Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2012, Article ID 213727, 9 pages
doi:10.1155/2012/213727

Research Article

Distributed Beamforming for Relay Assisted Multiuser Machine-to-Machine Networks

Chen Chen,[1] Lin Bai,[2] Meiping Feng,[1] Minhua Huang,[1] and Tian Tian[3]

[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*
[3] *Strategic Investment Department, China Unicom, Beijing 100033, China*

Correspondence should be addressed to Lin Bai, l.bai@buaa.edu.cn and Meiping Feng, feng.meiping@pku.edu.cn

Received 20 April 2012; Revised 5 July 2012; Accepted 9 July 2012

Academic Editor: Jianhua He

We consider signal transmission with the aid of multiple half-duplex single-antenna relay nodes using the amplify-and-forward (AF) strategy for a multiuser wireless machine-to-machine (M2M) communication system. In such a scenario, relay beamforming has been proved to be an effective way to improve system performance by employing spatial diversity gains. Early works have mostly focused on various centralized relay beamforming schemes based on global channel state information (CSI). Since global CSI is often unavailable due to geometric locations, power limitation, or other constraints of the relay nodes in M2M networks, our work aims to develop distributed algorithms that each relay node individually learns its own beamforming weights with local CSI. We propose two suboptimal relay beamforming schemes that only require local CSI to minimize mean square error (MSE) for all the users with nonorthogonal channels. For multiuser systems with orthogonal channels, we divide the optimization problem into multiple single user problems which then can be solved by each relay independently. Numerical simulations for the proposed algorithms are presented showing the performance of the proposed schemes is close to that of the optimal scheme with global CSI in terms of bit error rate (BER) criterion.

1. Introduction

With the ability to provide reliable transmission and improve the coverage and capacity of wireless networks, cooperative communication using relay beamforming has attracted considerable attention [1]. Multiple cooperative relays can act as a virtual array of transmit antennas to provide spatial multiplexing and hence gain diversity for users. Such kind of relay techniques can be employed in many different communication scenarios. For instance, relays can be placed at the edge of a cell to extend the coverage of the network or at the intersection of adjacent cells for interference coordination [2]. Wireless machine-to-machine (M2M) sensor networks are another possible applications. In these networks, signals can be relayed by one or more relay sensor nodes while they might be attenuated beyond detection by propagation loss if directly targeting the destination sensor nodes, due to the low-power machine devices [3]. Also, the spatial diversity of distributed relays can help to mitigate the effect of fading channels.

Typically, communications with the aid of relay beamforming are implemented in two phases where the relays work in a half-duplex mode. In the first phase, signals are broadcast from source nodes to relay nodes. In the second phase, the relay nodes process the received signals according to relay beamforming strategies and then forward the processed messages to destination nodes. Orthogonal or nonorthogonal transmissions can be used in cooperative communication. In this paper, transmission systems over orthogonal channels are referred to as orthogonal systems, where each source node transmits messages to its destination node through a dedicated orthogonal channel with the help of relays. A practical example of such kind of system is the M2M networks that based on the long-term evolution or long-term evolution-advanced (LTE/LTE-A) system, in which each user receives its signals through an orthogonal frequency-division multiplexing (OFDM) subchannel. Transmission systems over nonorthogonal channels are referred to as nonorthogonal systems, where all users transmit signals simultaneously in a multiple access channel and cause interference to each other. Such kind of multiple access channel system can be realized with time division multiple access (TDMA). Since M2M networks could be connected by various wireless network technologies, we consider both orthogonal and nonorthogonal systems in this paper.

In general, there are broadly three kinds of relay beamforming strategies: amplify-and-forward (AF), compress-and-forward (CF), and decode-and-forward (DF) [4–6]. In the AF strategy, relay nodes receive and amplify the signals transmitted from the source nodes and forward them to the destination nodes. Among the three strategies, the AF strategy is the most attractive one due to its low implementation complexity, which means low cost for the relay node devices and is essentially important for M2M sensor networks with large amounts of distributed relay sensor nodes. In our paper, the AF beamforming strategy is used in relay schemes for M2M sensor networks.

Various research work has been presented to propose AF relay beamforming schemes. To guarantee certain quality of service (QoS), relay beamforming approaches are mostly focused on signal-to-noise ratio (SNR) at the destinations for single user systems or orthogonal multiuser systems and signal-to-interference-plus-noise ratio (SINR) for nonorthogonal multiuser systems. Optimal relay beamforming schemes with relay power constraints are studied in [7, 8], in which algorithms are designed to achieve maximum SNR (MSNR) for a single user system and an orthogonal multiuser system, respectively. In [9], optimal relay beamforming weights for a nonorthogonal multiuser system are found to meet a given set of target SINR at the destinations while minimizing transmission power at the relays. These relay schemes aiming to MSNR or target SINR assume that all the relay nodes can communicate with each other and therefore each relay has global channel state information (CSI), that is, channel coefficients of all the relay nodes. The requirement of global CSI makes the MSNR or target SINR relay beamforming schemes not applicable for M2M sensor networks with a large number of relay nodes, where either the overhead of CSI exchange could be exceedingly high or even CSI exchange among relay nodes might be impossible due to the geographical locations of the relay nodes. It is appealing to derive an algorithm that each relay can learn its own beamforming weights independently based on local CSI without knowing other relays' channel information. To avoid the need of global CSI, minimum mean square error (MMSE) criterion instead of MSNR or target SINR is considered in [10–12]. In [10], MMSE-based approaches subject to individual power constraints with local CSI are derived for a single user system, which yield suboptimal but effective results. It is also demonstrated in [12] that the MMSE-based distributed implementation of signal detection can guarantee the system performance close to that of joint implementation with global CSI. However, the previous works do not consider the relay networks, such as the M2M networks. As a result, it is expected that the MSE cost function can be used to design the relay beamforming schemes with local CSI for multiuser M2M sensor networks. Thus, in our work, we study the distributed beamforming scheme with multiple relay nodes. The MSE cost function instead of the SNR or SINR cost function is considered for relay beamforming schemes. We aim at developing efficient distributed relay beamforming algorithms with local CSI that minimize the sum MSE of all users for a multiuser wireless M2M network using the AF strategy. We define MMSE as the minimum of sum MSE of all users in this paper, and, therefore, the relay beamforming schemes studied in our work are also referred to as the MMSE-based relay beamforming schemes.

The rest of the paper is organized as follows. In Section 2, the system model for relay assisted multiuser M2M networks is presented. In Section 3, we study the relay beamforming schemes with local CSI that minimizes the sum MSE of all users in nonorthogonal systems. Relay beamforming schemes for orthogonal systems are discussed in Section 4. In Section 5, simulation results under various conditions are presented. Conclusion of the paper can be found in Section 6.

