

Original Research Article

Sum Rate Maximization Based on Joint Power Control and Beamforming in MIMO One Way AF Relay Networks

ABSTRACT

Aims: Joint Power control and beamforming in MIMO one way AF relay networks by obtaining beamforming weights on relay nodes through maximizing sum rate while the total power consumed in all relay nodes are not greater than the certain predefined threshold.

Study Design: Comparative study by simulation in MATLAB software.

Place and Duration of Study: Digital Communications Signal Processing (DCSP) Research Lab., Shahid Rajaei Teacher Training University, Since June 2012 to June 2014.

Methodology: A wireless communication network including multiple pairs of transmitter-receiver is considered which communicates peer to peer using R non regenerative one way relays. Our objective is maximizing sum rate supposing that the total power consumed in all relay nodes are not greater than the certain predefined threshold. It is shown that finding beamforming matrix which satisfies our goal is a non-convex problem. So, we use semidefinite relaxation technique to turn it into a semidefinite programming (SDP) problem. We propose two new algorithms which maximize total signal to total leakage (interference plus noise) ratio (TSTLR).

Results: Simulation results show that our proposed algorithm is a low-complex algorithm and outperforms the existing total leakage minimization algorithm, named TL. In addition, the effect of the number of relays, the number of transmitter-receiver pairs, quality of uplink as well as downlink channels and imperfect channel state information (CSI) is investigated.

Conclusion: The proposed method maximizes the total signal to total leakage ratio by maximizing the difference between the numerator and the denominator. It is shown that when the number of relays increases or the quality of uplink and downlink channels improves, higher sum rate can be achieved. Moreover, by increasing the number of source – destination pairs the sum rate increases, too. Also, it is shown that when uncertainty of channels increases the achievable sum rate decreases.

Keywords: AF relays, beamforming, power control, sum rate maximization.

1. INTRODUCTION

Due to the increasing requests for wireless communication services, we need systems which support higher data rates, capacity and quality in a joint state. Limited allocated frequency spectrum forces the wireless networks to use improved protocols and algorithms supporting higher spectral efficiency to achieve higher bit rate.

In the last decades, some efforts to improve the performance of communication systems are done. For this purpose, one of the main ideas is to increase the number of transmitter and receiver antennas. Using this idea, single input single output (SISO) systems which have one transmit antenna and one received antenna (or equally one channel), will be changed to

20 a system including multiple transmitters and receivers equipped with multi antennas which
 21 are called multi input multi output (MIMO) system.

22 Efficient use of bandwidth and two inherent abilities, achieving higher transmission data
 23 rates and offering higher bit rates are important advantages of MIMO communication
 24 systems. On the other hand, the efficiency of these systems will be decreased by undesired
 25 phenomena such as noise, interference and fading. Therefore, in order to improve the
 26 performance of these systems, several techniques such as power control, beamforming and
 27 space-time coding have been proposed and investigated. The most fundamental problem in
 28 a large wireless network which shares a limited frequency band is cochannel interference
 29 (CCI) and it is inevitable due to frequency reuse [2]. Also, it can reduce system performance.
 30 Therefore, some research works are focused on the methods that reduce CCI. Generally,
 31 beamforming and power control are used jointly in CCI wireless systems to increase system
 32 performance.

33 However, implementing multiple transmit antennas in mobile terminals is not always feasible
 34 due to power and space limitations as well as computational complexity. One approach to
 35 tackle these practical restrictions is to use relays [3] as virtual antennas helping
 36 communication between transmitter and receiver. It means that beamforming can be
 37 achieved by weighting the information transmitted to or received from relays. The main idea
 38 of these networks is to allow different nodes to be involved in transmission by making virtual
 39 array antennas. This method, avoids the problems related to implementing antenna arrays
 40 such as, physical limitations, mutual coupling and so on. Moreover, it makes the possibility of
 41 taking diversity and other benefits of MIMO systems and also applying ideas introduced for
 42 MIMO systems, beamforming and power control.

43 It should be mentioned that for long distance communications between transmitter and
 44 receiver, the direct path experience large attenuation which greatly reduces the
 45 communication quality. Hence, using relay based networks, transceiver nodes can connect
 46 to each other in two time steps. In the first step, transmitter sends the signal to relay and
 47 relay processes the received signal. This process in relay node depends on the type of
 48 relay. Afterwards, in the second step, the relay sends the processed signal to the receiver.

49 Relays can be classified based on the type of signal processing operation. For this purpose,
 50 several schemes have been proposed. Some of them are amplify-and-forward (AF), decode-
 51 and-forward (DF), compute-and-forward (CF) and estimation-and-forward (EF). Among
 52 these various schemes, the most effective and popular ones are DF and AF. DF relay
 53 decodes the received signal and then re-encodes it and finally sends it to the receiver. AF
 54 relay applies linear signal processing to the signal and forwards it to the receiver. AF relays
 55 are called non regenerative because decoding is not performed on them. Although they
 56 have no effect on the decreasing of error in system [4], compared to DF relay, AF relay does
 57 not need to know the code book. It means that AF relay offers less complexity and higher
 58 processing speed with respect to DF.

