ABSTRACT

This paper presents joint maximum signal-to-interference-plus-noise ratio (MSINR) and relay selection algorithms for distributed beamforming. We propose a joint MSINR and restricted greedy search relay selection (RGSRS) algorithm with a total relay transmit power constraint that iteratively optimizes both the beamforming weights at the relays nodes, maximizing the SINR at the destination. Specifically, we devise a relay selection scheme that based on greedy search and compare it to other schemes like restricted random relay selection (RRRS) and restricted exhaustive search relay selection (RESRS). A complexity analysis is provided and simulation results show that the proposed joint MSINR and RGSRS algorithm achieves excellent bit error rate (BER) and SINR performances.

1. INTRODUCTION

Distributed beamforming has been widely investigated in wireless communications [1][2][3] and cooperative diversity approaches [16][17][18][19][20][21][22][23][24] in recent years. It is key for situations in which the channels between the sources and the destination have poor quality so that devices cannot communicate directly and the destination relies on relays that receive and forward the signals [2]. The work in [3] formulates an optimization problem that maximizes the output signal-to-interference-plus-noise ratio (SINR) under the individual relay power constraints. The work in [4][7] focuses on the optimization of weights using all relays to increase the SINR in relay networks. Another related work [13] derives a reference signal based scheme that only uses the local channel state information (CSI).

However, in most scenarios relays are either not ideally distributed in terms of locations or the channels involved with some of the relays have poor quality. Possible solutions can be categorized in two approaches. One is to adaptively adjust the power of each relay according to the qualities of its associated channels, known as adaptive power control or power allocation. Some power control methods based on channel magnitude and relative analysis have been studied in [5][6]. An alternative solution is to use relay selection, which selects a number of relays according to a criterion of interest while discarding the remaining relays. In [8][14], several optimum single-relay selection schemes and single-relay selection schemes using relay ordering based on maximizing the output SNR under individual relay power constraints are developed and discussed, but the beamforming weights are not optimized iteratively and synchronously to enhance the SINR maximization. The work in [9] proposed a low-cost greedy search method for the uplink of cooperative direct sequence code-division multiple access systems, which approaches the performance of an exhaustive search. In [12], multi-relay selection algorithms have been developed to maximize the secondary receiver in a two-hop cognitive relay network. In [15], a combined cooperative beamforming and relay selection scheme that only selects two relays is proposed for physical layer security.

In this work, we propose a joint MSINR distributed beamforming and restricted greedy search relay selection (RGSRS) algorithm with a total relay transmit power constraint which iteratively optimizes both the beamforming weights [25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43][44][45][46][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61][62][63][64][65][66][67][68][69][70][71][72] at the relay nodes, maximizing the output SINR at the destination, provided that the second-order statistics of the CSI is perfectly known. Specifically, we devise a relay selection scheme based on a greedy search and compare it to other schemes like restricted random relay selection (RRRS) and restricted exhaustive search relay selection (RESRS). The RRRS scheme selects a fixed number of relays from all relays. The RESRS scheme employs the exhaustive search method that runs every single possible combination among all relays aiming to obtain the set with the best SINR performance. The proposed RGSRS scheme is developed from a greedy search method with a specific optimization problem that works in iterations and requires SINR feedback from the destination. These joint MSINR and restricted relay selection methods are compared with the scenario without relay selection and the results show significant improvements in terms of SINR and BER performances of the proposed algorithm. The computational cost of all algorithms are analyzed.

This paper is organized as follows. Section 2 presents the system model. In Section 3, the joint MSINR and relay selection method is introduced. Section 4 derives the joint MSINR and RGSRS algorithm and provides its computational complexity analysis. Section 5 presents the simulation results. Section 6 gives the conclusion.

2. SYSTEM MODEL

We consider a wireless communication network consisting of $K$ signal sources (one desired signal with the others as interferers), $M$ distributed single-antenna relays and a destination. It is assumed that the quality of the channels between the signal sources and the destination is poor so that direct communications are impossible and their links are negligible. The $M$ relays receive information transmitted by the signal sources and then retransmit to the destination as a beamforming procedure, in which a two-step amplify-and-forward (AF) protocol is considered for cooperative communications.

