Collaborative Relay Beamforming Strategies for Multiple Destinations with Guaranteed QoS in Wireless Machine-to-Machine Networks

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1. Introduction

Machine devices, such as sensors, communicate with each other in machine-to-machine (M2M) networks, which do not need intervention from human beings [1]. A wireless M2M device may act as a source point and communicate data packets on behalf of the other M2M destination devices [2]. However, the wireless M2M networks are composed of a large number of small and power-limited machine devices, which can only transmit low-power signals. Due to the propagation loss between the source devices and the destination devices, it is very challenging to guarantee the quality of service (QoS) requirements of the destination devices. Recently, many increasing researches showed interest in the relay devices to deal with this problem [3]. The sources transmit signals through one or more relay devices towards the destination devices in wireless M2M networks. Relay devices can be designed to work collaboratively to guarantee the QoS requirements by forming a virtual beamforming system [4, 5].

In general, there are three types of relay schemes, including the amplify-and-forward (AF) [6], decode-and-forward (DF) [7], and compress-and-forward (CF) [8] schemes. In the AF scheme, relay nodes receive the signals transmitted from the source and forward the amplified signals to the destinations. In the DF scheme, relay nodes decode and reencod the received signals to the destinations. In the CF scheme, relay nodes send quantized and compressed signals to the destinations. Among them, the AF scheme is the most attractive for the collaborative relay beamforming due to its low implementation complexity. With the aid of channel state information (CSI), the relay nodes can work collaboratively in a way similar to a multiple antenna systems to construct virtual beams towards the destinations [9].
In this paper, we study the collaborative relay beamforming for multiple destinations in the multiple relay M2M networks, where multiple relay M2M devices form virtual beams to transmit signals from a source M2M device with multiple antennas towards multiple destination M2M devices. Firstly, we present two methods to select the source antenna to transmit the destination’s signals. In Method 1, we use the greedy algorithm to select the best available channel for each destination until all the destinations are allocated properly with the source antennas; in Method 2, we balance the channel condition for each destination and its interference to the other destinations based on Method 1. Secondly, we optimize the relay beamforming weights with the aid of perfect CSI to maximize the worst-case received SINR under two different types of relay power constraints, which are the total relay power constraint and individual relay power constraints, respectively. Using the semidefinite relaxation (SDR) technique [10], we show that the optimization problem can be formulated as a semidefinite programming (SDP) problem, which can be optimally solved using interior-point methods [11]. Finally, according to the source antenna selection methods and relay beamforming schemes, we propose two iterative strategies to jointly optimize the source antenna selection and the relay beamforming weights. We show that after several iterations, the performance of the proposed iterative strategies can obtain near optimal performance.

According to our proposed iterative strategies, the source M2M device must know all the CSI of the wireless M2M networks to jointly optimize the source antenna selection and the relay beamforming weights. However in practice, the feedback channels are always limited and could be overloaded if the number of relays and destinations is large. To deal with this practical problem, Choi [12, 13] studied the distributed AF relay beamforming schemes for the single destination where the relays can work cooperatively to form a virtual beam with local CSI (The local CSI means that each relay node knows its instantaneous incoming and outgoing channel coefficients from relay nodes’ point of view). However, the CSI of the other relay nodes is assumed to be not known.) when a consensus algorithm was employed in [12], and different MMSE criteria were proposed in [13]. D. H. N. Nguyen and H. H. Nguyen [14] proposed two relay power allocation schemes in a distributed manner to minimize the sum relay power with guaranteed SNR at the destinations and maximize the SNR margin subject to individual relay power constraints, respectively, under the orthogonal transmissions of each source-destination pair. In the end of this paper, we discuss the distributed multirelay beamforming strategy to maximize the worst-case received SINR for multiple destinations, where each relay may independently calculate its beamforming weight with the local CSI.