59 Several algorithms are introduced and evaluated in joint beamforming and power control for
 60 MIMO relay networks. In [5], joint power control and receiver beamforming in MIMO relay
 61 networks are used to reduce CCI. In [6], in order to improve the performance of system,
 62 power control and beamforming at both transmitter and receiver are implemented. An
 63 amplify-and-forward scheme is developed in [3] where the instantaneous channel state
 64 information (CSI) is assumed to be known at relays and both ends. Each relay node in the
 65 network is assumed to have a predefined power constraint. In this technique, the relay
 66 nodes try to maximize the receiver signal-to noise ratio (SNR), not only by adjusting the
 67 phase of the received signal but also by adjusting their transmit powers according to the
 68 channels strength. In order to achieve the maximum SNR at the receiver, some of the relay
 69 nodes may not use their maximum allowable power [3]. In usual wireless communications
 70 systems just a single source and a single destination communicate with each other through
 71 multi relays [7,8,9]. In the most of investigations, due to the high attenuation, the direct path
 72 between the source and the destination is ignored. In contrast, in some studies such as [3],

the direct path is also considered but this path is the dominant one. The proposed method in [7] cannot be used when the number of pairs of source - destination is more than one. In [6, 10] the consumed power is minimized while the required signal to interference plus noise ratio (SINR) of each path is guaranteed. They are used semidefinite relaxation technique to turn the problem into a semidefinite programming (SDP) problem which can be solved by using interior point methods. In [10], a pair of source – destination and multiple relays which all nodes have just a single antenna are considered. In contrast, a system has been studied in [6, 11] which includes a pair of source - destination and multiple relays that all of them are equipped with multiple antennas. For a network with a pair of transmitter - receiver with multiple relays considering various receiver filters, the beamforming of the transmitter and relay is optimized in [12]. Ref. [13] proposes the optimal joint source and relay power allocation to maximize the end-to-end achievable sum rate. Transmit precoders, relay matrices and receive decoders are optimized in [14] to maximize the achievable sum rate. In this paper, a network consisting of multi pairs of transmitter - receiver that communicate with each other using multi non regenerative relays is considered. In this investigation, an algorithm is suggested which finds an optimal beamforming of relays and maximizes sum rate subject to relay power constraint. The rest of the paper is organized as follows. In the Section 2, system model is described. Then, we formulate the end-to-end sum-rate maximization problem and present our proposed approach. Simulation results for the different modes of the system are carried out to evaluate the performance of the proposed algorithm in Section 3. Finally, Section 4 presents conclusions and introduces some suggestions for further works.

2. SYSTEM MODEL

The system consists of two pairs of source - destination with R relays. It is assumed that there is no direct path between the source and the destination as shown in Fig.1. A processed version of received signal by adjusting the amplitude and phase of received signal in each relay will be sent to the receiver. In other words, relay multiplies its received signal by a complex weight and then transmits it to the receiver.

Assuming that the coefficient matrix of the channel between p th source and r th relay and also between r th relay and p th destination are denoted by f_{rp} and g_{rp} , respectively, the received signal at r th relay can be obtained by (1) [10].

$$x_r = \sum_{p=1}^d f_{rp} s_p + v_r \quad (1)$$

where s_p is the information symbol transmitted by the p th source and v_r is the additive zero mean noise at the r th relay node.

Using the following assumptions throughout this section, (1) can be rewritten in the form of (2).

1- The relay noise is white, i.e., $E\{v_r v_r^*\} = \sigma_v^2 \delta_{rr'}$.

where σ_v^2 is the relay noise power.

2- The p th source uses maximum power P_p , i.e., $E\{|s_p|^2\} = P_p$.

3- The information symbols transmitted by different sources are uncorrelated, i.e., $E\{s_p s_q^*\} = P_p \delta_{pq}$.

4- The information symbols and the r th relay noise are statistically independent.

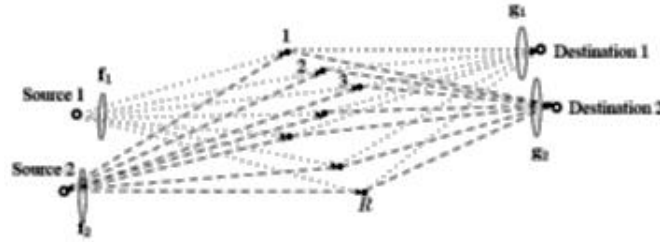
$$\mathbf{X} = \sum_{p=1}^d \mathbf{f}_p \mathbf{s}_p + \mathbf{V} \quad (2)$$

122

123 where $\mathbf{X} = [x_1 \ x_2 \ \dots \ x_R]^T$, $\mathbf{V} = [v_1 \ v_2 \ \dots \ v_R]^T$ and $\mathbf{f}_p = [f_{1p} \ f_{2p} \ \dots \ f_{Rp}]^T$.

124

125 The r th relay multiplies its received signal by a complex weight coefficient w_r^* . Thus, signals
126 transmitted by all relays can be expressed as (3).
127
128



129

130 **Fig. 1. A system consists of R relays and 2 source-destination pairs [10].**

131

132

$$\mathbf{t} = \mathbf{W}^H \mathbf{X} \quad (3)$$

134

135 where $\mathbf{W} = \text{diag}(w_1, w_2, \dots, w_R)^T$ and $\mathbf{t}$ is an $R \times 1$ vector whose r th entry is the r th relay
136 transmitted signal.