In the first step, the sources transmit the signals to the relays as

$$
\mathbf{x} = \mathbf{F}s + \mathbf{v},
$$

where $s = [s_1, s_2, \cdots, s_K]^T \in \mathbb{C}^{K \times 1}$ are signal sources with zero mean, $[\cdot]^T$ denotes the transpose, $s_k = \sqrt{P_{s,k}}s$, $E[|s|^2] = 1$, $P_{s,k}$ is the transmit power of the $k$th signal source, $k = 1, 2, \cdots, K$, $s$ is
the information symbol. Without loss of generality we can assume
$s_1$ as the desired signal while the others are treated as interferers.
$\mathbf{F} = [f_1, f_2, \cdots, f_k] \in \mathbb{C}^{M \times K}$ is the channel matrix between the
signal sources and the relays, $f_k = [f_{1,k}, f_{2,k}, \cdots, f_{M,k}]^T \in 
\mathbb{C}^{M \times 1}$. $f_{m,k}$ denotes the channel between the $m$th relay and
the $k$th source ($m = 1, 2, \cdots, M$, $k = 1, 2, \cdots, K$). $\mathbf{v} = [\nu_1, \nu_2, \cdots, \nu_M]^T \in \mathbb{C}^{M \times 1}$ is the complex Gaussian noise vec-
tor at the relays and $\sigma_n^2$ is the noise variance at each relay ($\nu_m \sim 
\mathcal{CN}(0, \sigma_n^2)$). The vector $\mathbf{x} \in \mathbb{C}^{M \times 1}$ represents the received data
at the relays. In the second step, the relays transmit $\mathbf{y} \in \mathbb{C}^{M \times 1}$ which
is an amplified and phase-steered version of $\mathbf{x}$ that can be written as

$$\mathbf{y} = \mathbf{Wx},$$  \hspace{1cm} (2)

where $\mathbf{W} = \text{diag}([w_1, w_2, \cdots, w_M]) \in \mathbb{C}^{M \times M}$ is a diagonal ma-
trix whose entries denote the beamforming weights. Then the signal
received at the destination is given by

$$z = \mathbf{g}^T \mathbf{y} + n,$$  \hspace{1cm} (3)

where $z$ is a scalar, $\mathbf{g} = [g_1, g_2, \cdots, g_M]^T \in \mathbb{C}^{1 \times M}$ is the complex
Gaussian channel vector between the relays and the destination, $n$
($n \sim \mathcal{CN}(0, \sigma_n^2)$, $\sigma_n^2 = \sigma_z^2$) is the noise at the destination and $z$ is
the received signal at the destination.

It should be noted that both $\mathbf{F}$ and $\mathbf{g}$ are modeled as Rayleigh
distributed. Using the Rayleigh distribution for the channels, we also
consider distance based large-scale channel propagation effects that
include fading (or path loss) and shadowing. Distance based fading
(or path loss) is a representation of how a signal is attenuated
the further it travels in the medium the system operates within, and
they may contribute to poor network performance due to their poor
performance for receiving and transmitting signals. The aim of joint
maximum SINR beamforming and relay selection is to compute the
beamforming weights according to the maximum SINR criterion and
optimize the relay system by discarding the relays with poor perfor-
mance and making the best use of the relays with good channels in
order to improve the overall system performance.

A joint SINR maximization problem with relay selection using
a total relay transmit power constraint encountering interferers can be
generally described as

$$S_{\text{opt}} = \arg\max_{\alpha, \mathbf{w}} \text{SINR}(\mathcal{S}, \mathcal{H}, \mathbf{P}_s, \mathbf{P}_r, \mathbf{P}_f, \alpha, \mathbf{w})$$
subject to

$$\sum_{m=1}^M \alpha_m P_{r,m} \leq P_r,$$
$$\alpha_m \in \{0, 1\}, m = 1, 2, \cdots, M,$$

where $S_{\text{opt}}$ is the optimum relay set of size $M_{\text{opt}}$ ($1 \leq M_{\text{opt}} \leq M$)
and $\text{SINR}$ is a function of $\mathcal{S}, \mathcal{H}, \mathbf{P}_s, \mathbf{P}_r$ and $\mathbf{P}_f$, where $\mathcal{S}$ is
the original relay set of size $M$, $\mathcal{H}$ is the set containing parameters of
the CSI (i.e., $\mathcal{H} = \{\mathbf{F}, \mathbf{g}, \sigma_n^2\}$), $\mathbf{P}_s = [P_{s,1}, P_{s,2}, \cdots, P_{s,K}] \in 
\mathbb{R}^{1 \times K}$, $k = 1, 2, \cdots, K$, $\mathbf{P}_r = [P_{r,1}, P_{r,2}, \cdots, P_{r,M}] \in \mathbb{R}^{M \times 1}$,
$m = 1, 2, \cdots, M$, $P_{r,m}$ refers to the transmit power of the $m$th
relay (Note that before selection we have $\sum_{m=1}^M P_{r,m} \leq P_r$ and
we consider that each relay cooperates with its full power as long
as it is selected), $P_r$ is the maximum allowable total transmit power of
all relays, $\alpha = [\alpha_1, \alpha_2, \cdots, \alpha_M]^T$, $\alpha_m (m = 1, \cdots, M)$ is
the relay cooperation parameter which determines weather the $m$th
relay cooperates or not, $\mathbf{w} = [w_1, w_2, \cdots, w_M]^T \in \mathbb{C}^{M \times 1}$ is the
beamforming weight vector. The received signal at the $m$th relay as:

$$x_m = \sum_{k=1}^K \sqrt{P_{s,k}} f_{m,k} + \nu_m,$$  \hspace{1cm} (9)

then the transmitted signal at the $m$th relay can be written as:

$$y_m = \alpha_m w_m x_m.$$  \hspace{1cm} (10)

Note that we can express the transmit power at the $m$th relay
$P_{r,m}$ as $E[|y_m|^2]$ so that the total relay transmit power can be
written as $\sum_{m=1}^M E[|y_m|^2] = \sum_{m=1}^M E[|\alpha_m w_m x_m|^2]$ or in ma-
trix form as $(\alpha^H \otimes \mathbf{w}^H) \mathbf{D} (\alpha \otimes \mathbf{w})$ where $\mathbf{D} =$
$\text{diag}(\alpha \otimes (\sum_{k=1}^K P_{s,k} E[|f_{k}|^2], E[f_{k,1}^2], \cdots, E[f_{M,k}^2])) + \sigma_n^2$ is a full-
rank matrix. The signal received at the destination can be expanded by
substituting $9$ and $10$ in $7$, which gives

$$z = \sum_{m=1}^M \alpha_m w_m y_m \sqrt{P_{s,k}} f_{m,k} s + \sum_{m=1}^M \alpha_m w_m y_m \sum_{k=2}^K \sqrt{P_{s,k}} f_{m,k} s$$
desired signal
$$+ \sum_{m=1}^M \alpha_m w_m y_m \nu_m + n.$$  \hspace{1cm} (11)

By taking expectations of the components of $11$, we can compute the
desired signal power $P_{s,1}$, the interference power $P_{s,1}$, and the
The number of iterations of this alternating optimization depends on parameter $w$ solved with respect to $f$.

Fine parameter, and if the maximum SINR is achieved, which is both the minimum required number of relays, which is a user power constraint SNR maximization problem similarly to [4], with $\alpha$ elements of product which computes element-wise multiplications, they are such perfectly known. Then, a closed-form solution for $\tilde{w}$ obtain the solutions for both operators. At this point, we use an alternating optimization strategy to be cast in terms of solving for $\tilde{w}$, and defined by

\[
R = \frac{P_{s,1}}{P_{s,1} + P_{s,2}}.
\]

\[\text{SINR} = \frac{P_{s,1}}{P_{s,1} + P_{s,2}}.\]

\[
\tilde{w} = \frac{R}{\sigma^2 + \tilde{w}^H(Q + \sum_{k=2}^K R_k)(\alpha \odot \tilde{w})}w
\]

subject to $\text{Rank}(\tilde{w}w^H) = \text{Rank}(\alpha H)$, $\alpha_m \in \{0,1\}, m = 1, 2, \cdots, M$,

where $R_1$, $Q$, and $R_k$ are covariance matrices that are associated with the desired signal, the noise at the relays and the 4th interferer and defined by $P_{s,1}E[(\alpha \odot f_1 \odot g)(\alpha \odot f_1 \odot g)^H] \in \mathbb{C}^{M \times M}$, $\sigma^2_\alpha E[(\alpha \odot g)(\alpha \odot g)^H] \in \mathbb{C}^{M \times M}$, $P_{s,k}E[(\alpha \odot f_k \odot g)(\alpha \odot f_k \odot g)^H] \in \mathbb{C}^{M \times M}$, respectively, where $\odot$ denotes the Schur-Hadamard product which computes element-wise multiplications, they are such defined so that their ranks are equal to the number of non-zero elements of $\alpha$. The second constraint indicates and ensures $\tilde{w}$ has the same number of zero elements as $\alpha$ and $\text{Rank}$ denotes the rank operator. At this point, we use an alternating optimization strategy to obtain the solutions for both $w$ and $\alpha$, i.e., we fix the vector parameter $w$ and optimize $\alpha$ and vice-versa in an alternating fashion. The number of iterations of this alternating optimization depends on both the minimum required number of relays, which is a user defined parameter, and if the maximum SINR is achieved, which is determined by the system feedback. The problem in (16) can be solved with respect to $w$ in a closed-form solution as in the total power constraint SNR maximization problem similarly to [2], with the assumption that the second-order statistics of the CSI (i.e., $H$) is perfectly known. Then, a closed-form solution for $\tilde{w}$ is obtained by