The rest of this paper is organized as follows. In Section 2, we present a brief discussion of related works on relay beamforming which motivated our work. Section 3 describes the multiple relay M2M networks with multiple destinations. Section 4 presents two methods to select the source antenna for each destination. In Section 5, we optimize the multi-relay weights that achieve the maximum worst-case SINR under two different types of relay power constraints. Then, two iterative strategies to jointly select the source antennas and optimize the multirelay weights are proposed, respectively. Section 6 presents and analyzes the simulation results. The distributed multi-relay beamforming strategy is discussed in Section 7. Conclusions are drawn in Section 8.

Notation. Vectors are written in boldface lowercase letters, for example, \( \mathbf{x} \), while matrices are denoted by boldface uppercase letters for example, \( \mathbf{X} \). The superscripts \( *, T, \) and \( H \) stand for the conjugate, transposition, and hermitian of a complex vector or matrix, respectively. \( \text{Tr}(S) \) represents the trace of a matrix \( S \), and \( \text{diag}(s_1, s_2, \ldots, s_k) \) denotes a diagonal square matrix with \( s_1, s_2, \ldots, s_k \) as the diagonal elements. \( E[z] \) calculates the expectation of a random entity \( z \), while \( |z| \) takes the modulus of a complex number \( z \). The real and complex number fields are denoted by \( \mathbb{R} \) and \( \mathbb{C} \), respectively. In addition, \( \mathbf{A} \succeq 0 \) means that \( \mathbf{A} \) is a hermitian semidefinite matrix, and \( O \) means the upper bound of the computational complexity.

2. Related Works

Andre et al. [2] studied a typical smart metering M2M application and proposed a client relay scheme to improve the performance of M2M devices with poor communication link. Khajehnouri and Sayed [3] designed relay strategies in sensor networks with minimum mean square error (MMSE) performance subject to local and global relay power constraints, respectively. Elkheir et al. [15] presented an M2M communication scheme, where the source communicates with the corresponding destination node with the help of one or more relay nodes. The objective in [15] was to minimize the total relay power under specific performance constraints and the individual power of each relay. Zheng et al. [16, 17] proposed the relay beamforming schemes that achieve the maximum received signal-to-noise ratio (SNR) for a single destination under both total and individual power constraints with the aid of perfect CSI [16] and imperfect CSI [17]. In addition, distributed beamforming for AF relay nodes was investigated when a consensus algorithm was employed for cooperative beamforming in [12], and the minimum mean square error (MMSE) criteria were used in [13].

However, existing approaches focused on relay strategies with the single or multiple relay beamforming for only one destination in wireless M2M networks or sensor networks. The relay M2M devices can be used to support multiple destinations for the M2M communications. Nguyen et al. [18, 19] studied the optimal relay beamforming schemes in a multiple AF relay cooperating network with multiple source-destination pairs. The aim in [18] was to minimize the total relay power under the signal-to-interference-and-noise ratio (SINR) requirement at each destination. In [19], Nguyen et al. minimized the sum relay power with the guaranteed QoS in terms of SNR at the destinations in orthogonal channels. Liu and Petropulu [20] studied the relay beamforming to minimize the sum transmit power at the relays with multiple pairs of the source and destination, assisted by multiple relays. Zheng and Blostein [21] considered the collaborative relay beamforming system to minimize the sum power at the
It is assumed that the AF relay protocol has two steps. During the first step, the source selects the best available antenna to broadcast the $k$th destination's signal $s_k$ to the relay nodes. Two methods to select the best antenna for the destination $k$ will be presented in Section 4. We assume that the destinations’ signals are independent with $\mathbb{E}[s_k] = 0$ and $\mathbb{E}[|s_k|^2] = P_k$. The received signal at the relay node $m$ is given by

$$r_m = g_m \sum_{k=1}^{K} d_k s_k + w_m,$$

where $w_m$ is independent white Gaussian noise at relay node $m$ with zero mean and variance of $N_m$. The column vector $d_k$ is the vector that represents the source antenna selection for the $k$th destination.