137 Denoting the vector of the channel coefficients from the relays to the k th destination as
138 $\mathbf{g}_k = [g_{1k} \ g_{2k} \ \dots \ g_{Rk}]$, the received signal at k th destination can be written as:
139
140

$$\begin{aligned} \mathbf{y}_k &= \mathbf{g}_k^T \mathbf{t} + \mathbf{n}_k \\ &= \mathbf{g}_k^T \mathbf{W}^H \sum_{p=1}^d \mathbf{f}_p \mathbf{s}_p + \mathbf{g}_k^T \mathbf{W}^H \mathbf{V} + \mathbf{n}_k \\ &= \underbrace{\mathbf{g}_k^T \mathbf{W}^H \mathbf{f}_k \mathbf{s}_k}_{\text{desired signal component}} + \underbrace{\mathbf{g}_k^T \mathbf{W}^H \sum_{p=1, p \neq k}^d \mathbf{f}_p \mathbf{s}_p}_{\text{interference component}} + \underbrace{\mathbf{g}_k^T \mathbf{W}^H \mathbf{V} + \mathbf{n}_k}_{\text{noise component}} \end{aligned} \quad (4)$$

142 where $\mathbf{n}_k$ is the zero-mean noise at the k th destination with a variance of σ_n^2 . Also, it is
143 assumed that the channel coefficients between sources and relays, the channel coefficients
144 between relays and destinations, the source signals, the relay noise and the destination
145 noises are independent from each other.

146 2.1 Sum rate maximization considering consumed power constraint

147 In general, there are two ways to control relays' power. Let $P_{x,r}^{\max}$ be the maximum transmit
148 power at r th relay and $P_x^{\max}$ be the maximum sum transmit power at all the relays.
149 Considering power control, the individual relay power constraints are [11]:

$$P_{x,r} \leq P_{x,r}^{\max}, \forall r \in R \quad (5)$$

151 where the sum of relays' power constraint is:

$$\sum_{r=1}^R P_{x,r} \leq P_x^{\max} \quad (6)$$

Our goal is to achieve the weight of optimum beamforming $\{\mathbf{w}_r^*\}_{r=1}^R$, in such a way that sum rate became maximized while the sum of consumed powers in all relay should not be greater than the certain predefined threshold. Thus, the optimization problem can be written as:

$$\begin{aligned} & \max \quad \text{Sum Rate} \\ & \text{subject to} \quad \sum_{r=1}^R P_{x,r} \leq P_x^{\max} \end{aligned} \quad (7)$$

If $\sum_{r=1}^R P_{x,r} = P_T$, from (3) sum of consumed power in relays can be given as:

$$\begin{aligned} P_T &= E\{\mathbf{t}^H \mathbf{t}\} \\ &= E\{\mathbf{X}^H \mathbf{W} \mathbf{W}^H \mathbf{X}\} \\ &= \text{tr}\{\mathbf{W}^H E\{\mathbf{X} \mathbf{X}^H\} \mathbf{W}\} \end{aligned} \quad (8)$$

Now, the total consumed power can be rewritten of the form (9):

$$P_T = \text{tr}\{\mathbf{W}^H \mathbf{R}_x \mathbf{W}\} = \sum_{r=1}^R |\mathbf{w}_r|^2 [\mathbf{R}_x]_{r,r} = \mathbf{w}^H \mathbf{D} \mathbf{w} \quad (9)$$

where $\mathbf{R}_x = E\{\mathbf{x} \mathbf{x}^H\}$ is the correlation matrix of the received signal at the

relay, $\mathbf{w} = \text{diag}(\mathbf{W})$ and $\mathbf{D} = \text{diag}([\mathbf{R}_x]_{1,1}, [\mathbf{R}_x]_{2,2}, \dots, [\mathbf{R}_x]_{R,R})$.

Using (2) and assumptions 1-4, Eq. (10) is given:

$$\begin{aligned} \mathbf{R}_x &= \sum_{p,q=1}^d E\{\mathbf{f}_p \mathbf{f}_q^H\} E\{s_p s_q^*\} + \sigma_v^2 \mathbf{I} \\ &= \sum_{p=1}^d P_p E\{\mathbf{f}_p \mathbf{f}_p^H\} + \sigma_v^2 \mathbf{I} \\ &= \sum_{p=1}^d P_p \mathbf{R}_f^p + \sigma_v^2 \mathbf{I} \end{aligned} \quad (10)$$

where

$$\mathbf{R}_f^p = E\{\mathbf{f}_p \mathbf{f}_p^H\} \quad (11)$$

Note that the total relay transmit power depends on the variance of the coefficients of the channel between source and relay, as well as the relay noise powers [10]. According to the variables that we described in previous equations, sum rate for the system shown in Fig. 1 can be achieved from (12) [14]:

$$R_{\text{sum}} = \frac{1}{2} \sum_{k=1}^d \log_2 \det(1 + \mathbf{F}_k^{-1} \mathbf{T}_{kk} \mathbf{T}_{kk}^H) \quad (12)$$

where $\mathbf{T}_q = \sum_{r \in R} g_{kr} w_r f_{rq}$, $\bar{g}_{kr} = g_{kr} w_r$ and $\mathbf{F}_k = \sum_{q \neq k, q \in d} \mathbf{T}_{kq} \mathbf{T}_{kq}^H + \sum_{r \in R} \bar{g}_{kr} \bar{g}_{kr}^H + \sigma_n^2$.