\[
\tilde{w} = \sqrt{P_T}D^{-\frac{1}{2}}P\{E\},
\]

and the corresponding SINR is

\[
\text{SINR} = P_T\lambda_{\text{max}}\{E\},
\]

where $P\{\cdot\}$ denotes the principal eigenvector operator, $\lambda_{\text{max}}\{\cdot\}$ denotes the largest eigenvalue of the argument, $E = (\sigma^2_\alpha^2I + P_TD^{-\frac{1}{2}}(Q + \sum_{k=2}^K R_k)D^{-\frac{1}{2}})^{-1}D^{-\frac{1}{2}}R_1D^{-\frac{1}{2}}$ has the same rank as $R_1$. It is easy to observe that once we know $\alpha$, we can compute the optimum weights and SINR from (17) and (18), respectively, by using only the currently selected relay nodes and their weights. The weight optimization steps are detailed in Table 1.

### Table 1. Beamforming weight vector optimization

1. Using a search algorithm to optimize and obtain $\alpha$.
2. $R_1 = P_{s,1}E[(\alpha \odot f_1 \odot g)(\alpha \odot f_1 \odot g)^H]$ The interferers related covariance matrices for $k = 2, \cdots, K$:
3. $R_k = P_{s,k}E[(\alpha \odot f_k \odot g)(\alpha \odot f_k \odot g)^H] \in \mathbb{C}^{M \times M}$ The noise related covariance matrix:
4. $Q = \sigma^2_\alpha^2E[(\alpha \odot g)(\alpha \odot g)^H]$ The transmit power related full-rank matrix $D$:
5. $D = \text{diag}(\alpha \odot (\sum_{k=2}^K P_{s,k} [E[f_{1,k}][2], E[f_{2,k}][2], \cdots, E[f_{M,k}][2]]) + \sigma^2_\alpha^2)$ The defined matrix $E$:
6. $E = (\sigma^2_\alpha^2I + P_TD^{-\frac{1}{2}}(Q + \sum_{k=2}^K R_k)D^{-\frac{1}{2}})^{-1}D^{-\frac{1}{2}}R_1D^{-\frac{1}{2}}$
7. $\tilde{w} = \sqrt{P_T}D^{-\frac{1}{2}}P\{E\}$ Compute the output SINR at the destination:
8. $\text{SINR} = P_T\lambda_{\text{max}}\{E\}$

3.2. Relay Selection

In order to solve the problem in (16) with respect to $\alpha$, we consider

\[
\max_\alpha \text{SINR}
\]

subject to $\sum_{m=1}^M \alpha_m^2 P_{r,m} \leq P_T$, (19)

\[
\alpha_m \in \{0,1\}, m = 1, 2, \cdots, M
\]

that can be solved with algorithms like greedy search and exhaustive search, which can be determined by the designer. To emphasize, $\alpha$ is obtained before $w$ is computed in each recursion. An alternative way that computes $\tilde{w}$ before obtaining $\alpha$ also works but the above equations will be different. This joint MSINR beamforming and relay selection method requires output SINR comparisons and feedback from the destination to the relay nodes as a form of information exchange, which is similar to [3], but weight optimization is neglected in their work.

4. PROPOSED JOINT MSINR AND RGSR ALGORITHM

The joint MSINR and RGSR algorithm works in iterations with excellent performance. We consider a user-defined parameter $M_{\text{min}}$, as a restriction to the minimum number of relays that must be used to allow a higher flexibility for the users to control the number of relays. Before the first iteration all relays are considered (i.e., $S(0) = S$).
Consequently, we solve the following problem once for each iteration in order to cancel the relay with worst performance from set $S(i-1)$ and evaluate $SINR(i)$:

$$S(i) = \arg\max_{\alpha(i)} \ SINR(i)$$

subject to

$$\sum_{m=1}^{M} \alpha_{m}^{2}(i) P_{r,m}(i) \leq P_T, \alpha_{m}(i) \in \{0,1\}, \|\alpha(i)\|_1 = M-i, \|\alpha(i)-\alpha(i-1)\|_1 = 1, M-i \geq M_{min},$$

(20)

where $SINR(i) = SINR(S(i-1), H, P_r, P_s, P_r, P_r, \rho)$ and can be computed by (13). If the SINR in the current iteration is higher than that in the previous iteration (i.e. $SINR(i) > SINR(i-1)$), then the selection process continues; if $SINR(i) \leq SINR(i-1)$, we cancel the selection of the current iteration and remain the relay set $S(i-1)$ and $SINR(i-1)$. The joint MSINR and RGSRS algorithm can be implemented as in Table 2.