Then, during the second step, the relay nodes forward the received signals to the destinations using complex weights $v_{m}$, $m = 1, 2, \ldots, M$ for all destinations for the collaborative relay beamforming. Thus, the transmitted signal vector from the $m$th relay node is

$$x_m = v_m r_m.$$  

The destination $k$ receives the additive signals from all the relay nodes, which is given by

$$y_k = \sum_{m=1}^{M} h_{k,m} v_m r_m + n_k$$

$$= \sum_{m=1}^{M} h_{k,m} v_m g_m d_k s_k + \sum_{m=1}^{M} h_{k,m} v_m g_m \sum_{j=1; j \neq k}^{K} d_j s_j$$

$$+ \sum_{m=1}^{M} h_{k,m} v_m w_m + n_k,$$

where $n_k$ is independent white Gaussian noise at the $k$th destination with zero mean and variance of $N_k$. Thus, the received SINR of the destination $k$ is given by

$$\text{SINR}_k = \frac{P_k \left| \sum_{m=1}^{M} h_{k,m} v_m g_m d_k \right|^2}{\sum_{j=1; j \neq k}^{K} P_j \left| \sum_{m=1}^{M} h_{k,m} v_m g_m d_j \right|^2 + P_n}$$

$$= \frac{P_k \left| b_k^T d_k \right|^2}{\sum_{j=1; j \neq k}^{K} P_j \left| b_j^T d_j \right|^2 + P_n},$$

where

$$P_n = \sum_{m=1}^{M} \left| h_{k,m} \right|^2 |v_m|^2 N_m + N_k,$$

$$b_k = \left[ \sum_{m=1}^{M} h_{k,m} v_m g_1, \ldots, \sum_{m=1}^{M} h_{k,m} v_m g_L \right]^T.$$
4. Source Antenna Selection for Each Destination

In this section, we present two methods to optimize the source-antenna selecting vector \( d_k \) for the \( k \)th destination with fixed relay weights: (1) a greedy algorithm, that is, select the best available channel for each destination until all the destinations are allocated properly with the source antennas; (2) balance the channel condition for each destination \( k \) and its interference to the other destinations.

In Method 1, we first choose the element with the maximum magnitude denoted as \( G_{l_k,k} \) from the \( L \times K \) composite channel matrix \( G = [b_1, b_2, \ldots, b_K] \). Then the antenna \( l_k \) is selected to transmit signals to the destination \( k \). The channel coefficients between the rest antennas and destinations form a new \((L-1) \times (K-1)\) channel matrix. We can repeat the above processes \( K \) times until each destination is allocated with one antenna.

In Method 2, when we select the \( l_k \)th antenna to transmit signals towards the \( k \)th destination using Method 1, we consider its interference to the other destinations, that is, \( \sum_{m=1}^{M} h_{j,m} v_m g_{l_k,m} \) \( j \neq k \), which are the \( l_k \)th row elements of the composite channel matrix \( G \). If all the magnitudes of the interference are less than or equal to the interference threshold \( \xi \), we keep the channel and allocate the antenna for the corresponding destination on this channel. When one of the magnitudes of the interference is larger than the threshold \( \xi \), we drop the selected channel and choose the second largest magnitude element from the composite channel matrix. We repeat the above processes until all the magnitudes of the interference are less than or equal to the threshold \( \xi \). If the feasible solution can not be obtained under the interference threshold \( \xi \), then we may double the threshold value and repeat the above processes to select another antenna for the destination.

In our methods, the computational complexity of selecting one antenna scales linearly with the dimension of channel matrix \( G \), that is, \( KL \). Since we need to select \( K \) antennas for \( K \) destinations from the channel matrices whose dimensions decrease step by step, the computational complexity of our methods is at most \( O(K!L/(L-K)) \).