Due to transferring data in two periods of time, 1/2 coefficient is appeared in (12). According to theorem 1 expressed in [14], then:

$$\log_2(1 + \text{TSTLR}) \leq 2R_{\text{sum}} \quad (13)$$

where $\mathbf{B}_k^H \mathbf{B}_k = \mathbf{I}_{\text{dk}}$, $\mathbf{B}_k$ is the destination beamforming.

In our investigation, destinations have single-antenna, so $\mathbf{B}_k = 1$ and the condition of theorem 1 in [14] is satisfied.

TSTLR is the sum power of desired signals to total leakage power ratio, i.e.,

$$\text{TSTLR} = \frac{\sum_{k=1}^d P_s^k}{\sum_{k=1}^d (P_n^k + P_i^k)} \quad (14)$$

The desired signal power, interference power and noise power in terms of $\{\mathbf{w}_r^*\}_{r=1}^R$ can be achieved. Using (4), for the noise power at k th receiver, we have [10]:

$$\begin{aligned} P_n^k &= E\left\{\mathbf{v}^H \mathbf{W} \mathbf{g}_k^* \mathbf{g}_k^T \mathbf{W}^H \mathbf{v}\right\} + \sigma_n^2 \\ &= \text{tr}\left\{\mathbf{W}^H E\left\{\mathbf{v} \mathbf{v}^H\right\} \mathbf{W} E\left\{\mathbf{g}_k^* \mathbf{g}_k^T\right\}\right\} + \sigma_n^2 \\ &= \sigma_v^2 \text{tr}\left\{\mathbf{W}^H \mathbf{R}_g^k \mathbf{W}\right\} + \sigma_n^2 \end{aligned} \quad (15)$$

where $\mathbf{R}_g^k = E\left\{\mathbf{g}_k \mathbf{g}_k^H\right\}$.

The k th receiver noise power can be rewritten as:

$$\begin{aligned} P_n^k &= \sigma_v^2 \sum_{r=1}^R |w_r|^2 \left[R_g^k\right]_{rr} + \sigma_n^2 \\ &= \mathbf{w}^H \mathbf{D}_k \mathbf{w} + \sigma_n^2 \end{aligned} \quad (16)$$

The k th desired signal power is given by:

$$\begin{aligned} P_s^k &= E\left\{\mathbf{g}_k^T \mathbf{W}^H \mathbf{f}_k \mathbf{f}_k^H \mathbf{W} \mathbf{g}_k^*\right\} E\left\{|s_k|^2\right\} \\ &= P_k E\left\{\mathbf{w}^H \text{diag}\left(\mathbf{g}_k\right) \mathbf{f}_k \mathbf{f}_k^H \text{diag}\left(\mathbf{g}_k^*\right) \mathbf{w}\right\} \\ &= P_k E\left\{\mathbf{w}^H \left(\mathbf{g}_k \circ \mathbf{f}_k\right) \left(\mathbf{f}_k^H \circ \mathbf{g}_k^H\right) \mathbf{w}\right\} \\ &= P_k \mathbf{w}^H E\left\{\mathbf{h}_k \mathbf{h}_k^H\right\} \mathbf{w} \\ &= \mathbf{w}^H \mathbf{R}_h^k \mathbf{w} \end{aligned} \quad (17)$$

where

$$\begin{aligned} \mathbf{h}_k &= \left(\mathbf{g}_k \circ \mathbf{f}_k\right) = \left[g_{1k} f_{1k}, g_{2k} f_{2k}, \dots, g_{Rk} f_{Rk}\right]^T \\ \mathbf{R}_h^k &= P_k E\left\{\mathbf{h}_k \mathbf{h}_k^H\right\} \end{aligned} \quad (18)$$

It is obvious that $\mathbf{h}_k$ contains the total path gains from the k th source to its corresponding destination via different relays. Also, with using (4) and denoting $\mathbf{A}_k = \{1, 2, \dots, d\} - \{k\}$, the interference power is given by [10]:

$$\begin{aligned}
 P_i^k &= E \left\{ \mathbf{g}_k^T \mathbf{W}^H \left(\sum_{p,q \in A_k} \mathbf{f}_p \mathbf{f}_q^H \right) \mathbf{W} \mathbf{g}_k^* \right\} \\
 &= E \left\{ \mathbf{w}^H \text{diag}(\mathbf{g}_k) \left(\sum_{p \in A_k} P_p \mathbf{f}_p \mathbf{f}_p^H \right) \text{diag}(\mathbf{g}_k^*) \mathbf{w} \right\} \\
 &= E \left\{ \mathbf{w}^H \left(\sum_{p \in A_k} P_p (\mathbf{g}_k \circ \mathbf{f}_p) (\mathbf{f}_p^H \circ \mathbf{g}_k^H) \right) \mathbf{w} \right\} \\
 &= \mathbf{w}^H \mathbf{Q}_k \mathbf{w}
 \end{aligned} \tag{19}$$

where

$$\begin{aligned}
 \mathbf{h}_k^p &= \mathbf{g}_k \circ \mathbf{f}_p \\
 \mathbf{Q}_k &= E \left\{ \sum_{p \in A_k} P_p \mathbf{h}_k^p (\mathbf{h}_k^p)^H \right\}
 \end{aligned} \tag{20}$$