Notations. Bold lower letters are used for vectors, for example, $\mathbf{x}$, and bold capital letters for matrices, for example, $\mathbf{X}$. $[\mathbf{X}]_{ij}$ stands for the (i,j)th element of $\mathbf{X}$. $\mathbf{diag}(\mathbf{x})$ denotes a diagonal square matrix with vector $\mathbf{x}$ as the diagonal elements. Superscripts $\mathbf{X}^{\mathcal{T}}$, $\mathbf{X}^*$, and $\mathbf{X}^\dagger$ stand for transpose, complex conjugate, and Hermitian transpose of $\mathbf{X}$, respectively. $|x|$ takes the modulus of a complex number and $\|\mathbf{X}\|$ gives the Frobenius norm of a vector or matrix. In this paper, the operator $\cdot$ stands for element-wise multiplication. The real and complex number fields are denoted by $\mathbb{R}$ and $\mathbb{C}$. $\mathbb{E}$ is the expectation operator. The notation $x \sim \mathcal{CN}(m, \sigma^2)$ means that x is a complex Gaussian random variable with mean m and variance σ^2.

2. System Model

Consider an AF relay assisted wireless M2M network, consisting of L pairs of source-destination user nodes and K relay nodes. All the users and the relays are equipped with only one antenna. As discussed in Section 1, relays operate in a half-duplex mode, that is, they cannot receive and transmit at the same time. The communication is implemented in two phases. Assume there is no direct link between any source node and destination node. In this paper, we consider both orthogonal and nonorthogonal systems. In orthogonal system, each user-destination pair takes up one orthogonal subchannel and the relay nodes design different sets of beamforming weights for different users. In nonorthogonal systems, each user causes interference to the other users in the same system, and only one set of beamforming weights are designed for all the users to cooperatively transmit all the signals to the destination nodes on the same frequency band. In addition, both cases face the relay power transmission constraints. The system model is depicted in Figure 1.

Let $\mathbf{s} = [s_1, \ldots, s_L]^{\mathcal{T}}$, an $\mathbf{L} \times 1$ column vector, denote the transmitted signal vector from the L source nodes. It is assumed that each source node transmits at the same power level, that is, $P_s = \mathbb{E}[|s_i|^2]$ with $\mathbb{E}(s_i) = 0$ for $i = 1, \ldots, L$. $\mathbf{h}_i = [h_{i1}, h_{i2}, \ldots, h_{iK}]^{\mathcal{T}} \in \mathbb{C}^{K\times 1}$ is

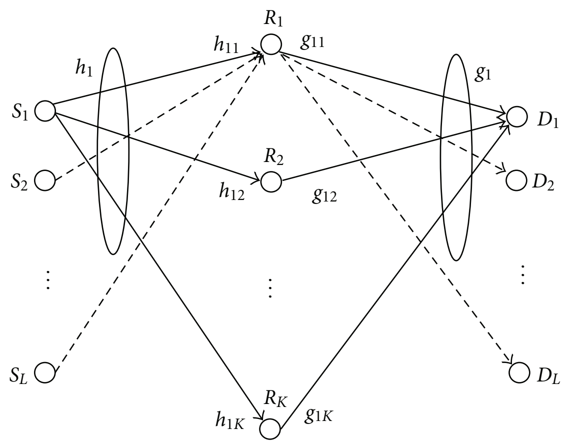

FIGURE 1: AF multiuser multirelay M2M communication system model.

the channel coefficient vector from source node i to the K relay nodes. Column vector $\mathbf{g}_i = [g_{i1}, g_{i2}, \ldots, g_{iK}]^{\mathcal{T}} \in \mathbb{C}^{K\times 1}$ is the channel coefficient vector from the K relay nodes to destination node i. In nonorthogonal systems, $\mathbf{n}_r = [n_{r1}, n_{r2}, \ldots, n_{rK}]^{\mathcal{T}}$ represents the relay background noise over the shared channel, with independent variable $n_{ri} \sim \mathcal{CN}(0, \sigma_{ri}^2)$ denoting the background noise at relay i, for $i = 1, \ldots, K$. In orthogonal systems, $\mathbf{n}_{lr} = [n_{lr1}, n_{lr2}, \ldots, n_{lrK}]^{\mathcal{T}}$ represents the relay background noise over the subchannel of user l, with independent variable $n_{lri} \sim \mathcal{CN}(0, \sigma_{lri}^2)$ denoting the background noise at relay i, for $i = 1, \ldots, K$. $n_i \sim \mathcal{CN}(0, \sigma_{di}^2)$ is the background noise at destination i.

As in most research work, in this paper, all the channels are assumed to be independent, with a Rayleigh flat fading distribution expressed as $h_{ij} \sim \mathcal{CN}(0, \sigma_h^2)$ and $g_{ij} \sim \mathcal{CN}(0, \sigma_g^2)$ for all i and j. For convenience, we assume that each relay faces a same level of added white Gaussian noise (AWGN), that is, $\sigma_{ri}^2 = \sigma_{rli}^2 = \sigma_r^2$, for $i = 1, \ldots, K$ and $l = 1, \ldots, L$. The power of AWGN at each destination node is assumed to be the same, that is, $\sigma_{di}^2 = \sigma_0^2$, for $i = 1, \ldots, L$.

2.1. Nonorthogonal Channel Scenario. If the channels are nonorthogonal, the received signals at the relays in the first phase can be written as

$$\mathbf{r} = \sum_{l=1}^{L} \mathbf{h}_l s_l + \mathbf{n}_r, \tag{1}$$

where $\mathbf{r}$ is a $\mathbb{C}^{K\times 1}$ column vector $(r_1, \ldots, r_K)^{\mathcal{T}}$ and r_i is the signal received by the ith relay.

The relays then process the received signals with complex beamforming weights. Define a row vector $\mathbf{w} = [w_1, \ldots, w_K] \in \mathbb{C}^{1\times K}$ as the beamforming weight vector. The signals transmitted by the relays can be expressed as

$$\mathbf{x} = \mathbf{w}^{\mathcal{T}} \cdot \mathbf{r}. \tag{2}$$

In the second phase, the relays broadcast the processed signals to all the destination nodes simultaneously. The channels between relay nodes and destination nodes are also nonorthogonal. As a result, the received signal at the ith destination node is given by

$$\begin{aligned} y_i &= \mathbf{g}_i^{\mathcal{T}} \mathbf{x} + n_i \\ &= \mathbf{g}_i^{\mathcal{T}} \left[\mathbf{w}^{\mathcal{T}} \cdot \left(\sum_{l=1}^{L} \mathbf{h}_l s_l + \mathbf{n}_r \right) \right] + n_i. \end{aligned} \tag{3}$$

2.2. Orthogonal Channel Scenario. In the case of orthogonal channels, relays can separate the messages sent from different users. For user l, the received signal at the relays can be written as

$$\mathbf{r}_l = \mathbf{h}_l s_l + \mathbf{n}_{rl}, \tag{4}$$

where $\mathbf{r}_l$ is a $\mathbb{C}^{K\times 1}$ column vector and r_{li} is the signal received by the ith relay from user node l. $\mathbf{n}_{rl}$ is the relay AWGN for user l over its subchannel.

