

TECHNICAL REPORT ON JOINT MMSE CONSENSUS AND RELAY SELECTION ALGORITHMS FOR DISTRIBUTED BEAMFORMING

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ABSTRACT

This work presents joint minimum mean-square error (MMSE) consensus algorithm and relay selection algorithms for distributed beamforming. We propose joint MMSE consensus relay and selection schemes with a total power constraint and local communications among the relays for a network with cooperating sensors. We also devise greedy relay selection algorithms based on the MMSE consensus approach that optimize the network performance. Simulation results show that the proposed scheme and algorithms outperform existing techniques for distributed beamforming.

Index Terms— Distributed beamforming, relay selection, consensus algorithms.

1. INTRODUCTION

Distributed beamforming has been widely investigated in wireless communications in recent years [1, 2, 3, 15]. 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 approach in [7] proposes an MMSE consensus cooperative relay networking scheme to exchange data among all the relays under a total power constraint, which limits the total power of all relays regardless of the power allocation. While local communications among the relays are enabled, the ability to mitigate fading effects in wireless channels of the network can be improved [8]. Further earlier works in [12] and [13] explored local communications, while avoiding network centralized processing, which is not desirable and always comes along with the use of total power constraints [7].

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 has been studied in [6, 14]. 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 [4], multi-relay selections algorithm have been developed to maximize the secondary receiver in a two-hop cognitive relay network. In [8], several optimum single-relay selection schemes and a multi-relay selection scheme using

relay ordering based on maximizing the output SNR under individual relay power constraints are developed and discussed. 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. Other approaches include the use of subspace techniques [16, 17, 18, 19, 20, 21, 22, 135, 37, 25, 26, 27, 28, 29, 30, 31, 137, 33, 34, 35, 36, 47, 37, 38, 39, 40, 41, 42, 43, 44, 49, 46, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 196, 68, 69, 70, 71], and large sensor arrays [197, 198, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 99, 89, 90, 91, 92, 93, 95, 96, 97, 98, 100, 101],[174, 161, 179, 176, 164, 107, 108, 138, 163, 131, 112, 138, 114, 193, 116, 117, 133].

In this work, we propose a joint minimum mean-square error (MMSE) consensus and relay selection approach and develop iterative greedy search based relay selection algorithms for distributed beamforming. In the first proposed algorithm we aim to find largest minimum value of a cost function regarding the desired signal by enabling only one relay at once, testing through all the relays one by one, then we select all the disabled relays when the network has the largest MMSE (LMMSE) value in each iteration, namely, the SMMSE consensus greedy (LMMSEC-G) relay selection algorithm. In the second proposed approach, we aim to find the smallest minimum value of the same cost function, by disabling only one relay at once, testing through all the relays one by one, then preserve all the selected relays when the network has the smallest MMSE (SMMSE) estimate in each iteration, namely, the SMMSE consensus greedy (SMMSEC-G) relay selection algorithm. We compare the proposed greedy relay selection algorithms to the exhaustive search and the scenario without relay selection, showing their excellent output SINR performance which is close to the exhaustive search approach.

This paper is organized as follows. In Section 2, the system model is introduced. In Section 3, the joint MMSE consensus and relay selection scheme is presented. In Section 4, the greedy relay selection algorithms are proposed. In Section 5, simulations are presented and discussed. Finally, conclusions are drawn in Section 6.

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 very poor so that direct communications is not possible 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

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(AF) protocol (as shown in Fig. 1) is considered as required for cooperative communications.

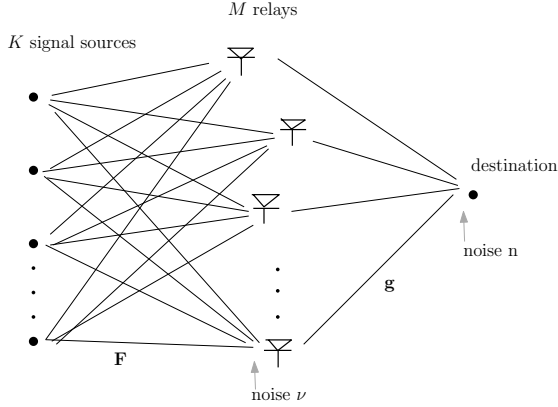


Fig. 1. System model.