By using (16), (17) and (19), we can rewrite (14) as (21):

$$\text{TSTLR} = \frac{\mathbf{w}^H \left(\sum_{k=1}^d \mathbf{R}_h^k \right) \mathbf{w}}{\mathbf{w}^H \left(\sum_{k=1}^d (\mathbf{Q}_k + \mathbf{D}_k) \right) \mathbf{w} + d \sigma_n^2} \tag{21}$$

Now, the optimization problem can be rewritten as:

$$\begin{aligned}
 &\max \quad \text{TSTLR} \\
 &\text{subject to} \quad P_T \leq P_x^{\max}
 \end{aligned} \tag{22}$$

Using the previous equations, we can write:

$$\begin{aligned}
 &\max \quad \frac{\mathbf{w}^H \left(\sum_{k=1}^d \mathbf{R}_h^k \right) \mathbf{w}}{\mathbf{w}^H \left(\sum_{k=1}^d (\mathbf{Q}_k + \mathbf{D}_k) \right) \mathbf{w} + d \sigma_n^2} \\
 &\text{subject to} \quad P_T \leq P_x^{\max}
 \end{aligned} \tag{23}$$

(23) is not a convex optimization problem and may not have a low-complex solution. Hence, it makes a difficult problem. To fix this problem, there are three ways, minimizing the denominator, maximizing the numerator, and maximizing the difference between the numerator and the denominator.

We exploit a semi-definite relaxation approach to solve a relaxed version of (23). To do so, let us define $\mathbf{X} = \mathbf{w} \mathbf{w}^H$ [10,6]. Then, the optimization problem in (23) can be rewritten as (24):

$$\begin{aligned}
 &\max \quad \text{tr}(\mathbf{Z} \mathbf{X}) \\
 &\text{subject to} \quad \text{tr}(\mathbf{D} \mathbf{X}) \leq P_x^{\max} \\
 &\quad \text{rank}(\mathbf{X}) = 1, \quad \mathbf{X} \geq 0
 \end{aligned} \tag{24}$$

233

234 where $\mathbf{X} \geq 0$ means that $\mathbf{X}$ is a positive semi definite (PSD) matrix, and $\text{rank}(\cdot)$ denotes the
 235 rank of a matrix.

236 Maximizing TSTLR will be achieved in one of the following forms:

237

238 1- Minimizing the denominator, $\mathbf{Z} = \sum_{k=1}^d \mathbf{R}_h^k$.

239 2- Maximizing the numerator, $\mathbf{Z} = \sum_{k=1}^d (\mathbf{Q}_k + \mathbf{D}_k)$.

240 3- Maximizing the difference between the numerator and the denominator,

241 $\mathbf{Z} = \sum_{k=1}^d \{\mathbf{R}_h^k - (\mathbf{Q}_k + \mathbf{D}_k)\}.$

242 The first approach is introduced in [11] named TL. In simulations, TL method is called
 243 algorithm 1 and the two other proposed methods are named algorithm 2 and 3, respectively.
 244 As the next problem, the rank constraint in (24) is not convex. Using semi-definite relaxation,
 245 we remove this non-convex constraint and solve the following optimization problem:

246

$$\begin{aligned} & \max \quad \text{tr}(\mathbf{Z}\mathbf{X}) \\ & \text{subject to} \quad \text{tr}(\mathbf{D}\mathbf{X}) \leq P_x^{\max} \\ & \quad \mathbf{X} \geq 0 \end{aligned} \tag{25}$$

248

249 The optimization problem (25) is indeed convex and can be solved efficiently using interior
 250 point based software tools such the convex optimization (CVX) MATLAB toolbox [15].

251 By solving the optimization problem (25), the matrix $\mathbf{X}_{opt}$, is not necessarily of rank one. It

252 means that the minimum value of the relaxed problem (25) only provides a lower bound on
 253 the minimum value of the original problem (24). Proof of this is available in [10]. As it is
 254 shown in [16], we can always find a rank-one solution to the relaxed problem (25) as long as
 255 $d \leq 3$. Otherwise, one might resort randomization techniques to obtain a suboptimal rank-
 256 one solution. In these techniques, the optimal matrix $\mathbf{X}_{opt}$ is used to generate several
 257 suboptimal weight vectors, from which the best solution will be selected [17, 18, 19].

258 3. RESULTS AND DISCUSSION

259 In this section, the impact of various factors on the performance of the algorithms is shown.

260 In all simulations, it is assumed that maximum sum power consumption at relays is equal to
 261 unit ($P_x^{\max} = 1$), the channel coefficients f and g are generated as identically independent

262 distribution (i.i.d) complex Gaussian random variables with variances σ_f^2 and σ_g^2 ,

263 respectively. It is also assumed that all transmitters have equal unit powers. All simulation
 264 results are averaged over 500 independent channel realizations. All MATLAB simulation
 265 codes are run on a PC with RAM=4GB, Processor: Intel (R) Core™ i5-2400 CPU @
 266 3.10GHz, System Type: 64bit.