The relays design different sets of complex beamforming weights for different users. Define a row vector $\mathbf{w}_l = [w_{l1}, \ldots, w_{lK}] \in \mathbb{C}^{1\times K}$ as the beamforming weight vector for user l. The lth user's signal transmitted by the relays can be written as

$$\mathbf{x}_l = \mathbf{w}_l^{\mathcal{T}} \cdot \mathbf{r}_l. \tag{5}$$

In the second phase, the relay nodes simultaneously broadcast the processed signals to all the destination nodes. The transmission to each destination node is carried out over orthogonal channels to avoid interuser interference. Thus, the received signal at the lth destination node is given by

$$\begin{aligned} y_l &= \mathbf{g}_l^{\mathcal{T}} \mathbf{x}_l + n_l \\ &= \mathbf{g}_l^{\mathcal{T}} \left[\mathbf{w}_l^{\mathcal{T}} \cdot (\mathbf{h}_l s_l + \mathbf{n}_{lr}) \right] + n_l. \end{aligned} \tag{6}$$

It can be seen from the above that the goal of relay beamforming schemes for nonorthogonal systems is to design a set of $K \times 1$ row vector $\mathbf{w}$ for all the users, while for orthogonal system L sets of $K \times 1$ row vectors, that is, $\mathbf{w}_1, \ldots, \mathbf{w}_L$, each one corresponding to one source-destination pair.

As mentioned in Section 1, the aim of this paper is to develop distributed algorithms using local CSI instead of full global CSI. In the discussed system, local CSI for relay i is referred to as incoming channel coefficients h_{li} from the source nodes to relay node i, outgoing channel coefficients g_{li} from relay node i to the destination nodes for $l = 1, \ldots, L$ and its noise variance σ_r^2. We can denote $\overline{h}_i = [h_{1i}, h_{2i}, \ldots, h_{Li}]$ and $\overline{g}_i = [g_{1i}, g_{2i}, \ldots, g_{Li}]$ as the local CSI vectors for relay node i. Besides, the signal power P_s and the destination noise variance σ_0^2 are assumed to be known at the relays. In the following sections, we will derive suboptimal beamforming schemes based on MMSE that only require local CSI for nonorthogonal and orthogonal systems.

3. MMSE-Based Distributed Beamforming for Nonorthogonal Systems

In this section, we are interested in choosing a beamforming weight vector that minimizes the sum of the mean square error between the uncorrupted received signals at the destination nodes and the transmitted signals at the source nodes for nonorthogonal systems. The optimization problem is first formulated and then two suboptimal ways to obtain beamforming weights from the original problem using local CSI are put forward.

3.1. MMSE Optimization Problem Formulation. The uncorrupted received signal at the ith destination node is $\mathbf{g}_i^{\mathcal{T}}\mathbf{x}$, so the MSE of the ith user is expressed as

$$\begin{aligned}\mathrm{MSE}_i(\mathbf{w}) &= \mathbb{E}\left[\left|\mathbf{g}_i^{\mathcal{T}}\mathbf{x} - s_i\right|^2\right] \\ &= P_s\sum_{l=1}^{L}\mathbf{w}(\mathbf{h}_l\cdot\mathbf{g}_i)(\mathbf{h}_l\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} - P_s\mathbf{w}(\mathbf{h}_i\cdot\mathbf{g}_i) \\ &\quad - P_s(\mathbf{h}_i\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} + \sigma_r^2\mathbf{w}\{\mathbf{diag}(\mathbf{g}_i\cdot\mathbf{g}_i^{*})\}\mathbf{w}^{\dagger} \\ &\quad + P_s.\end{aligned} \tag{7}$$

The sum of the MSE of all the source and destination pairs is given by

$$\begin{aligned}\mathrm{SUM\_MSE}(\mathbf{w}) &= \sum_{i=1}^{L}\mathrm{MSE}_i(\mathbf{w}) \\ &= P_s\sum_{i=1}^{L}\sum_{l=1}^{L}\mathbf{w}(\mathbf{h}_l\cdot\mathbf{g}_i)(\mathbf{h}_l\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} \\ &\quad - P_s\mathbf{w}\sum_{i=1}^{L}(\mathbf{h}_i\cdot\mathbf{g}_i) - \sum_{i=1}^{L}P_s(\mathbf{h}_i\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} \\ &\quad + \sigma_r^2\mathbf{w}\left\{\sum_{i=1}^{L}\mathbf{diag}(\mathbf{g}_i\cdot\mathbf{g}_i^{*})\right\}\mathbf{w}^{\dagger} + LP_s.\end{aligned} \tag{8}$$

Transmission power limitation of the relay sensor nodes needs to be taken into consideration in wireless M2M networks. The transmission power of each relay node is constrained within the maximum power capacity denoted by P_{rel}. Then we have the relay power constraints as

$$\begin{aligned}P_i &= \mathbb{E}\left[\|x_i\|^2\right] = w_i w_i^{*}\left[P_s\sum_{l=1}^{L}h_{li}h_{li}^{*} + \sigma_r^2\right] \\ &= \mathbf{w}\mathbf{D}_i\mathbf{w}^{*} \le P_{\mathrm{rel}}, \quad i = 1,\ldots,K,\end{aligned} \tag{9}$$

where $\mathbf{D}_i$ has only one nonzero element with $[\mathbf{D}_i]_{ii} = P_s\sum_{l=1}^{L}h_{li}h_{li}^{*} + \sigma_r^2$.