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

$$\mathbf{x} = \mathbf{F}\mathbf{s} + \boldsymbol{\nu}, \quad (1)$$

where $\mathbf{s} = [s_1, s_2, \dots, s_K] \in \mathbb{C}^{1 \times K}$ are signal sources with zero mean, $[\cdot]^T$ denotes the transpose, $s_k = \sqrt{P_k}s$, $E[|s|^2] = 1$, P_k is the transmit power of the k th signal source, $k = 1, 2, \dots, K$, 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. $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_K] \in \mathbb{C}^{M \times K}$ is the channel matrix between the signal sources and the relays, $\mathbf{f}_k = [f_{1,k}, f_{2,k}, \dots, f_{M,k}]^T \in \mathbb{C}^{M \times 1}$, $f_{m,k}$ denotes the channel between the m th relay and the k th source ($m = 1, 2, \dots, M$, $k = 1, 2, \dots, K$). $\boldsymbol{\nu} = [\nu_1, \nu_2, \dots, \nu_M]^T \in \mathbb{C}^{M \times 1}$ is the complex Gaussian noise vector at the relays and σ_ν^2 is the noise variance at each relay ($\nu_m \sim \mathcal{CN}(0, \sigma_\nu^2)$). 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} , which can be written as

$$\mathbf{y} = \mathbf{W}\mathbf{x}, \quad (2)$$

where $\mathbf{W} = \text{diag}[w_1, w_2, \dots, w_M] \in \mathbb{C}^{M \times M}$ is a diagonal matrix whose diagonal entries denote the beamforming weights. The signal received at the destination is given by

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

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

Note that both \mathbf{F} and \mathbf{g} are modeled as Rayleigh distributed (i.e., both the real and imaginary coefficients of the channel parameters have Gaussian distribution). Using the Rayleigh distribution for the channels, we also consider distance based large-scale channel propagation effects that include distance-based fading (or path loss) and shadowing. Distance-based fading represents how a signal is attenuated as a function of the distance and can be highly affected by the environment. [10, 11] An exponential based path loss model can be described by

$$\gamma = \frac{\sqrt{L}}{\sqrt{d}^\rho}, \quad (4)$$

where γ is the distance based path loss, L is the known path loss at the destination, d is the distance of interest relative to the destination and ρ is the path loss exponent, which can vary due to different environments and is typically set within 2 to 5, with a lower value representing a clear and uncluttered environment which has a slow attenuation and a higher value describing a cluttered and highly attenuating environment. Shadow fading describes the phenomenon where objects can obstruct the propagation of the signal attenuating the signal further, and can be modeled as a random variable with probability distribution given by

$$\beta = 10^{\left(\frac{\sigma_s \mathcal{N}(0,1)}{10}\right)}, \quad (5)$$

where β is the shadowing parameter, $\mathcal{N}(0, 1)$ means the Gaussian distribution with zero mean and unit variance, σ_s is the shadowing spread in dB. The shadowing spread reflects the severity of the attenuation caused by shadowing, and is typically given between 0dB to 9dB. The channels modeled with both path-loss and shadowing are described by

$$\mathbf{F} = \gamma\beta\mathbf{F}_0, \quad (6)$$

$$\mathbf{g} = \gamma\beta\mathbf{g}_0, \quad (7)$$

where \mathbf{F}_0 and \mathbf{g}_0 denote the Rayleigh distributed channels without path-loss and shadowing [10, 11].

3. PROPOSED JOINT MMSE CONSENSUS AND RELAY SELECTION

In this section, we detail the proposed joint MMSE consensus and relay selection scheme for distributed beamforming using an alternating optimization approach in which the relay selection is followed by MMSE consensus of beamformers. We assume at the m th relay the MMSE estimate of the desired signal $\hat{s}_{m,1}$ can be found as

$$\hat{s}_{m,1} = \phi_m x_m, \quad (8)$$

where

$$\phi_m = \arg \min_{\phi} E[|s_1 - \phi x_m|^2] = \frac{f_{m,1}^* P_1}{\sum_{k=1}^K |f_{m,k}|^2 P_k + \sigma_n^2}.$$