267 3.1 Comparison of sum rate maximization methods

268 In the first experiment, three methods to maximize TSTLR criterion are compared in the case
 269 of the two pairs of source-destination ($d=2$) considering 20 relays ($R=20$) and

270 $\sigma_f^2 = \sigma_g^2 = 10$ dB. It can be seen in Fig. 2 that the third method offers the highest sum rate

271 with respect to two others.

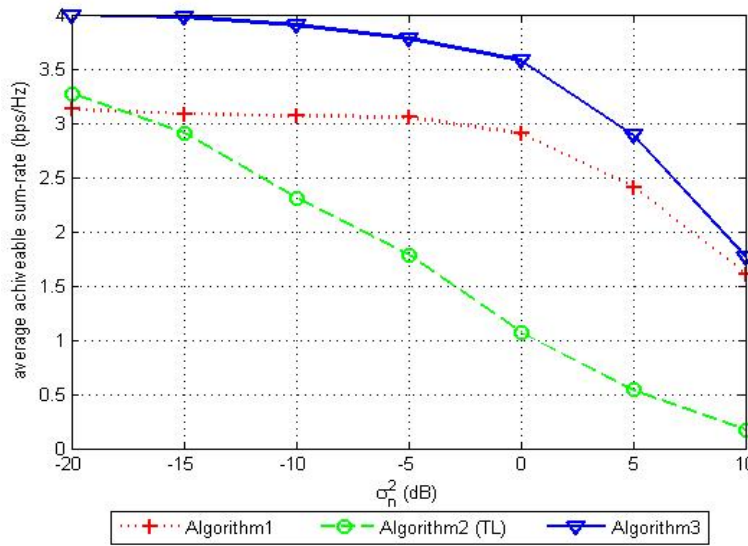


Fig. 2. Comparison of different sum rate maximization methods

Also, the required simulation time to run the above mentioned algorithms are obtained. It is assumed that $R=20$, $d=2$, $\sigma_f^2 = \sigma_g^2 = 10$ dB and $\sigma_n^2 = -20$ dB. Algorithm 3 is considered as the reference one. The required times for algorithms 1 and 2 with respect to the third one are 1.112 and 1.003, respectively. In other words, the complexity of the proposed algorithm (algorithm 3) is lower than the two other methods (algorithm 2 and TL). Therefore, in subsequent experiments the third method is examined.

3.2 The effect of the number of relays in the performance of the proposed algorithm

Figure 3 illustrates sum rate in terms of noise power σ_n^2 for different values of the number of relays, when $d=2$ and $\sigma_f^2 = \sigma_g^2 = 10$ dB. It can be seen that increasing the number of relays is the reason for increasing the achievable sum rate. It is obvious that higher number of relays offers additional higher diversity. It should be noted that increasing the number of relays also introduces more computational complexity. Another important point is that although we achieve higher sum rate for a specific noise variance using higher number of relays, the sum rate difference for the same difference number of relays are not the same. For example, in $\sigma_n^2 = -5$ dB, the difference between sum rate for $R=10$ and $R=20$ is 0.775 (b/s/Hz), for $R=20$ and $R=30$ is 0.503 (b/s/Hz) and for $R=30$ and $R=40$ is 0.404 (b/s/Hz).

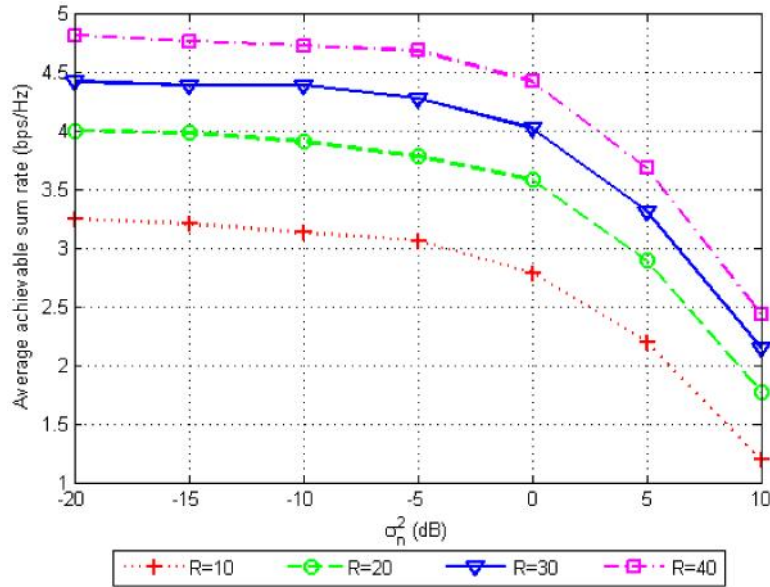


Fig. 3. Average sum rate versus noise variance for different number of relays

3.3 The effect of channel variance

In two following experiments, the effect of the uplink and downlink channel qualities is examined. According to [1] by increasing channel variance or equivalently the quality of channel, average received signal power is increased.