5. Iterative Strategies for Max-Min SINR with Relay Power Constraints

In this section, we assume that the source-antenna selection vector \( d_k \) for each destination \( k \) has been already chosen by the methods in Section 4. Thus, we assume that the \( l_k \)th antenna transmits \( s_k \) to the \( k \)th destination. We can rewrite the expression of the received SINR at the destination \( k \) in (4) as

\[
\text{SINR}_k = \frac{P_k \left| \sum_{m=1}^{M} h_{k,m} g_{l_k,m} v_m \right|^2}{\sum_{j=1, j \neq k}^{K} P_j \left| \sum_{m=1}^{M} h_{j,m} g_{l_k,m} v_m \right|^2 + P_n}
\]

where

\[
v = [v_1, v_2, \ldots, v_M]^T,
\]

\[
f_k = [h_{k,1} g_{l_k,1}, h_{k,2} g_{l_k,2}, \ldots, h_{k,M} g_{l_k,M}]^T,
\]

\[
H_k = \text{diag} \left( |h_{k,1}|^2 N_1, |h_{k,2}|^2 N_2, \ldots, |h_{k,M}|^2 N_M \right).
\]

In the following, we optimize the multi-relay beamforming weights to maximize the worst-case received SINR for multiple destinations and propose the iterative strategies under two different types of relay power constrained in the multiple relay M2M network. We first investigate the case where the total relay power is limited, and then study the scenario where the individual relay transmit power is constrained.

5.1. Total Relay Power Constraint. In this subsection, we optimize the multi-relay beamforming weights for multiple destinations under a total relay power constraint \( P_{\text{total}} \). Then we present the iterative strategy to jointly optimize the source-antenna selection and the relay beamforming weights under the total relay power constraint in the multiple relay M2M networks.

For the optimum, we can formulate the problem as

\[
\max \min_{v_k} \text{SINR}_k
\]

s.t. \( P_l \leq P_{\text{total}} \)

where \( P_l \) is the total transmission power of relay nodes, it can be presented as

\[
P_l = \sum_{m=1}^{M} |v_m|^2 \mathbb{E} \left[ |r_m|^2 \right]
\]

\[
= \sum_{m=1}^{M} |v_m|^2 \left( \sum_{k=1}^{K} |g_{l_k,m}|^2 P_k + N_m \right)
\]

\[
= v^H E v,
\]

\[
E = \text{diag} \left( \sum_{k=1}^{K} |g_{l_k,1}|^2 P_k + N_1, \ldots, \sum_{k=1}^{K} |g_{l_k,M}|^2 P_k + N_M \right).
\]

In order to guarantee the QoS for multiple destinations, we consider the maximization of the worst SINR among all destinations in (8). However, the objective function of the optimization problem (8) is quasi-convex. Directly solving Problem (8) is usually difficult due to its nonconvexity. We could adopt the bisection search algorithm to efficiently find the optimal solution of Problem (8). Specifically, we could solve a sequence of the following feasibility problems for each given \( \Gamma \) [11].

\[
\min_{v_k} P_l
\]

s.t. \( \begin{cases} \text{SINR}_k \geq \Gamma, & k = 1, 2, \ldots, K. \end{cases} \)

\[\]
Denote the optimal solution of (8) by $y_{opt}$. If $\Gamma = y_{opt}$ in (11), then the optimal solution $v$ of (11) is also optimal for (8). Thus we can repeatedly search for the optimal $\Gamma$ using the bisection search method [11]. In the following, we focus on solving the problem in (11) for a given $\Gamma$.

With the received SINR in (6) and the total relay transmit power in (9), we can express Problem (11) as

$$\begin{align*}
\min_v & \quad v^H E v \\
\text{s.t.} & \quad \begin{cases}
\frac{P_k}{\Gamma} |f_k^T v|^2 - \sum_{j=1, j \neq k}^{K} P_j |f_j^T v|^2 \\
-v^H H_k v \succeq N_k, & k = 1, 2, \ldots, K.
\end{cases}
\end{align*}$$

(12)

Using the definition $V \triangleq vv^H$, we can reformulate Problem (12) as

$$\begin{align*}
\min_v & \quad \text{Tr}(EV) \\
\text{s.t.} & \quad \begin{cases}
V \succeq 0, & \text{rank}(V) = 1 \\
\text{Tr}(EV) \leq P_{\text{total}}, \\
\frac{1}{\Gamma} \text{Tr}(F_k V) - \sum_{j=1, j \neq k}^{K} \text{Tr}(F_j V) \\
- \text{Tr}(H_k V) \succeq N_k, & k = 1, 2, \ldots, K.
\end{cases}
\end{align*}$$