For convenience we define $\tilde{s}_{m,1} = \frac{\hat{s}_{m,1}}{E[|\hat{s}_{m,1}|^2]}$ and the normalized relay weight as $\frac{w_m \phi_m}{E[|\hat{s}_{m,1}|^2]}$, so that the total transmission power can be expressed as $\sum_{m=1}^M E[|w_m \tilde{s}_{m,1}|^2] = \sum_{m=1}^M |w_m|^2$. Therefore, the MMSE consensus optimization associated with a fixed set of relays under a total power constraint is given by

$$\begin{aligned} w_m^* = \arg \min_{w_m} \sum_{m=1}^M E[|s_1 - g_m w_m \tilde{s}_{m,1}|^2] \\ \text{s.t. } \sum_{m=1}^M |w_m|^2 \leq P_T, \end{aligned} \quad (9)$$

where P_T is the maximum allowable total transmit power of all relays. The relay selection problem for the MMSE consensus can be described as an optimization problem using a total relay transmit power constraint described by

$$\begin{aligned} \mathcal{S}_{\text{opt}} = \arg \min_{\boldsymbol{\alpha}, \mathbf{w}} MMSE(\mathcal{S}) \\ \text{s.t. } \sum_{m=1}^M \alpha_m |w_m|^2 \leq P_T, \\ \alpha_m \in \{0, 1\}, m = 1, 2, \dots, M \end{aligned} \quad (10)$$

where $MMSE(\mathcal{S}) = \sum_{m=1}^M \alpha_m E[|s_1 - g_m w_m \tilde{s}_{m,1}|^2]$, $\mathbf{w} = [w_1, w_2, \dots, w_M]^T \in \mathbb{C}^{M \times 1}$, \mathcal{S}_{opt} and \mathcal{S} are the optimum relay set of size M_{opt} , ($1 \leq M_{opt} \leq M$) and the original relay set of size M , respectively. The vector $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \dots, \alpha_M]^T \in \mathbb{R}^{M \times 1}$, α_m ($m = 1, \dots, M$) is the relay cooperation parameter vector which determines if the m th relay will cooperate. The solution of (10) regarding w_m indicates the following relationship:

$$w_m^* = \frac{\alpha_m g_m^*}{\lambda + \alpha_m |g_m|^2} \sqrt{\frac{|f_{m,1}|^2 P_1^2}{\sum_{k=1}^K |f_{m,k}|^2 P_k + \sigma_n^2}}, \quad (11)$$

where λ is the Lagrange multiplier, which can be determined by enabling the local communication of the relays with an MMSE consensus approach. To this end, we employ an auxiliary beamforming weight vector $\tilde{\mathbf{w}}_m = [\tilde{w}_{1,m}, \dots, \tilde{w}_{M,m}]^T$ and consider the following joint optimization problem:

$$\begin{aligned} \min_{\tilde{\mathbf{w}}_m, \boldsymbol{\alpha}} \quad & \alpha_m E[|s_1 - g_m w_m \tilde{s}_{m,1}|^2] \\ \text{s.t.} \quad & \|\boldsymbol{\alpha}\|_1 \|\tilde{\mathbf{w}}_m\|^2 \leq P_T, \tilde{\mathbf{w}}_m = \mathbf{w}, \\ & \alpha_m \in \{0, 1\}, m = 1, 2, \dots, M \end{aligned} \quad (12)$$

where $\mathbf{w} = \text{diag}(\mathbf{W}) \in \mathbb{C}^{M \times 1}$. It is supposed that the m th relay is connected to a subset of relays denoted by \mathcal{M}_m . The second constraint in (12) can be replaced by $\tilde{\mathbf{w}}_m = \tilde{\mathbf{w}}_q, q \in \mathcal{M}_m$ so that (12) is reformulated as

$$\begin{aligned} \min_{\tilde{\mathbf{w}}_m, \boldsymbol{\alpha}} \quad & \alpha_m E[|s_1 - g_m w_m \tilde{s}_{m,1}|^2] + \lambda_m(i) (\|\boldsymbol{\alpha}\|_1 \|\tilde{\mathbf{w}}_m\|^2 - P_T) \\ & + \sum_{q \in \mathcal{M}_m} \tau_{m,q}^T (\tilde{\mathbf{w}}_m - \tilde{\mathbf{w}}_q), \end{aligned} \quad (13)$$

