_{\text{II}}}{P_1} \gamma_{\text{II},m,u} \right\} \\
\leq \min \left\{ \max_u \frac{\xi_m(\theta_m,u)}{1-\xi_m(\theta_m,u)} \frac{P_{\text{II}}}{P_1} \gamma_{\text{II},m,u} \max_u \gamma_{\text{II},m,u} \right\},
\]

we have

\[
P_{\text{out}}(\Gamma) \geq 1 - \left( 1 - F_{\chi^2}(\Gamma) \right) \left( 1 - F_{\chi^2}(\frac{2\sigma^2\Gamma}{P_{\text{II}}}) \right),
\]

where \(F_{\chi^2}(\cdot)\) denotes the chi-square CDF with \(n\) degrees of freedom. The proof of (37) is in details given in Appendix B.

The average achievable rate per subcarrier for Group II is

\[
\bar{r} = E \left[ \log_2 \left( 1 + \max_u \text{SINR}_{\text{II},m,u,\sigma_m} \right) \right],
\]

and the average throughput per becomes

\[
E \left[ R_u \right] = \frac{M}{U} \bar{r}.
\]

We consider a lower-bound on the average achievable rate using the outage probability in (37). For a given target threshold SINR \(\Gamma\), we have

\[
\bar{r} \geq E \left[ \log_2 \left( 1 + \max_u \text{SINR}_{\text{II},m,u,\sigma_m} \right) \right] \\
\geq \text{Pr} \left( \max_u \text{SINR}_{\text{II},m,u,\sigma_m} < \Gamma \right) \times 0 \\
+ \text{Pr} \left( \max_u \text{SINR}_{\text{II},m,u,\sigma_m} > \Gamma \right) \log_2 (1 + \Gamma) \\
= (1 - P_{\text{out}}(\Gamma)) \log_2 (1 + \Gamma).
\]

A tight lower-bound on \(\bar{r}\) can be achieved if the lower-bound is maximized with respect to \(\Gamma\), which results in

\[
E \left[ R_u \right] \geq \frac{M}{U} \max_u \left( 1 - P_{\text{out}}(\Gamma) \right) \log_2 (1 + \Gamma).
\]

Note that the asymptotic throughput performance is first characterized by (39) using (28). This result is then lower-bounded in (41). We will use (41) as an indication of the system performance with limited feedback.

### 5. Simulation Results

In this section we present various numerical results to further investigate the performance of the proposed MBS scheme. The simulation settings are described as follows: the channel elements are independent and identically distributed (i.i.d.) CSCG random variables, that is, \(\mathcal{C} \sim \mathcal{N}(0,1/L)\); the cellular radius is normalized as one; the base band channel is considered in the simulation without a specified radio frequency.

In the following two subsections, we will first assume that the BS knows each users’ SINR: in Section 5.1, the effect of increasing feedback bits, that is, increasing the number of candidate beams \(N\), is investigated; in Section 5.2, the throughput performance of the proposed MBS is compared with that of the conventional feedback scheme. Then, in the last subsection, the effect of limited feedback of SINR is shown with different number of users in Group II. The simulation results are presented under Assumption 1 with \(M = 128\), \(P_1 = P_{\text{II}}\), and \(P_{\text{II}}/\sigma^2 = 20\) dB.

#### 5.1. Effect of Increasing Feedback Bits

Simulation results for different number of active users in Group I are presented to show the effect of increasing feedback bits. As conceived, the throughput per MTCD gateway increases as the increase of the number of beams generated by the BS, unlike the results in [8] where increasing channel shape feedback does not necessarily lead to better performance.

In Figure 4, the number of transmitter antennas is set to \(L = 10\). Only single active user is considered in Group I. From Figure 4, when the number of beams increases from 1 to 10 beams with \(U = 2\), we can see that the throughput increases about 80%. The lower bound of the asymptotic performance is also plotted in Figure 4. Theoretical result (41) gives a good prediction of the system performance with limited feedback.

In Figures 5 and 6, the number of active users in Group I are 2 and 4, respectively. As expected, theoretical result (41) can be used as a good indication of the system performance with limited feedback.