(13)

where $F_k = P_k (f_k^T f_k^T)$ and $V \succeq 0$ means that $V$ is a hermitian semidefinite matrix. Note that the rank constraint $\text{rank}(V) = 1$ comes from $V \triangleq vv^H$, which is not convex. Thus, the optimization problem (13) is not convex. We can use the SDR technique to relax Problem (13). Here, we drop the rank-one constraint and obtain the following problem.

$$\begin{align*}
\min_v & \quad \text{Tr}(EV) \\
\text{s.t.} & \quad \begin{cases}
V \succeq 0 \\
\text{Tr}(EV) \leq P_{\text{total}}, \\
\frac{1}{\Gamma} \text{Tr}(F_k V) - \sum_{j=1, j \neq k}^{K} \text{Tr}(F_j V) \\
- \text{Tr}(H_k V) \succeq N_k, & k = 1, 2, \ldots, K.
\end{cases}
\end{align*}$$

(14)

Note that Problem (14) becomes an SDP problem, which can be optimally solved using interior-point methods, whose computational complexity is polynomial [11]. As shown in [24], for a given solution accuracy $\epsilon$, the interior-point methods need at most $O(\beta(a^2 + \beta^2)\sqrt{\alpha} \log(1/\epsilon))$ arithmetic operations, where $a$ is the dimension of the matrix variable, and $\beta$ is the number of constraints. In our SDP problem in (14), the dimension of the matrix variable is $a = M$, and the number of constraints is $\beta = K$. Therefore, the computational complexity of Problem (14) is $O(K^3 M^{3.5} \log(1/\epsilon))$.

The solution of the SDP problem in (14) provides a lower bound of the objective function in the original problem in (13) due to excluding the rank-one constraint. However, in our extensive simulations, we have never observed that the optimal solution of Problem (14) has a rank higher than one. The similar observation was also reported in [18] and [25] to design the optimal beamforming schemes. Thus, the original problem in (13) can be optimally solved. For the cases where Problem (14) has a rank higher than one, several randomization techniques [26] can be used to provide a good approximation solution $\tilde{v}$ from the optimal solution $\hat{V}$ of Problem (14).

Based on the above results, we propose an iterative strategy (see, Algorithm 1) to jointly select the source antennas and optimize the multi-relay beamforming weights with the total relay power constraint for multiple destinations.

According to [11], the bisection search method requires $\lceil \log_2((\gamma_{UB} - \gamma_{LB})/\epsilon) \rceil$ iterations. Thus, the complexity of Algorithm 1 is $O(K!(L!/\left(L - K\right)!))K^3 M^{3.5} \log(1/\epsilon)$ $\lceil \log_2((\gamma_{UB} - \gamma_{LB})/\epsilon) \rceil$ for each iteration. Since the best available channel is selected for each destination in Step 4, and the worst-case SINR is maximized from Step 5 to Step 18, after several iterations, Algorithm 1 will converge to a fixed point. We can observe this convergence in the simulations.

5.2. Individual Relay Power Constraints. In this subsection, we study the scenario where each relay power is constrained by $P^r_m$, $m = 1, 2, \ldots, M$. Note that the individual relay power constraints are important when the battery lifetime of the relay nodes is limited. Then we present the iterative strategy under individual relay power constraints in the multiple relay M2M networks.