where $\lambda_m(i)$ and $\tau_{m,q}$ are Lagrange multipliers. The proposed algorithmic solution relies on the alternating optimization associated with relay selection, computation of the optimal weights and Lagrange multipliers at the m th relay as

$$\tilde{w}_{t,m} = \begin{cases} \frac{\alpha_m g_m^*}{\lambda_m(i) + \alpha_m |g_m|^2} \left(\sqrt{\frac{|f_{m,1}|^2 P_1^2}{\sum_{k=1}^K |f_{m,k}|^2 P_k + \sigma_n^2}} - \frac{\sum_{q \in \mathcal{M}_m} \tau_{m,q;t}}{2} \right), & \text{if } t = m \\ -\frac{\alpha_m \sum_{q \in \mathcal{M}_m} \tau_{m,q;t}}{2\lambda_m(i)}, & \text{if } t \neq m \end{cases} \quad (14)$$

where $\tau_{m,q;t}$ denotes the t th element of $\tau_{m,q}$. The Lagrange multipliers are updated as follows

$$\lambda_m(i) = |\lambda_m(i-1) + \mu_\lambda (\|\tilde{\mathbf{w}}_m\|^2 - P_T)|, \quad (15)$$

$$\tau_{m,q}(i) = \tau_{m,q}(i-1) + \mu_\tau (\mathbf{u}_m - \mathbf{u}_q), \quad (16)$$

where μ_λ and μ_τ are step sizes with small positive values, $\mathbf{u}_m = [|w_{1,m}|, \dots, |w_{M,m}|]^T$ and i is the time index [7].

4. PROPOSED GREEDY RELAY SELECTION ALGORITHMS

In this section, we detail the algorithms that perform relay selection, develop the LMMSEC-G and SMMSEC-G relay selection algorithms and review the exhaustive search.

Table 1. LMMSEC-G relay selection algorithm

Initialize $\mathcal{S}_{opt} = \mathcal{S}(0)$, $\boldsymbol{\alpha} = \mathbf{1}$, $\tilde{\mathbf{w}}_m = \mathbf{1}$,
 $\lambda_m(0) = 1$, $\tau_{m,q}(0) = 1$ and compute $MMSE_o = MMSE(0)$.
for $i = 1, \dots, M - M_{min}$

step 1:
compute $\tau_{m,q}(i) = \tau_{m,q}(i-1) + \mu_\tau (\mathbf{u}_m - \mathbf{u}_q)$,
and $\tau_{m,q}(i) = \tau_{m,q}(i-1) + \mu_\tau (\mathbf{u}_m - \mathbf{u}_q)$.

step 2:
compute the consensus weight using (14).

step 3:
solve the optimization problem (17) and obtain $\tilde{\mathcal{S}}(i)$.
compute $\mathcal{S}(i)$ using $\mathcal{S}(i-1) - \tilde{\mathcal{S}}(i)$.
compute $MMSE(i)$ using $\mathcal{S}(i)$.
compare $MMSE(i)$ to $MMSE(i)(i-1)$,
if $MMSE(i) < MMSE(i-1)$
 update $\mathcal{S}_{opt} = \mathcal{S}(i)$ and $MMSE_o = MMSE(i)$.
 update $\boldsymbol{\alpha}(i)$.
else
 keep $\mathcal{S}_{opt} = \mathcal{S}(i-1)$ and $MMSE_o = MMSE(i-1)$.
 break.
end if.
end for.