3.3.1 Different uplink qualities

In Fig. 4, average achievable sum rate is plotted versus σ_n^2 where $R=20$, $d=2$ and $\sigma_g^2 = 10$ dB for different values of σ_f^2 . As can be seen in this Figure, by increasing σ_f^2 sum rate will be increased.

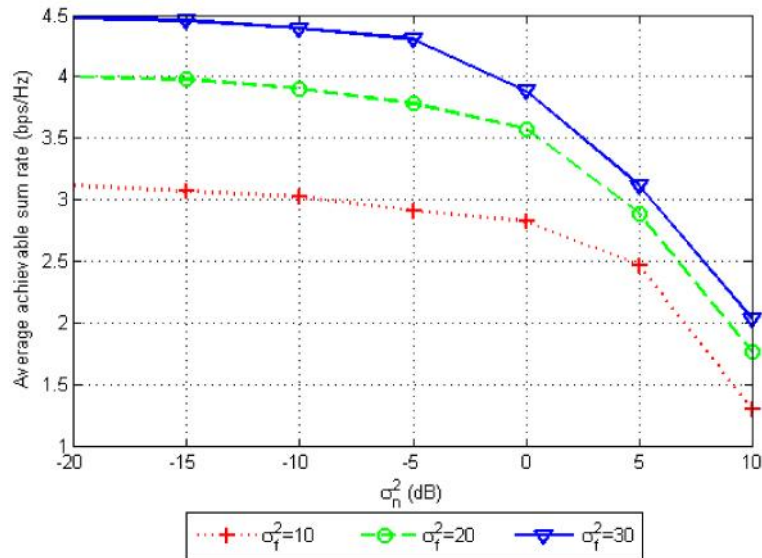


Fig. 4. Performance of the proposed algorithm for different values of σ_f^2

3.3.2 Different downlink qualities

In the case of $R=20$, $d=2$ and $\sigma_f^2 = 10$ dB for different values of σ_g^2 , the average achievable sum rate versus σ_n^2 is plotted in Fig. 5. It can be seen that increasing the quality of downlink causes increasing the achievable sum rate.

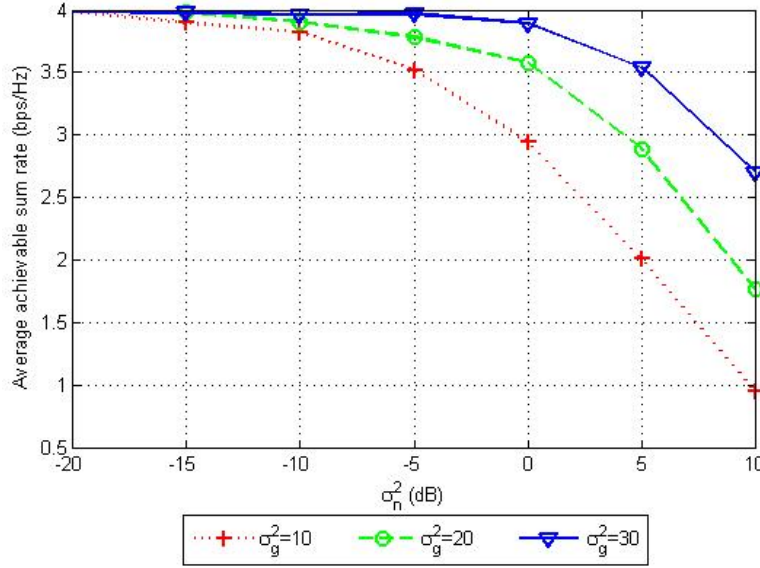


Fig. 5. Performance of the proposed algorithm for different values of σ_g^2

3.4 The effect of transmitter–receiver pairs

In this experiment, the effect of the number of source-destination pairs on the performance of the algorithm is investigated when $R=20$, $\sigma_f^2 = \sigma_g^2 = 10$ dB. Fig. 6 shows that the higher the number of pairs offers the higher sum rate for a certain σ_n^2 . As can be seen from this Figure, for lower σ_n^2 , the effect of the number of pairs is more evident and when the channel became noise dominant the effect of the transmitter – receiver pairs in increasing the sum rate will be decreased. In other words, MIMO channel tends to SISO channel.

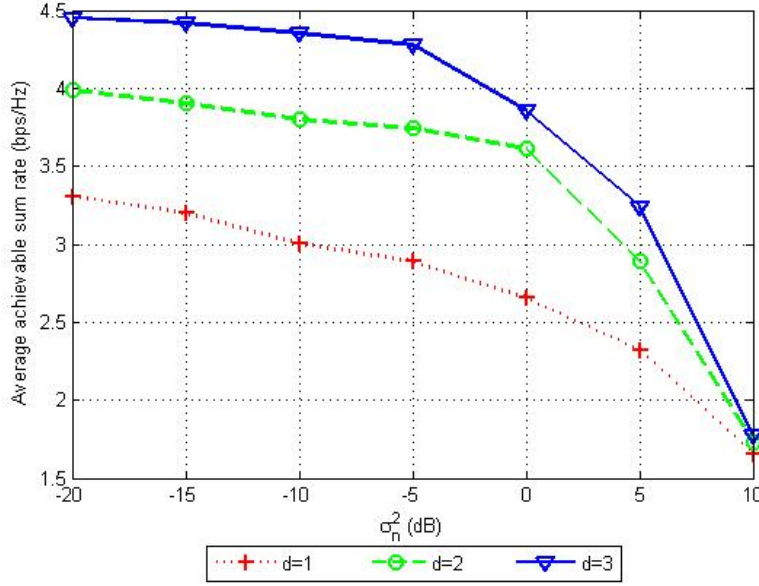


Fig. 6. Performance of the proposed algorithm for different number of source-destination pairs