We can formulate the problem as

$$\begin{align*}
\max_{v, k} & \quad \text{SINR}_k \\
\text{s.t.} & \quad P_m \leq P^r_m, \quad m = 1, 2, \ldots, M,
\end{align*}$$

(15)

where $P_m$ is the transmission power of relay node $m$, it can be given by

$$P_m = |v_m|^2 E[|r_m|^2] = |v_m|^2 \left( \sum_{k=1}^{K} |g_{k,m}|^2 P_k + N_m \right).$$

(16)

Since the optimization problem in (15) is quasi-convex, we can also obtain the optimal solution of (15) by repeatedly solving the following problem using the bisection search method to search for the $\Gamma$ [11].

$$\begin{align*}
\min_v & \quad P_t \\
\text{s.t.} & \quad \begin{cases}
P_m \leq P^r_m, \quad m = 1, 2, \ldots, M, \\
\text{SINR}_k \geq \Gamma, \quad k = 1, 2, \ldots, K.
\end{cases}
\end{align*}$$

(17)
1: Initialize $\gamma_{LB}$, $\gamma_{UB}$ and $P_{total}$. For some given $\varepsilon > 0$
2: while $\gamma_{UB} - \gamma_{LB} > \varepsilon$ do
3: Initialize the multirelay beamforming weights $v_m = c_m e^{j\theta_m}$, $m = 1, 2, \ldots, M$, where $c_m = P_{total}/M$, $\theta_m$
is a uniform random variable chosen from the interval $[0, 2\pi]$.
4: Apply Method 1 or Method 2 in Section 4 to select
the source antenna for each destination with the current
fixed relay weights.
5: Optimally solve Problem (14) with $\Gamma = (\gamma_{LB} + \gamma_{UB})/2$.
6: If Problem (14) is feasible, then obtain the optimal
solution $V_{opt}$.
7: if $\text{rank}(V_{opt}) = 1$ then
8: obtain the multirelay beamforming weights vector $v$
which is the optimal solution of the original problem
(11).
9: else
10: obtain the multirelay beamforming weights vector $v$
using the randomization techniques.
11: end if
12: If the total relay power is su
ffi
ciently close to a fixed
point, or the iteration number exceeds a predetermined
number, then stop the iteration and go to Step 13.
Otherwise go back to Step 4.
13: if Problem (14) is feasible then
14: $\gamma_{LB}$ = $\Gamma$
15: else
16: $\gamma_{UB}$ = $\Gamma$
17: end if
18: end while
19: return the maximization of the worst-case SINR $\Gamma$
and the multirelay beamforming weights vector $v$.

Algorithm 1: Iterative Strategy under the total relay power constraint.

With the received SINR in (6) and the $m$th relay transmit
power in (16), we can express Problem (17) as

$$\min_{v} \quad v^{H}Ev$$

subject to

$$|v_m|^2 \times \left( \sum_{k=1}^{K} |g_{lb,m}|^2 P_k + N_m \right) \leq P_{m}^i,$$

$$\frac{P_k}{\Gamma} |f_m^* f_k^T| v^2 - \sum_{j=1, j \neq k}^{K} P_j |f_j^* f_k^T| v^2$$

$$-v^{H}H_k v \geq N_k, \quad m = 1, 2, \ldots, M,$$

$$k = 1, 2, \ldots, K. \quad (18)$$

Using the definition $V = vv^{H}$, $F_k = P_k(f_k^{T}f_k^{*})$ and $A = (\sum_{k=1}^{K} |g_{lb,m}|^2 P_k + N_m)$, we can reformulate Problem (18) as

$$\min_{V} \quad \text{Tr}(EV)$$

subject to

$$V \succeq 0,$$

$$\text{rank}(V) = 1,$$

$$[V]_{m,m} \leq \frac{P_{m}^i}{A}, \quad m = 1, 2, \ldots, M,$$

$$\frac{1}{\Gamma} \text{Tr}(F_k V) - \sum_{j=1, j \neq k}^{K} \text{Tr}(F_j V)$$

$$-\text{Tr}(H_k V) \geq N_k, \quad k = 1, 2, \ldots, K, \quad (19)$$

where $[V]_{m,m}$ denotes the $(m,m)$th element of $V$ and $V \succeq 0$ means that $V$ is a hermitian semidefinite matrix. Note that the constraint rank$(V) = 1$ is not convex. As mentioned in Section 5.1, we also use the SDR technique to relax Problem (19) and obtain the following SDP problem.
As that of Problem (14), which is the computational complexity of Problem (20) is the same as that of Problem (14), which is $O(K^3 M^{3.5} \log(1/\varepsilon))$. As shown in Section 5.1, our extensive simulations, we have never observed that the constraints for multiple destinations.