4.1. LMMSEC-G relay selection algorithm

We develop the LMMSEC-G algorithm to obtain the solution of (12), which depends on the relay selection parameter vector $\boldsymbol{\alpha}$ to find the optimum $\boldsymbol{\alpha}$. The LMMSEC-G works in an iterative way and discards only the worst relay to find the optimal relay set in each iteration. Additionally, the parameter M_{min} can be introduced to restrict the minimum number of relays that must be used. The LMMSEC-G algorithm finds the largest MMSE at each iteration and selects the complementary relays, which is described as follows

$$\begin{aligned} \tilde{\mathcal{S}}(i) &= \arg \max_{\boldsymbol{\alpha}^{(i)}} MMSE(\mathcal{S}(i-1)) \\ \text{s.t.} \quad & \|\tilde{\mathbf{w}}_m(i)\|^2 \leq P_T, \tilde{\mathbf{w}}_m(i) = \mathbf{w}(i), \\ & \alpha_m(i) \in \{0, 1\}, m = 1, 2, \dots, M \\ & M - i \geq M_{min}, \end{aligned} \quad (17)$$

where $\tilde{\mathcal{S}}(i)$ denotes the complement of the set $\mathcal{S}(i)$ from set $\mathcal{S}(i-1)$. The optimization problem compares all the MMSE values assuming that only one different single relay is enabled while the others are disabled. LMMSEC-G cancels the relay with largest MMSE value from set $\mathcal{S}(i-1)$ and evaluates the MMSE performance of the remaining relays, which is solved only once in each iteration. If the MMSE in the current iteration is smaller than that in the previous iteration (i.e. $MMSE(i) < MMSE(i-1)$), then the selection process continues; if $MMSE(i) \geq MMSE(i-1)$, we cancel the selection of the current iteration and keep the relay set $\mathcal{S}(i-1)$ and $MMSE(i-1)$. The LMMSEC-G algorithm is shown in Table. 1.

4.2. SMMSEC-G relay selection algorithm

The proposed SMMSEC-G algorithm is an alternative way to find the solution of (12) regarding $\boldsymbol{\alpha}$, which aims to find the smallest MMSE from the remaining relays after disabling a single relay each time. It is an improved greedy search based method which also

Table 2. SMMSECG

Initialize $\mathcal{S}_{opt} = \mathcal{S}(0)$, $\alpha = \mathbf{1}$, $\tilde{\mathbf{w}}_m = \mathbf{1}$,
 $\lambda_m(0) = 1$, $\tau_{m,q}(0) = 1$ and compute $MMSE_o = MMSE(0)$.
for $i = 1, \dots, M - M_{min}$

step 1:
compute $\tau_{m,q}(i) = \tau_{m,q}(i-1) + \mu_\tau(\mathbf{u}_m - \mathbf{u}_q)$,
and $\tau_{m,q}(i) = \tau_{m,q}(i-1) + \mu_\tau(\mathbf{u}_m - \mathbf{u}_q)$.

step 2:
compute the consensus weight using (14).

step 3:
solve the optimization problem (18) and obtain $\mathcal{S}(i)$.
compute $MMSE(i)$ using $\mathcal{S}(i)$.
compare $MMSE(i)$ to $MMSE(i-1)$,
if $MMSE(i) < MMSE(i-1)$
 update $\mathcal{S}_{opt} = \mathcal{S}(i)$ and $MMSE_o = MMSE(i)$.
 update $\alpha(i)$.
else
 keep $\mathcal{S}_{opt} = \mathcal{S}(i-1)$ and $MMSE_o = MMSE(i-1)$.
 break.
end if.
end for.

works in iterations but with higher complexity and much better performance. We also consider M_{min} as a restriction to the minimum number of relays that must be used. Before the first iteration all relays are considered (i.e., $\mathcal{S}(0) = \mathcal{S}$). Consequently, we solve the following problem once for each iteration in order to cancel the relay with worst performance from set $\mathcal{S}(i-1)$ and evaluate the $MMSE(i)$ at time instant i :

$$\begin{aligned} \mathcal{S}(i) &= \arg \min_{\alpha(i)} MMSE(\mathcal{S}(i-1)) \\ \text{s.t. } &(M-i) \|\tilde{\mathbf{w}}_m(i)\|^2 \leq P_T, \tilde{\mathbf{w}}_m(i) = \mathbf{w}(i), \\ &\alpha_m(i) \in \{0, 1\}, m = 1, 2, \dots, M \\ &M-i \geq M_{min}, \end{aligned} \quad (18)$$

If the MMSE in the current iteration is lower than that in the previous iteration (i.e. $MMSE(i) < MMSE(i-1)$), then the selection process continues; if $MMSE(i) \geq MMSE(i-1)$, we cancel the selection of the current iteration and keep the relay set $\mathcal{S}(i-1)$ and $MMSE(i-1)$. The SMMSEC-G algorithm is shown in Table. 2.