To obtain the best performance for the system, we design a beamforming scheme that generates the smallest sum of MSE. Thus, the optimization problem can be formulated as an MMSE problem subject to individual relay transmission power constraints and is expressed as

$$\begin{aligned}&\underset{\mathbf{w}}{\text{minimize}}\ \mathrm{SUM\_MSE} \\ &\text{subject to } P_{\mathrm{rel}} \ge P_i, \quad i = 1,\ldots,K.\end{aligned} \tag{10}$$

To solve the optimization problem, we first introduce the Lagrangian of the problem

$$\begin{aligned}\mathcal{L}(\mathbf{w},\boldsymbol{\lambda}) &= \mathrm{SUM\_MSE} + \sum_{k=1}^{K}\lambda_k(P_k - P_{\mathrm{rel}}) \\ &= P_s\sum_{i=1}^{L}\sum_{l=1}^{L}\mathbf{w}(\mathbf{h}_l\cdot\mathbf{g}_i)(\mathbf{h}_l\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} \\ &\quad - P_s\mathbf{w}\sum_{i=1}^{L}(\mathbf{h}_i\cdot\mathbf{g}_i) - \sum_{i=1}^{L}P_s(\mathbf{h}_i\cdot\mathbf{g}_i)^{\dagger}\mathbf{w}^{\dagger} \\ &\quad + \sigma_r^2\mathbf{w}\left\{\sum_{i=1}^{L}\mathbf{diag}(\mathbf{g}_i\cdot\mathbf{g}_i^{*})\right\}\mathbf{w}^{\dagger} + LP_s \\ &\quad + \sum_{i=1}^{K}\lambda_i(\mathbf{w}\mathbf{D}_i\mathbf{w}^{*} - P_{\mathrm{rel}}),\end{aligned} \tag{11}$$

where $\boldsymbol{\lambda} = [\lambda_1,\ldots,\lambda_K]$ are the Lagrangian multipliers and $\lambda_i \ge 0$, for $i = 1,\ldots,K$.

The Lagrangian dual function is defined as

$$g(\boldsymbol{\lambda}) = \min_{\mathbf{w}}\mathcal{L}(\mathbf{w},\boldsymbol{\lambda}). \tag{12}$$

The dual problem is to maximize $g(\boldsymbol{\lambda})$. According to Karush-Kuhn-Tucker (KKT) conditions, the optimal solution should satisfy

$$\frac{\partial\mathcal{L}}{\partial\mathbf{w}} = 0, \tag{13}$$

$$\lambda_i(P_{\mathrm{rel}} - P_i) = 0, \tag{14}$$

$$\lambda_i \ge 0, \quad i = 1,\ldots,K. \tag{15}$$

Due to the symmetry of $\mathbf{w}$ and $\mathbf{w}^{\dagger}$ in (13), (13) is equivalent to $\partial\mathcal{L}/\partial\mathbf{w}^{\dagger} = 0$. Expand the differentiation equation, we have

$$\frac{\partial\mathcal{L}}{\partial\mathbf{w}^{\dagger}} = P_s\mathbf{w}\mathbf{A} + \sigma_r^2\mathbf{w}\mathbf{B} - P_s\mathbf{c} + \mathbf{w}\mathbf{D}, \tag{16}$$

where $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are $K\times K$ matrices while $\mathbf{c}$ is a $1\times K$ row vector. For $\mathbf{A}$, $[\mathbf{A}]_{mk} = \sum_{i=1}^{L}\sum_{j=1}^{L}(g_{im}h_{jm})(g_{ik}h_{jk})^{*}$. $\mathbf{B}$ and $\mathbf{D}$ are both diagonal with $[\mathbf{B}]_{kk} = \sum_{i=1}^{L}g_{ik}g_{ik}^{*}$ and $[\mathbf{D}]_{kk} = \lambda_k(P_s\sum_{j=1}^{L}h_{jk}h_{jk}^{*} + \sigma_r^2)$ for $k = 1,\ldots,K$, respectively. As for row vector $\mathbf{c}$, $c_m = \sum_{i=1}^{L}(g_{im}h_{im})^{*}$.

Note that $\mathbf{w}$ is a $1\times K$ row vector, and (16) is consisted of K equations. The jth equation of (16) can be reformulated as

$$\begin{aligned}w_j &= \frac{P_s c_j - P_s\sum_{i=1,i\ne j}^{K}w_i[\mathbf{A}]_{ij}}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + \lambda_j\left[\mathbf{D}_j\right]_{jj}} \\ &= \frac{P_s\sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^{*} - P_s\sum_{i=1,i\ne j}^{K}w_i[\mathbf{A}]_{ij}}{P_s[\mathbf{A}]_{jj} + \sigma_r^2\sum_{i=1}^{L}g_{ij}g_{ij}^{*} + \lambda_j\left(P_s\sum_{m=1}^{L}h_{mj}h_{mj}^{*} + \sigma_r^2\right)},\end{aligned} \tag{17}$$

where $[\mathbf{A}]_{jj}$, $[\mathbf{B}]_{jj}$, c_j, and $[\mathbf{D}_j]_{jj}$ only contain local CSI at relay j while $[\mathbf{A}]_{ij}$ for $i \neq j$ has other relays' CSI. It can be seen clearly that to calculate the optimal beamforming weight of relay j requires the complete knowledge of all channels, that is, the global CSI. This is not desirable for wireless M2M networks, where there are a large number of relay nodes limited in memory, battery, and processing capability. As a result, we proposed two suboptimal algorithms that each relay can learn its own beamforming weight with local CSI.

3.2. MSE Minimization Suboptimal Algorithm. In this part, we are dedicated to find the suboptimal beamforming weights assuming that each relay only has local CSI and there is no information exchange between the relays. Below, we propose two suboptimal approaches to deal with the lack of global CSI.

3.2.1. Suboptimal Algorithm 1. First, in (17), we can see that it does not involve channel information from other relays except for the second term of the numerator. It can also be seen from (14) that λ_j corresponds to relay j's transmission power constraint which is determined by local beamforming weights and local CSI. In this case, we can ignore the other relays' contribution to the sum MSE in (8). As a result, we can set all the elements $[A]_{ij}$ where $i \neq j$ to zero for relay j. Then we have the following expression:

$$\begin{aligned} w_j &= \frac{P_s c_j}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + [\mathbf{D}]_{jj}} \\ &= \frac{P_s c_j}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + \lambda_j\left[\mathbf{D}_j\right]_{jj}} \\ &= \frac{P_s \sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^*}{P_s[\mathbf{A}]_{jj} + \sigma_r^2\sum_{i=1}^{L} g_{ij}g_{ij}^* + \lambda_j\left(P_s\sum_{m=1}^{L} h_{mj}h_{mj}^* + \sigma_r^2\right)}. \end{aligned} \tag{18}$$

Substitute (18) into (14), and λ_j is given by $\lambda_j = \max\{0, z_{j1}\}$, where z_{j1} is

$$z_{j1} = \frac{1}{\left[\mathbf{D}_j\right]_{jj}}\left\{\frac{P_s\left|c_j\right|\sqrt{\left[\mathbf{D}_j\right]_{jj}}}{\sqrt{P_{\text{rel}}}} - P_s[\mathbf{A}]_{jj} - \sigma_r^2[\mathbf{B}]_{jj}\right\}. \tag{19}$$