3.5 The effect of imperfect CSI

In this experiment, the effect of imperfect CSI in our proposed algorithm is investigated. We assume a network with 20 relays ($R=20$). Also, the channels coefficients f_{rp} and $g_{r'q}$ are assumed to be independent from each other for any p, q, r and r' . Also, we assume that the channel coefficient f_{rp} can be written as $f_{rp} = \bar{f}_{rp} + ef_{rp}$ where $\bar{f}_{rp}$ is the known mean value of f_{rp} and ef_{rp} is a zero-mean random variable with variance σ_{ef}^2 [10]. We assume that ef_{rp} and $ef_{r'p}$ are independent for any $r \neq r'$. We generate $\bar{f}_{rp} = \sqrt{1 - \sigma_{ef}^2} e^{j\theta}$, where θ is a uniform random variable chosen from the interval $[0, 2\pi]$. Since $E\{|f_{rp}|^2\} = 1$, if σ_{ef}^2 is increased, the mean value, $\bar{f}_{rp}$ is decreased. This, in turn, means that the level of the uncertainty in the channel coefficient f_{rp} is increased. Similarly, we model the channel coefficient g_{rq} as $g_{rq} = \bar{g}_{rq} + eg_{rq}$ where $\bar{g}_{rq}$ is the known mean value of g_{rq} and eg_{rq} is a zero-mean random variable with variance σ_{eg}^2 . We assume that eg_{rq} and $eg_{r'q}$ are independent for any $r \neq r'$. We choose $\bar{g}_{rq} = \sqrt{1 - \sigma_{eg}^2} e^{j\alpha}$, where α is a uniform random variable chosen from the interval $[0, 2\pi]$. Here, σ_{eg}^2 is a parameter which determines the level of uncertainty in the channel coefficient, g_{rq} . Based on this channel modeling, we can write the (r, r') entry matrices as:

$$\mathbf{R}_f^p = \bar{\mathbf{f}} \bar{\mathbf{f}}^H + \mathbf{e} \mathbf{f} \mathbf{I} \quad (26)$$

$$\mathbf{R}_g^p = \bar{\mathbf{g}} \bar{\mathbf{g}}^H + \mathbf{e} \mathbf{g} \mathbf{I} \quad (27)$$

$$\mathbf{R}_h^k(r, r') = P_k \mathbf{R}_f(r, r') \mathbf{R}_g(r, r') \quad (28)$$

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$$\mathbf{Q}_k(r, r') = \sum_{1, k \neq p}^d P_p \mathbf{R}_f^p(r, r') \cdot \mathbf{R}_g^k(r, r') \quad (29)$$

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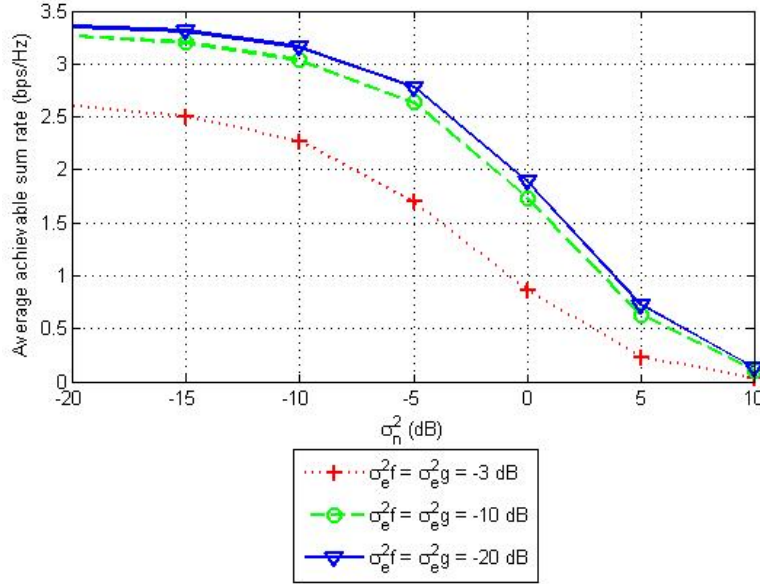
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In this experiment, we choose the source power equal to 0dB. The average sum rate versus σ_n^2 is plotted in the case of $R=20$ and $d=2$ for different values of σ_{ef}^2 and σ_{eg}^2 in Fig. 8. As shown in this figure, increasing the uncertainty of the channels, σ_{ef}^2 and σ_{eg}^2 , is the reason for decreasing the achievable sum rate.



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Fig. 7. Performance of the proposed algorithm for imperfect CSI

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4. CONCLUSION

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