In this section, we present simulation results to validate the performance of our iteration strategies for multiple destinations in the multiple relay M2M networks. It is assumed that the flat channel coefficients $g_m = [g_{1,m}, \ldots, g_{L,m}]$, $m = 1, 2, \ldots, M$ and $h_k = [h_{k,1}, \ldots, h_{k,M}]$, $k = 1, 2, \ldots, K$ are independent Rayleigh random variables with zero mean and unit variance. For convenience, it is assumed that the noise at all nodes has the same power density, that is, $N_m = N_k = N_0$. In the scenario of individual relay power constraints, we assume that each relay has the same power constraint, that is, $P_m^r = P_{\text{total}}/M$. The source transmission SNR is set to $P_k/N_0 = 10 \, \text{dB}$, $k = 1, 2, \ldots, K$, which is the same for all destinations. We use CVX [27] to numerically solve the SDP problems.

In Figure 2, we compare the performance of the proposed iteration strategies for different values of the total relay SNR of $P_{\text{total}}/N_0$. The multiple relay M2M network has one source with 8 antennas, 20 relays, and 5 destinations. We run simulations for our proposed strategies using Method 1 and Method 2 mentioned in Section 4 to select the antenna for each destination in Figures 2(a) and 2(b), respectively. The results in Figures 2(a) and 2(b) show that the performance increases as the number of iterations increases and after 3 iterations, the proposed iteration strategies can obtain each iteration. We can observe that Algorithm 2 will converge to a fixed point after several iterations in the simulations.

### 6. Simulation Results

In this section, we present simulation results to validate the performance of our iteration strategies for multiple destinations in the multiple relay M2M networks. It is assumed that the flat channel coefficients $g_m = [g_{1,m}, \ldots, g_{L,m}]$, $m = 1, 2, \ldots, M$ and $h_k = [h_{k,1}, \ldots, h_{k,M}]$, $k = 1, 2, \ldots, K$ are independent Rayleigh random variables with zero mean and unit variance. For convenience, it is assumed that the noise at all nodes has the same power density, that is, $N_m = N_k = N_0$. In the scenario of individual relay power constraints, we assume that each relay has the same power constraint, that is, $P_m^r = P_{\text{total}}/M$. The source transmission SNR is set to $P_k/N_0 = 10 \, \text{dB}$, $k = 1, 2, \ldots, K$, which is the same for all destinations. We use CVX [27] to numerically solve the SDP problems.

In Figure 2, we compare the performance of the proposed iteration strategies for different values of the total relay SNR of $P_{\text{total}}/N_0$. The multiple relay M2M network has one source with 8 antennas, 20 relays, and 5 destinations. We run simulations for our proposed strategies using Method 1 and Method 2 mentioned in Section 4 to select the antenna for each destination in Figures 2(a) and 2(b), respectively. The results in Figures 2(a) and 2(b) show that the performance increases as the number of iterations increases and after 3 iterations, the proposed iteration strategies can obtain each iteration. We can observe that Algorithm 2 will converge to a fixed point after several iterations in the simulations.
Figure 2: Expected worst-case received SINR of the proposed iteration strategies with the total relay power constraint (solid lines) and the individual relay power constraints (dashed lines) for different numbers of iterations.

Figure 3: Expected worst-case received SINR of the proposed iteration strategies with the total relay power constraint (solid lines) and the individual relay power constraints (dashed lines).

7. Discussion

In the above results, the source M2M device must calculate the collaborative relay beamforming weights with the aid of perfect CSI and then broadcast them to the relays, respectively. Thus, the perfect CSI from the source to relays and from relays to the destinations needs to provide feedback to the source M2M device. The source can also know the

near-optimal performance. Thus, 3 iterations could be enough for the proposed iteration strategies in various multiple destination scenarios. The results indicate that the performance of the proposed iteration strategy with the total power constraint (solid lines) achieves 1~2 (dB) higher SINR than that of the iteration strategy with the individual power constraints (dashed lines). In addition, comparing between Figures 2(a) and 2(b), the performance of our proposed strategies using Method 2 is slightly superior to that of our proposed strategies using Method 1, as Method 2 considers the interference to the other destinations from a selected channel based on Method 1.