At this point, we analyze the computational complexity required by the relay selection algorithms. The MSINR based method for SINR driven beamforming weights optimization has a cost of $O(M^3)$ since matrix inversion and eigen-decomposition are required. However, $M$ is usually not large so that many same attentions should be paid to the computational cost caused by the number of iterations required in these relay selection algorithms. For the joint MSINR and RRRS algorithm, there is no weight vector or relay selection vector optimization required, which means there is only one iteration and the complexity is simply $O(M^3)$. The joint MSINR and RESRS algorithm has the highest computational cost due to the fact it almost searches for all possible combinations of the relays even though an extra restriction of the minimum number of relays required is added in our case. With a restriction of that at least $M_{min}$ relays must be selected, the number of iterations is $\sum_{M_{min}}^{M} \binom{M-1}{M_{min}-1}$. In the joint MSINR and RGSRS algorithm, (20) is solved once per iteration, which can be done by disabling only one relay while enabling all the others and computing and comparing their output SINRs. The total number of iterations is no greater than $\sum_{M_{min}}^{M} \binom{M-1}{M_{min}-1}$. The proposed joint MSINR and RGSRS algorithm has much lower complexity compared to the joint MSINR and RESRS algorithm when the value of $M$ is large.

Table 2. Joint MSINR and RGSRS Algorithm

| step 1: Initialize $S_{opt} = S(0), \alpha(0) = 1$ and obtain $SINR_{opt} = SINR(0)$ using Table 1 | Computational Cost |
|-------------------------------------------------|---------------------|
| step 2: for $i = 1, \ldots, M - M_{min}$ | $O(M^3)$ |
| solve the optimization problem (20) to obtain $\alpha(i)$, $S(i)$ and compute $SINR(i)$ using Table 1 | $O(M^3)$ |
| compare $SINR(i)$ to $SINR(i-1)$, if $SINR(i) > SINR(i-1)$ | $O(M^3)$ |
| update $S_{opt} = S(i)$ and $SINR_{opt} = SINR(i)$ | $O(M^3)$ |
| else | $O(M^3)$ |
| keep $S_{opt} = S(i-1)$ and $SINR_{opt} = SINR(i-1)$ | $O(M^3)$ |
| break. | $O(M^3)$ |
| end if. | $O(M^3)$ |
| end for. | $O(M^3)$ |

5. SIMULATION RESULTS

In the simulations, we compare the joint MSINR and relay selection algorithms to the scenario without relay selection in terms of their SINR and bit error rate (BER) performances. The generic parameters used for all scenarios include: number of signal sources $K = 3$, the path loss exponent $\rho = 2$, the power path loss from signals to the destination $L = 10$dB, shadowing spread $\sigma_s = 3$dB, $P_T = 1$dBW. Fig. 1a illustrates the SINR versus SNR (from 0dB to 20dB) performance of the compared algorithms, in which the total number of relays and interference-to-noise ratio (INR) are fixed at $M = 8$ and INR=10dB, respectively. Fig. 1b illustrates how the SINR varies when the total number of relays in the network increases, in which the input SNR=10dB and INR=10dB are fixed. In this case, a minimum total number of relays observed is chosen as $M = 3$, whereas the maximum is at $M = 10$. For each of the above two scenarios, 500 repetitions are carried out for each algorithm. In Fig. 1c, we evaluate the BER versus SNR performance of all algorithms using Binary Phase Shift Keying (BPSK) for the system and test all algorithms with 100000 bits, while keeping INR=10dB. For all the above scenarios, we fix the number of randomly selected relays at 3 for the joint MSINR and random relay selection algorithm, the minimum required selected relays also at 3 for the other algorithms. As observed, the joint MSINR and RESRS and the joint MSINR and RGSRS algorithms have the best performance.

![Fig. 1. SINR versus SNR and M](image_url)

6. CONCLUSION

We have proposed a joint MSINR and RGSRS algorithm for distributed beamforming which is derived based on a greedy search relay selection scheme. The computational cost of the proposed algorithm has been analyzed and compared to prior work that employ RRRS and RESRS schemes. The results have shown excellent SINR and BER performances of the proposed algorithm which are very close to the joint MSINR and RESRS algorithm.
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