When $z_{j1} < 0$, λ_j is 0, and w_j is

$$\begin{aligned} w_j &= \frac{P_s c_j}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj}} \\ &= \frac{P_s \sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^*}{P_s\sum_{i=1}^{L}\sum_{l=1}^{L}\left(g_{ij}h_{lj}\right)\left(g_{ij}h_{lj}\right)^* + \sigma_r^2\sum_{i=1}^{L} g_{ij}g_{ij}^*}. \end{aligned} \tag{20}$$

In this case, the relay node does not need to turn to the maximum transmission power. To let $z_{j1} < 0$, we have

$$\frac{P_s^2\left|\sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^*\right|^2}{P_{\text{rel}}\left(\sum_{i=1}^{L}\left|g_{ij}\right|^2\right)^2\left(P_s\sum_{l=1}^{L}\left|h_{lj}\right|^2 + \sigma_r^2\right)} < 1. \tag{21}$$

With the inequality $|\sum_{i=1}^{L}(g_{ij}h_{ij})^*|^2 \le \sum_{i=1}^{L}|g_{ij}|^2\sum_{l=1}^{L}|h_{lj}|^2$, the left term of (21) satisfies the inequality below,

$$\begin{aligned} &\frac{P_s^2\left|\sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^*\right|^2}{P_{\text{rel}}\left(\sum_{i=1}^{L}\left|g_{ij}\right|^2\right)^2\left(P_s\sum_{l=1}^{L}\left|h_{lj}\right|^2 + \sigma_r^2\right)} \\ &\quad\le \frac{P_s^2\sum_{i=1}^{L}\left|h_{ij}\right|^2}{P_{\text{rel}}\left(\sum_{i=1}^{L}\left|g_{ij}\right|^2\right)\left(P_s\sum_{l=1}^{L}\left|h_{lj}\right|^2 + \sigma_r^2\right)}. \end{aligned} \tag{22}$$

When the right term of (22) is less than 1, (21) is satisfied. It means that if the channel gains between the relay nodes and the destination nodes are strong enough, that is,

$$\frac{\sum_{i=1}^{L}\left|g_{ij}\right|^2}{\sum_{i=1}^{L}\left|h_{ij}\right|^2} > \frac{P_s^2}{P_{\text{rel}}\left(P_s\sum_{l=1}^{L}\left|h_{lj}\right|^2 + \sigma_r^2\right)}, \tag{23}$$

the relays do not need to transmit the maximum power. This result is similar to that in single user systems [10]. However, if $z_{j1} > 0$, then $P_i = P_{\text{rel}}$, and the relay transmits at the maximum relay power level.

By ignoring other relays' CSI, the above algorithm allows each relay to calculate its own beamforming weight independently. Simulation results show that this suboptimal approach can give satisfactory performance which is very close to the optimal approach.

3.2.2. Suboptimal Algorithm 2. Second, instead of ignoring other relays' channel coefficients, we may substitute them with appropriate approximations. In [10], it assumes symmetric conditions for all the channels in a single user system, that is, it uses the corresponding local CSI statistics as approximations of the unknown global CSI. Here, we extent this idea to our multiuser system. As shown in (17), relay node j still needs to know $w_i[\mathbf{A}]_{ij}$ where $i \neq j$ to learn its own weight. Under the assumption of symmetric channel condition, we have $w_j[\mathbf{A}]_{jj} = w_i[\mathbf{A}]_{ij}$. Replace this into (17), and we can get

$$\begin{aligned} w_j &= \frac{P_s c_j - P_s\sum_{i=1,\, i\neq j}^{K} w_i[\mathbf{A}]_{ij}}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + [\mathbf{D}]_{jj}} \\ &\approx \frac{P_s c_j - (K-1)P_s w_j[\mathbf{A}]_{jj}}{P_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + [\mathbf{D}]_{jj}}. \end{aligned} \tag{24}$$

Reformulate the above equation, and the suboptimal solution of relay j's beamforming weight is given by

$$w_j \approx \frac{P_s c_j}{KP_s[\mathbf{A}]_{jj} + \sigma_r^2[\mathbf{B}]_{jj} + [\mathbf{D}]_{jj}} = \frac{P_s \sum_{i=1}^{L}\left(g_{ij}h_{ij}\right)^*}{KP_s[\mathbf{A}]_{jj} + \sigma_r^2 \sum_{i=1}^{L} g_{ij}g_{ij}^* + \lambda_j\left[\mathbf{D}_j\right]_{jj}}. \quad (25)$$

As discussed in the Suboptimal Algorithm 1, substitute (25) into the power constraint of (14). The Lagrangian multiplier λ_j is given by $\lambda_j = \max\{0, z_{j2}\}$, where z_{j2} is

$$z_{j2} = \frac{1}{\left[\mathbf{D}_j\right]_{jj}}\left\{\frac{P_s\left|c_j\right|\sqrt{\left[\mathbf{D}_j\right]_{jj}}}{\sqrt{P_{\text{rel}}}} - KP_s[\mathbf{A}]_{jj} - \sigma_r^2[\mathbf{B}]_{jj}\right\}. \quad (26)$$

Similar to Suboptimal Algorithm 1, if

$$\frac{\sum_{i=1}^{L}\left|g_{ij}\right|^2}{\sum_{i=1}^{L}\left|h_{ij}\right|^2} > \frac{P_s^2}{P_{\text{rel}}\left(KP_s\sum_{l=1}^{L}\left|h_{lj}\right|^2 + \sigma_r^2\right)}, \quad (27)$$

then $z_{j2} < 0$, and the relay transmission power is less than the maximum allowable power. Otherwise the relay will transmit signals at the maximum power.

As can be seen, both of the proposed suboptimal algorithms only require local CSI.

4. MMSE Beamforming for Orthogonal Systems

In this section, we develop distributed relay beamforming algorithms for a different multiuser system where each user transmits signals through orthogonal channels. In this scenario, the sum of MSE criterion is also considered to design the beamforming weights. The optimization problem is first established and then we will show the optimization problem can be divided into several single user problems.