#### 5.2. Comparison with Conventional Feedback Schemes

From the analysis in Section 3, the proposed MBS scheme achieves better performance than the conventional feedback schemes. In this subsection, numerical results are given to verify our analysis.
In Figure 7, the performances of the proposed feedback scheme and the conventional one are compared with an increasing number of users in Group II. The number of beams generated by the BS in our proposed scheme and the number of the vectors in the codebook of the conventional feedback are the same and set to $N = 256$. The orthogonal beamforming matrices of the conventional feedback are generated using a method in [8]. As expected, the proposed feedback scheme outperforms the conventional one, especially when the number of active users in the Group is small. In general, a throughput increase of about 10% over the conventional feedback scheme is achieved by the proposed MBS.

5.3. Effect of SINR Quantization. The analyses and simulations above are based on the assumption that the BS has perfect knowledge of each user’s SINR. The effect of quantization of SINR on the performance is shown using numerical simulations in this subsection.

Figure 8 compares the cases of perfect and quantized SINR feedback with $G$-bit quantization, $G = 2, 3,$ and $4$. A simple scalar quantizer with equally spaced codebook is used to quantize each user’s SINR on the best beam. The number of beams generated by the BS $N = 10$, and the number of transmitter antennas $L = 10$. From Figure 8, we can see that the performance degradation is small. A magnified observation in Figure 8 shows that 4-bit feedback of SINR is sufficient for a performance as good as perfect feedback. From Figure 8, the throughput loss due to limited feedback of SINR is shown to be considerably low, even by employing few number of feedback bits. The same observation is made in the conventional feedback of per user unitary and rate control (PU2RC). In [8], 3 bits for SINR feedback is found to be sufficient to make the capacity loss due to negligible SINR quantization.

6. Conclusions

In this paper, we propose a scheme to combine cellular networks and M2M networks. The devices in an M2M network access a cellular network through some gateways, which are assumed as secondary users in the cellular network. With limited feedback of CSI at the BS, the new MBS method is proposed for the MTCD gateways with an overlaid...
transmission mode. The asymptotic performance of the proposed MBS method is characterized. Using a lower bound on the throughput with perfect CSI, we obtain a useful expression that shows the system performance with limited feedback. Simulation results show that, when the BS is equipped with 6 antenna elements, the throughput was improved by about 10\% when the proposed MBS method is employed compared with the conventional ones.

Appendices

A. Proof of (28)

In order to make the proving process convenient, we omit the subscripts in the following derivations. Denote $\text{SINR}_{i,m,u,c_m} = \text{SINR}_{w_{i,m}}$, and $w_{i,m}$ by $\text{SINR}$, $g$, $w$, and $w_{i}$, respectively.

From (7), the SINR is

$$\text{SINR} = \frac{|g^H w|^2 P_{i,m}}{\|g^H W^g\|^2 P_{i,m} + \sigma^2}. \quad (A.1)$$

From (10), the beamforming vector for the MTCD gateway is

$$w = \frac{1}{\|\bar{w}\|} \bar{w}, \quad (A.2)$$

where

$$\bar{w} = (I - W_i W_i^H) g,$$

$$\|\bar{w}\| = \sqrt{\bar{w}^H \bar{w}} = \sqrt{g^H (I - W_i W_i^H) (I - W_i W_i^H) g} \quad (A.3)$$

Equation (a) is due to the following features of the matrix $A = (I - W_i W_i^H)$:

1. $A^H = A$
2. $A^n = A, n = 1, 2, \ldots$

The numerator of SINR is

$$|g^H W_i^g|^2 P_{i,m} = \frac{|g^H (I - W_i W_i^H) g|^2}{\|g^H W_i^g\|^2} P_{i,m}$$

$$= \frac{|g^H (I - W_i W_i^H) g|^2}{\|g^H g||^2 - \|g^H W_i^g||^2} P_{i,m}$$

$$= \frac{|g^H (I - W_i W_i^H) g|^2}{\|g^H g|^2 - \|g^H W_i^g||^2} P_{i,m}$$

$$= (\|g^H g|^2 - \|g^H W_i^g||^2) P_{i,m}.$$ \quad (A.4)

The denominator of SINR is

$$\|g^H W_i^g||^2 P_{i,m} + \sigma^2. \quad (A.5)$$

Thus, the SINR is

$$\text{SINR} = \frac{(1 - (\|g^H W_i^g||^2 / \|g^H g||^2))}{(\|g^H W_i^g||^2 / \|g^H g||^2) (P_{i,m} / P_{i,m}) + (\sigma^2 / \|g^H g||^2)}.$$ \quad (A.6)

Define $\xi = 1 - (\|g^H W_i^g||^2 / \|g^H g||^2)$, and $\gamma_{i,m} = (\|g^H g||^2 / \sigma^2$. The SINR expression becomes

$$\text{SINR} = \frac{\xi}{(1 - \xi)(P_{i,m} / P_{i,m}) + \gamma_{i,m}.} \quad (A.7)$$