4.3. Exhaustive Search

In an exhaustive search procedure, we test every possible combinations among all the relays, which means the change of status if a relay is chosen or not will contribute to a different possible combination. To obtain the global optimum solution, we need to run the consensus algorithm once without iterations. Also, we can predefine M_{fix} as the required selected number of relays as an additional requirement. However, the complexity can be extremely high depending on the number of relays.

5. SIMULATIONS

In the simulations we focus on the output SINR performance comparison of the proposed LMMSEC-G and SMMSEC-G algorithms

by varying the input SNR or the total number of relays in the network. The parameters used include: number of signal sources $K = 3$, the path loss exponent $\rho = 2$, the power path loss from signals to the destination $L = 10\text{dB}$, shadowing spread $\sigma_s = 3\text{dB}$, $P_T = 1\text{dBW}$, $M_{min} = 1$. For the local communication between the relays, we set $\mathcal{M}_m = \{m+1\}$ and $\mathcal{M} = 1$, $\mu_\lambda = \mu_\tau = 0.001$. 100 repetitions are executed for each of the studied methods. In Fig. 2, we fixed the total number of relays $M = 5$ and interference-to-noise ratio (INR) at 10dB and evaluate the SINR versus SNR performance of the joint MMSE consensus and relay selection approaches and the existing techniques. Both the greedy search based methods, namely, LMMSEC-G and SMMSEC-G, increase the SINR performance as compared with the case without any relay selection and approach the exhaustive search especially at low SNRs. Fig. 3 illustrates that with a fixed SNR(0dB) and INR(0dB) how the output SINR varies when the total number of relays in the network increases. It is clear that using more relays enhance the overall network performance and the SMMSEC-G method performs very close to the exhaustive search. The proposed techniques could also be evaluated in terms of BER performance [90, 91, 92, 93, 94, 174, 163, 131, 138, 114, 193, 116, 117, 133, 199].

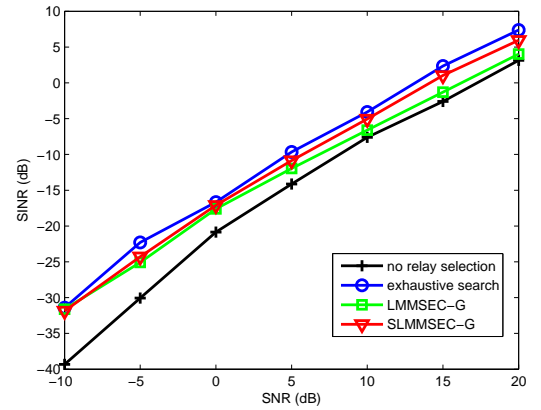


Fig. 2. SINR performance versus SNR

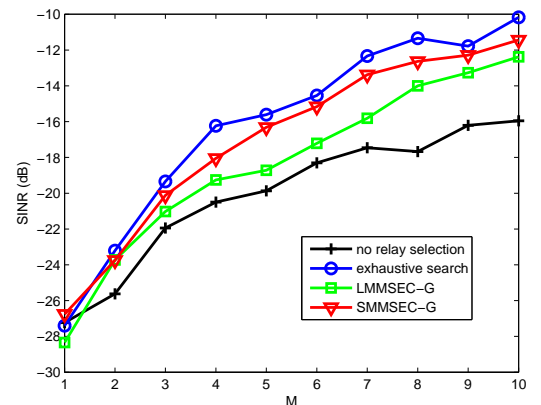


Fig. 3. SINR performance versus M

6. CONCLUSION

We have proposed a joint MMSE consensus and relay selection approach and developed efficient algorithms for distributed beamforming. We have proposed the LMMSEC-G and SMMSEC-G greedy optimization algorithms based on the MMSE criterion with known network quantities and relay selection strategies, which determines if a relay should cooperate or not in the network. The LMMSEC-G and SMMSEC-G algorithms have shown excellent performance and outperformed previously reported techniques.

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