4.1. Optimization Problem Formulation. The uncorrupted received signal at the ith destination node is $\mathbf{g}_i^{\mathcal{T}}\mathbf{x}_i$, so the MSE of the ith user is expressed as

$$\begin{aligned}\text{MSE}_i(\mathbf{w}_i) &= \mathbb{E}\left[\left|\mathbf{g}_i^{\mathcal{T}}\mathbf{x}_i - s_i\right|^2\right] \\ &= P_s\mathbf{w}_i(\mathbf{h}_i\cdot\mathbf{g}_i)(\mathbf{h}_i\cdot\mathbf{g}_i)^\dagger\mathbf{w}_i^\dagger - P_s\mathbf{w}_i(\mathbf{h}_i\cdot\mathbf{g}_i) \\ &\quad - P_s(\mathbf{h}_i\cdot\mathbf{g}_i)^\dagger\mathbf{w}_i^\dagger + \sigma_r^2\mathbf{w}_i\{\mathbf{diag}(\mathbf{g}_i\cdot\mathbf{g}_i^*)\}\mathbf{w}_i^\dagger \\ &\quad + P_s.\end{aligned} \quad (28)$$

The sum of MSE of all the source nodes and destination nodes is given by

$$\begin{aligned}&\text{SUM\_MSE}(\mathbf{w}_1,\dots,\mathbf{w}_L) \\ &\quad = \sum_{i=1}^{L}\text{MSE}_i(\mathbf{w}_i) \\ &\quad = P_s\sum_{i=1}^{L}\mathbf{w}_i(\mathbf{h}_i\cdot\mathbf{g}_i)(\mathbf{h}_i\cdot\mathbf{g}_i)^\dagger\mathbf{w}_i^\dagger - P_s\sum_{i=1}^{L}\mathbf{w}_i(\mathbf{h}_i\cdot\mathbf{g}_i) \\ &\qquad - P_s\sum_{i=1}^{L}(\mathbf{h}_i\cdot\mathbf{g}_i)^\dagger\mathbf{w}_i^\dagger + \sum_{i=1}^{L}\sigma_r^2\mathbf{w}_i\{\mathbf{diag}(\mathbf{g}_i\cdot\mathbf{g}_i^*)\}\mathbf{w}_i^\dagger \\ &\qquad + LP_s.\end{aligned} \quad (29)$$

Similar to that in nonorthogonal channel systems, power constraints of the relay sensor nodes also need to be taken into consideration. The transmission power of each relay is constrained within the maximum power denoted by P_{rel}, and then we have the relay power constraints as

$$\begin{aligned}P_i &= \sum_{l=1}^{L}\mathbb{E}\left[\|x_{li}\|^2\right] = \sum_{l=1}^{L}w_{li}w_{li}^*\left[P_s h_{li}h_{li}^* + \sigma_r^2\right] \\ &= \sum_{l=1}^{L}\mathbf{w}_l\mathbf{D}_{li}\mathbf{w}_l^* \le P_{\text{rel}}, \quad i = 1,\dots,K,\end{aligned} \quad (30)$$

where $\mathbf{D}_{li}$ has only one nonzero element with $[\mathbf{D}_{li}]_{ii} = P_s h_{li}h_{li}^* + \sigma_r^2$.

Then the optimization problem can be formulated as

$$\begin{aligned}&\underset{\mathbf{w}_1,\dots,\mathbf{w}_L}{\text{minimize}}\ \text{SUM\_MSE} \\ &\text{subject to } P_{\text{rel}} \ge P_i, \quad i = 1,\dots,K.\end{aligned} \quad (31)$$

4.2. Suboptimal Algorithms for Orthogonal Scenarios. In orthogonal systems, each relay needs to learn L weights for L users. To learn the beamforming weights independently by relay nodes, we can establish the Lagrangian function as in the nonorthogonal cases,

$$\mathcal{L}(\mathbf{w}_1,\dots,\mathbf{w}_L,\boldsymbol{\lambda}) = \text{SUM\_MSE} + \sum_{k=1}^{K}\lambda_k(P_k - P_{\text{rel}}). \quad (32)$$

The optimal solution $\mathbf{w}_1,\dots,\mathbf{w}_L,\boldsymbol{\lambda}$ should satisfy the KKT conditions. We can have

$$w_{li} = \frac{P_s(h_{li}g_{li})^* - P_s\sum_{k=1,\,k\ne i}^{K}w_{lk}[\mathbf{A}_l]_{ki}}{P_s[\mathbf{A}_l]_{ii} + \sigma_r^2 g_{li}g_{li}^* + \lambda_i\left(P_s h_{li}h_{li}^* + \sigma_r^2\right)}, \quad (33)$$

where w_{li} is the beamforming weight at relay i for user l, and $\mathbf{A}_l$ is a $\mathbb{C}^{K\times K}$ matrix with $[\mathbf{A}_l]_{ij} = h_{li}g_{li}h_{lj}^*g_{lj}^*$.

For relay i, it needs to decide the value of $w_{1i}, w_{2i},\dots,w_{Li}$. The expression of w_{li} exhibits similar features to those in nonorthogonal systems with only the second term on the numerator involving global CSI, which may be ignored or replaced with approximations.

Substituting the suboptimal w_{li} for $l = 1, \ldots, L$ into the power constraints of (30), we can get a polynomial equation concerning the Lagrange multiplier λ_i. It decides the allocation of the relay transmission power to different users. We can use iterative methods to solve the polynomial equations.

Also, note that the transmissions through orthogonal channels make the minimization of sum MSE without power constraints equivalent to each user minimizing its own MSE with its beamforming vector. By preallocating the total relay transmission power capacity to each user, the original problem can be decoupled into L single user beamforming problems expressed as

$$\begin{aligned} &\underset{\mathbf{w}_l}{\text{minimize}}\ \text{MSE}_l \\ &\text{subject to } P_{rli} \geq P_{li}, \quad i = 1, \ldots, K. \\ &\text{for} \quad l = 1, \ldots, L, \end{aligned} \tag{34}$$

where P_{rli} is the maximum transmission power allocated for user l at relay node i and should satisfy $\sum_{l=1}^{L} P_{rli} = P_{\text{rel}}$. P_{li} is the power that relay node i uses to transmit user l's signal. At this point, the original problem becomes L single user subproblems. The approaches introduced in the nonorthogonal section can be used for the relays to learn the weights based on local CSI. A simple way is to equally allocate the available transmission power to each user, that is, to let $P_{rli} = P_{\text{rel}}/L$. By decoupling the original problem into single user cases, relays are able to calculate the weights on local CSI avoiding any information exchange with low complexity. However, the cost is the sacrifice of resource efficiency which means performance degradation from another point of view.

5. Simulation Results

In this section, we present numerical results for the proposed algorithms. It is assumed that all the channel coefficients are generated as zero-mean and unit-variance independent complex Gaussian random variables. Noise variances at the relays and the destinations are set to be the same as $\sigma_r^2 = \sigma_0^2 = 1$. BPSK is employed in our simulation system for simplicity. Define SNR $= P_s/\sigma_r^2$. We study the bit error rate (BER) performance under different circumstances.