Thus, we have

$$\text{SINR}_{i,m,u,c_m} = \frac{\xi_m (C_{i,m}, u_m)}{(1 - \xi_m (C_{i,m}, u_m)) (P_{i,m} / P_{i,m}) + \gamma_{i,m}}.$$ \quad (A.8)

B. Proof of (37)

Consider

$$P_{\text{out}}(\Gamma) = \text{Pr} \left( \max_{u} \text{SINR}_{i,m,u,c_m} \leq \Gamma \right)$$

$$\geq \text{Pr} \left( \min_{u} \max_{u} \frac{\xi_m (C_{i,m}, u)}{1 - \xi_m (C_{i,m}, u)} P_{i,m} \frac{\gamma_{i,m}}{u} \right) \leq \Gamma \right)$$

$$= 1 - \text{Pr} \left( \max_{u} \frac{\xi_m (C_{i,m}, u)}{1 - \xi_m (C_{i,m}, u)} P_{i,m} \frac{\gamma_{i,m}}{u} > \Gamma \right)$$

$$= 1 - \text{Pr} \left( \max_{u} \frac{\xi_m (C_{i,m}, u)}{1 - \xi_m (C_{i,m}, u)} P_{i,m} > \Gamma \right)$$

$$\times \text{Pr} \left( \max_{u} \gamma_{i,m} > \Gamma \right). \quad (B.1)$$
Using the CDF of the maximum SINR among $U$ independent users (34), the first multiplier in (B.1) is

$$
\Pr \left( \max_u \text{Pr} \left( \frac{\sum_m \xi_m (\phi_m, u)}{1 - \sum_m \xi_m (\phi_m, u)} > \frac{P_{\text{II}}}{P_1} \right) > \frac{P_{\text{II}}}{P_1} \right) = 1 - F_{\max} \left( \frac{P_{\text{II}}}{P_1} \right).
$$

(B.2)

Now we calculate the second multiplier in (B.1). From (26) and Assumption I, $\gamma_{U,m} \sim \chi^2$ is distributed with $2L$ degrees of freedom and $1/2L$ variance. Denote $F_{\chi^2}(z)$ as the chi-square CDF with $n$ degrees of freedom and unit variance. From [25],

$$
F_{\chi^2}(z) = \int_0^z \frac{1}{2^{n/2} \Gamma ((1/2) n)} t^{(n-2)/2} e^{-t/2} dt,
$$

(B.3)

where $\Gamma(x)$ is the gamma function. The CDF of $\gamma_{U,m}$ is $F_{\chi^2}(2Lz)$. Thus,

$$
\Pr \left( \max_u \gamma_{U,m} > \Gamma \right) = 1 - F_{\chi^2} \left( \frac{2Lz^2 \Gamma}{P_{\text{II}}} \right).
$$

(B.4)

From (B.1), (B.2), and (B.4), we have

$$
P_{\text{out}} (\Gamma) \geq 1 - \left( 1 - F_{\max} \left( \frac{P_{\text{II}}}{P_1} \right) \right) \left( 1 - F_{\chi^2} \left( \frac{2Lz^2 \Gamma}{P_{\text{II}}} \right) \right).
$$

(B.5)

Acknowledgments

The authors would like to thank the anonymous reviewers for their valuable comments that have helped in improving the overall quality of the paper. This work has been supported by the Specialized Research Fund for the Doctoral Program of the Ministry of Education of China (Grand no. 20122001120125) and the National Natural Science Foundation of China (Grants no. 61250001, no. 61231011, and no. 61231013).

References

[1] J. Zhang, L. Shan, H. Hu, and Y. Yang, “Mobile cellular networks and wireless sensor networks: toward convergence,” *IEEE Communications Magazine*, vol. 50, no. 3, pp. 164–169, 2012.

[2] G. Wang, X. Zhong, S. Mei, and J. Wang, “An adaptive medium access control mechanism for cellular based machine to machine (M2M) communication,” in *Proceedings of the IEEE International Conference on Wireless Information Technology and Systems (ICWITS’10)*, pp. 164–169, September 2010.

[3] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, “Radio resource allocation in LTE-advanced cellular networks with M2M communications,” *IEEE Communications Magazine*, vol. 50, no. 7, pp. 184–192, 2012.