Figure 3 demonstrates the worst-case received SINR results for the proposed iteration strategies with different values of the total relay SNR of $P_{\text{total}}/N_0$. In Figure 3, the curves with the square symbols represent that the multiple relay M2M network has 8 antennas, 20 relays, and 5 destinations; the curves with the circle symbols represent that the multiple relay M2M network has 6 antennas, 10 relays, and 5 destinations; the curves with the star symbols represent that the multiple relay M2M network has 6 antennas, 5 relays, and 5 destinations. We run simulations for the proposed iteration strategies using Method 1 to select the source antenna for each destination with 3 iterations in Figure 3. As shown in the figure, in order to improve the performance of the multiple relay M2M network, we can increase the number of antennas or relays with the same relay power constraint. It is also confirmed that the performance of the proposed iteration strategy with the total power constraint (solid lines) is superior than that of the iteration strategy with the individual power constraints (dashed lines). The reason is that in the case of total power constraints, more power can be allocated to the relay nodes with good channel gains by optimization.
noise level of relays and destinations from feedback channels. However in practice, wireless M2M networks, the feedback channels are always limited and could be overloaded if the number of relays and destinations is large. To deal with this issue, we can develop the distributed relay beamforming strategies to reduce the CSI exchange and allow each relay to learn its beamforming weight based on the local CSI. It is assumed that each relay node can learn the local CSI from the source by training and from destinations by feedback, respectively, and measure its noise level. In [16], a distributed strategy with local CSI is proposed for maximizing the received SNR at the single destination based on the Karush-Kuhn-Tucker (KKT) analysis. For the optimization problem of the received SINR at destinations, most previous works have focused on reducing the CSI exchange overhead. Instead of the instant CSI feedback, statistical channel information and partial CSI feedback are used in [28]. In [29], the CSI exchange overhead is drastically reduced by partitioning relays into two clusters which have different needs for CSI for calculating the relay beamforming weights. However, distributed relay beamforming strategies with the local CSI for maximizing the worst-case received SINR at multiple destinations have not been intensively discussed. In order to derive distributed beamforming strategies for the received SINR problem in the nonorthogonal systems, we can consider another criterion, that is, MMSE criterion to construct distributed relay beamforming strategies in [13] and [30]. It has been proved to be adopted for the single destination in the multiple relay systems to develop distributed beamforming strategies with the local CSI [13] and can be expected to be suitable for multiple destinations [30]. It is demonstrated that the MMSE minimization problems can be converted into the maximization of the worst-case SINR problems. Thus, in the future work, we can develop the maximization of the worst-case SINR distributed relay beamforming strategies by using the MMSE distributed beamforming strategies.

8. Conclusion

In this paper, we proposed two iterative strategies to jointly optimize the source-antenna selection and the AF relay beamforming weights with the guaranteed QoS in terms of SINR for multiple destinations in wireless M2M networks. We presented two methods to select the source antenna for each destination: (1) use the greedy algorithm to select the best available channel for each destination; (2) balance the channel condition for each destination and its interference to the other destinations based on Method 1. The maximization of the worst-case received SINR for collaborative relay beamforming was studied under two different types of power constraints, which are the total relay power constraint and the individual relay power constraints, respectively. To obtain the solution of the optimal relay beamforming weights, an SDR technique was employed to formulate the optimization problem as an SDP problem, which can be optimally solved. Simulation results demonstrated that after 3 iterations, the performance of the proposed iterative strategies can obtain near-optimal performance. In the end of this paper, we discussed the distributed relay beamforming strategy to maximize the worst-case received SINR for multiple destinations in the practical M2M networks.

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