Figures 2, 3, and 4 show the performance of Suboptimal Algorithm 1 in nonorthogonal systems. Figure 2 shows the BER performance over the level of SNR with different number of relays deployed in a three-user system. It is clearly that increasing the number of relays improves the system performance as expected because of the benefit of diversity gain. In Figure 3, BER performance is depicted when the number of users increases under different source transmission power. It shows that the number of users can have a great impact on the system performance. Although the source transmission power increases, the BER performance still degrades a lot with six or more users in the system. This is reasonable for that in nonorthogonal systems each user causes interference to the others and it needs sufficient relay nodes to provide a stronger beamforming to cancel out the interference for all the users at the same time. Thus, the same performance could be maintained for a larger number of users by increasing the number of relay nodes. Wireless M2M networks can deploy large numbers of low-cost relay nodes or allow some user nodes to act as relays to guarantee communication quality.

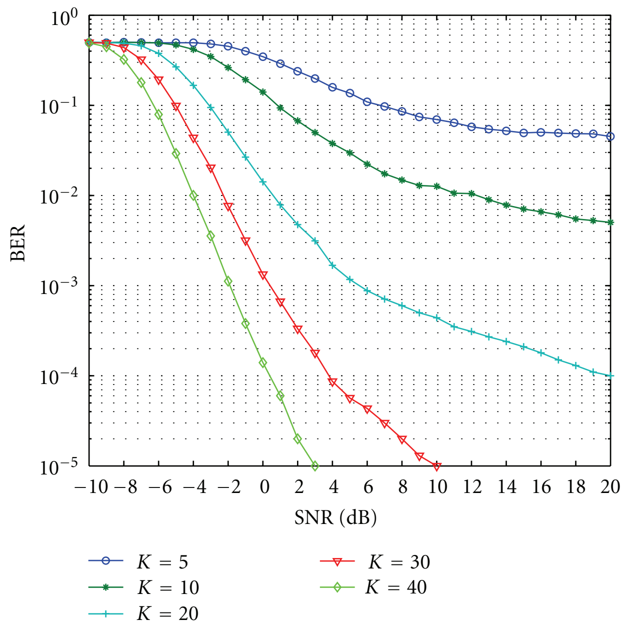

Figure 2: BER performance versus source transmission power with different number of relays in a 3 user nonorthogonal system.

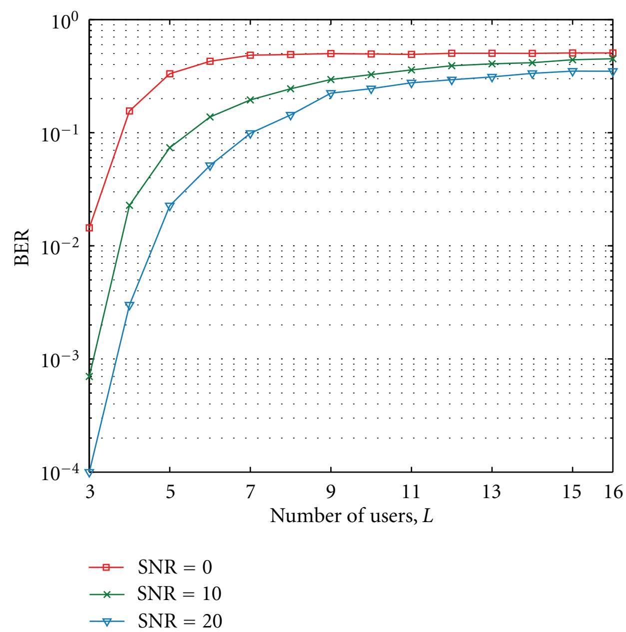

Figure 3: BER performance versus the number of users for different values of SNR with 20 relays in nonorthogonal system.

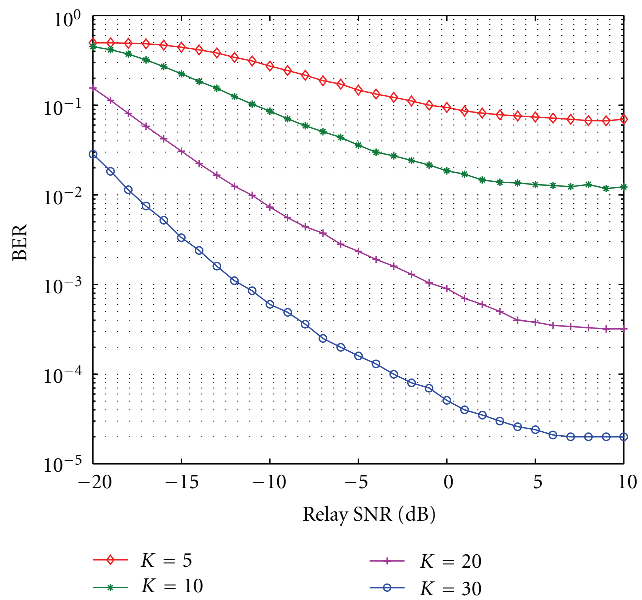

FIGURE 4: BER performance versus relay power constraint for different relays in nonorthogonal system.

Figure 4 shows the BER performance versus different relay power constraints when different number of relays are deployed. Relay SNR is defined as the relay maximum power with relay noise σ_r^2 set to be 0 dB. It can be seen that, at the beginning, with the maximum relay transmission power increasing, the BER drops greatly but then all the curves exhibit error floor even though the power value keeps rising. This result is consistent with the analysis in Section 3 that the best transmission power depends on (22). When the inequality satisfies, the relays do not need to transmit signals at the maximum power.

Figure 5 shows the performance in orthogonal channel systems. In Figure 5, we consider both cases where the relay power is equally allocated to all the users and optimized based on lagrange multipliers, with lines labeled as Eq and Ineq, respectively. Also, we compare the proposed schemes with the one based on MSNR criterion using global CSI proposed in [8] labeled as MSNR in Figure 5. It can be seen that the scheme optimizing the relay power allocation to different users have better performance than that with equal allocation. It is also clear that the performance of both schemes is close to that of [8]. Since users are not interfered with each other, BER performance is slightly affected by the number of users. However, as the number of users grows, the relay transmission capacity for each user decreases and ends in performance degradation. Compare Figure 5 with Figure 2, and it can be seen that the performance of orthogonal system is better than the nonorthogonal system at the cost of more frequency resource.