[4] 3GPP TR 23.888 v0.5.1, “System Improvements for Machine-Type Communications (Release 10),” July 2010.

[5] N. Tyler, B. Allen, and H. Aghvami, “Adaptive antennas: the calibration problem,” *IEEE Communications Magazine*, vol. 42, no. 12, pp. 114–122, 2004.

[6] S. Nanda, R. Walton, J. Ketchum, M. Wallace, and S. Howard, “A high-performance MIMO OFDM wireless LAN,” *IEEE Communications Magazine*, vol. 43, no. 2, pp. 101–109, 2005.

[7] D. J. Love, R. W. Heath, W. Santipach, and M. L. Honig, “What is the value of limited feedback for MIMO channels?” *IEEE Communications Magazine*, vol. 42, no. 10, pp. 54–59, 2004.

[8] K. Huang, J. G. Andrews, and R. W. Heath, “Performance of orthogonal beamforming for SDMA with limited feedback,” *IEEE Transactions on Vehicular Technology*, vol. 58, no. 1, pp. 152–164, 2009.

[9] T. Yoo, N. Jindal, and A. Goldsmith, “Multi-antenna downlink channels with limited feedback and user selection,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 7, pp. 1478–1491, 2007.

[10] Y. Ko and C. Tepedelenlioglu, “Orthogonal space-time block coded rate-adaptive modulation with outdated feedback,” *IEEE Transactions on Wireless Communications*, vol. 5, no. 2, pp. 290–295, 2006.

[11] Y. Ma, D. Zhang, A. Leith, and Z. Wang, “Error performance of transmit beamforming with delayed and limited feedback,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1164–1170, 2009.

[12] R. Bhagavatula and R. W. Heath, “Adaptive bit partitioning for multicell intercell interference nulling with delayed limited feedback,” *IEEE Transactions on Signal Processing*, vol. 59, no. 8, pp. 3824–3836, 2011.

[13] C. R. Murthy, J. Zheng, and B. D. Rao, “Performance of quantized equal gain transmission with noisy feedback channels,” *IEEE Transactions on Signal Processing*, vol. 56, no. 6, pp. 2451–2460, 2008.

[14] T. Wu and V. K. N. Lau, “Robust rate, power and precoder adaptation for slow fading MIMO channels with noisy limited feedback,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 6, pp. 2360–2367, 2008.

[15] S. Ekbatani, F. Etemadi, and H. Jafarkhani, “Outage behavior of quasi-static fading channels with partial power control and noisy feedback,” in *Proceedings of the 50th Annual IEEE Global Telecommunications Conference (GLOBECOM ’07)*, pp. 1556–1560, November 2007.

[16] D. J. Love, R. W. Heath, V. K. N. Lau, D. Gesbert, B. D. Rao, and M. Andrews, “An overview of limited feedback in wireless communication systems,” *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 8, pp. 1341–1365, 2008.

[17] C. K. Au-Yeung and D. J. Love, “On the performance of random vector quantization limited feedback beamforming in a MISO system,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 2, pp. 458–462, 2007.

[18] S. H. Simon and A. L. Moustakas, “Optimizing MIMO antenna systems with channel covariance feedback,” *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 406–417, 2003.

[19] E. A. Jorswieck and H. Boche, “Channel capacity and capacity-range of beamforming in MIMO wireless systems under correlated fading with covariance feedback,” *IEEE Transactions on Wireless Communications*, vol. 3, no. 5, pp. 1543–1553, 2004.

[20] N. Sharma and L. H. Ozarow, “A study of opportunism for multiple-antenna systems,” *IEEE Transactions on Information Theory*, vol. 51, no. 5, pp. 1804–1814, 2005.

[21] W. Choi, A. Forenza, J. G. Andrews, and R. W. Heath, “Opportunistic space–division multiple access with beam selection,” *IEEE Transactions on Communications*, vol. 55, no. 12, pp. 2371–2380, 2007.
[22] J. Choi and J. Ha, “Orthogonal beamforming for overlay mode of OFDMA-based rural broadband wireless access,” in Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC’12), Paris, France, April 2012.

[23] J. Choi, Optimal Combining and Detection: Statistical Signal Processing For Communications, Cambridge University Press, New York, NY, USA, 2010.

[24] T. Yoo and A. Goldsmith, “On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming,” IEEE Journal on Selected Areas in Communications, vol. 24, no. 3, pp. 528–541, 2006.

[25] J. Proakis, Digital Communications, McGraw-Hill, New York, NY, USA, 1995.