Figure 6 compares the optimal results using global CSI with that of the Suboptimal Algorithm 1 and Suboptimal Algorithm 2 in nonorthogonal systems. The schemes using global CSI are proposed in [9, 13], based on MSNR and MMSE criterion, and labeled as joint MSNR and joint

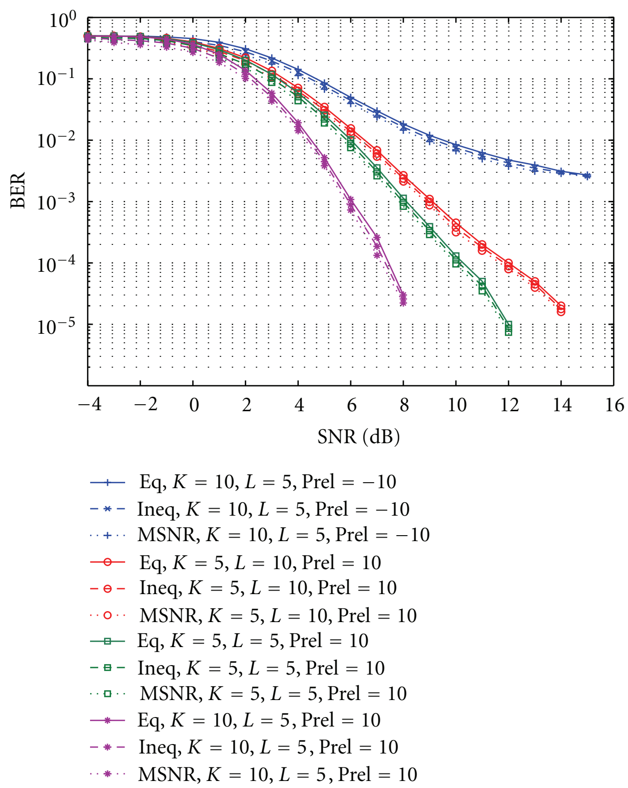

FIGURE 5: BER performance versus source transmission power for orthogonal system.

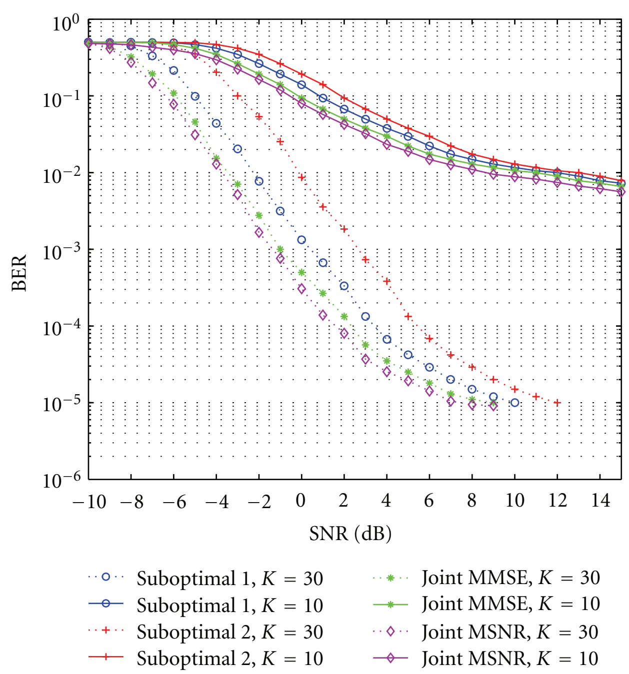

FIGURE 6: BER performance comparison for nonorthogonal system.

MMSE, respectively. It can be seen that the performance of Suboptimal Algorithm 1 is very close to the optimal performance. As the number of relays increases, the difference becomes larger but remains acceptable. Suboptimal Algorithm 2 gives quite good approximates when the number of relays is small. The instantaneous global CSI estimated with local CSI gets less accurate as the number grows, and hence degrades the performance of Suboptimal Algorithm 2.

6. Conclusion

In this paper, we considered distributed relay beamforming schemes with local CSI for AF multiuser multirelay M2M networks with orthogonal channels and nonorthogonal channels based on MMSE criterion. In nonorthogonal systems, two approximate approaches were provided where each relay could learn its own weight independently and respectively with local CSI. Simulation results showed that the performance of the proposed algorithm was close to the optimal one using global CSI. In orthogonal systems, the optimization problem was separated into single user problems which then could be solved with distributed algorithms. Simulation results were presented in the end of the paper to show the BER performance of the proposed relay beamforming schemes.

Acknowledgment

This work has been supported by the National Basic Research Program of China (973 Program no. 2009CB320403).

References

[1] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bölcskei, "An overview of MIMO communications—a key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198–217, 2004.

[2] M. Fadel, A. El-Keyi, and A. Sultan, "QOS-constrained multiuser peer-to-peer amplify-and-forward relay beamforming," *IEEE Transactions on Signal Processing*, vol. 60, no. 3, pp. 1397–1408, 2012.

[3] G. J. Pottie and W. J. Kaiser, "Wireless sensor networks," in *Proceedings of the IEEE Information Theory Workshop (ITW '98)*, pp. 139–140, June 1998.

[4] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3037–3063, 2005.

[5] T. M. Cover and A. A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Transactions on Information Theory*, vol. 25, no. 5, pp. 572–584, 1979.

[6] P. Gupta and P. R. Kumar, "Towards an information theory of large networks: an achievable rate region," *IEEE Transactions on Information Theory*, vol. 49, no. 8, pp. 1877–1894, 2003.

[7] G. Zheng, K. K. Wong, A. Paulraj, and B. Ottersten, "Collaborative-relay beamforming with perfect CSI: optimum and distributed implementation," *IEEE Signal Processing Letters*, vol. 16, no. 4, pp. 257–260.

[8] D. H. N. Nguyen and H. H. Nguyen, "SNR maximization and distributed beamforming in multiuser multi-relay networks," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '09)*, Honolulu, Hawai, USA, December 2009.

[9] D. H. N. Nguyen, H. H. Nguyen, and H. D. Tuan, "Distributed beamforming in relay-assisted multiuser communications," in *Proceedings of the IEEE International Conference on Communications (ICC '09)*, Dresden, Germany, June 2009.

[10] J. Choi, "MMSE-based distributed beamforming in cooperative relay networks," *IEEE Transactions on Communications*, vol. 59, no. 5, pp. 1346–1356, 2011.

[11] N. Khajehnouri and A. H. Sayed, "Distributed MMSE relay strategies for wireless sensor networks," *IEEE Transactions on Signal Processing*, vol. 55, no. 7, pp. 3336–3348, 2007.

[12] S. Verdu, *Multiuser Detection*, Cambridge University Press, 1998.

[13] S. Berger and A. Wittneben, "Cooperative distributed multiuser MSE relaying in wireless ad-hoc networks," in *Proceedings of the 39th Asilomar Conference on Signals, Systems and Computers*, pp. 1072–1076, November 2005.