Interference Mitigation Based Signal Forwarding Strategy for Wireless Relay Networks

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***Abstract*— A signal forwarding strategy with constraints on interference and noise leakage to multiple neighboring nodes and quality of services (QoS) to multiple destination nodes is proposed. The objective is to relay signals from multiple sources to multiple destinations using a set of relay nodes with minimum possible transmission power while achieving desired QoS for destination nodes and minimum possible interference and noise power leaked to other active nodes in the wireless systems. We solve the problem using a convex optimization framework by invoking semidefinite relaxation. The proposed approach has the ability to regulate interference temperature at various terminals in the wireless network while forwarding signals from multiple sources to destinations as demonstrated in the Monte Carlo based simulation results.**

***Index Terms*— Relay network, Wireless mesh network, Cooperative diversity.**

I. INTRODUCTION

In order to meet the increasing demand for higher data rates, for example, to support interactive and multimedia services on mobile terminals, it is essential to develop radically new techniques to efficiently utilize the limited radio spectrum while maintaining high QoS. One possible strategy is to use array processing techniques where multiple antennas are used at the transmitter and/or receiver to exploit spatial diversity. However, due to limitations on size, weight, power consumption and complexity at mobile terminals, it is undesirable to deploy multiple antennas at the mobile terminals. Furthermore, the use of multiple antennas could increase the cost of the communication system. Instead, relays can be used to transmit information from source to destination nodes in a multihop fashion in order to optimize coverage and resource utilization. Such schemes find applications in wireless backhaul network for broadband access in Wireless Mesh Networks (WMNs), where relay nodes could exploit spatial diversity by forming multipaths between source-destination nodes [1], [2]. In [3], the authors addressed the issues of deploying multiple antennas and proposed an *ad hoc* relay network scheme where relays assist in forwarding signal from multiple sources to multiple destinations. Semi-definite programming based framework is used to ensure target signal-to-interference noise ratios (SINRs) are achieved at the destination terminals. In this paper, we extend the work in [3] to consider interference and noise leaked to other neighboring nodes while forwarding signals to multiple destination nodes. This will facilitate other nodes that are not part of the particular relay network to reuse the frequency for its own transmission and reception. The problem is solved using semidefinite programming to minimize the total power transmitted by the relays subject to achieving a set of SINRs for all the desired users and minimizing interference and noise power leaked to the other users in the system. We study the tradeoff between interference control to neighboring nodes and QoS achieved for desired users.

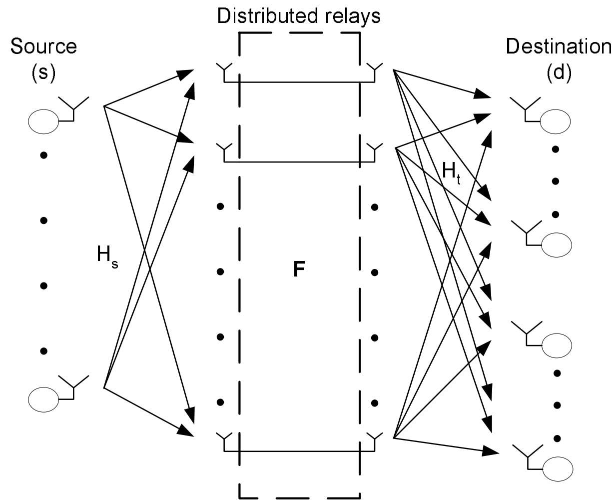

Fig. 1. A relay network of N sources, N desired users, L neighboring users and R distributed noncooperative relay nodes.

II. SYSTEM MODEL

We consider N sources communicating with N destinations in presence of L other active nodes with the aid of R relays. The L active users could be member of a different *ad hoc* network that uses the same carrier frequency. Each relay receives the combination of the data from all the sources, amplifies and adjusts the phase, and forwards the data to the corresponding destinations. The responsibility of the relays is to effectively transmit the received signals such that the SINR is maintained above a set of targets for all the users and the interference and noise leaked to other active user terminal in the network is kept below certain level.
Assuming s_k is the signal originated from the k^{th} source, and the channel between the k^{th} source and r^{th} relay is $\mathrm{h}_{r,k}$, then

the received signal y_r by the r^{th} relay node is given as

$$y_r = \sum_{k=1}^{N} h_{r,k} s_k + v_r \quad (1)$$

where $r = 1, 2, \cdots, R$, and v_r is Additive White Gaussian Noise (AWGN) at the r^{th} relay. The signals received by R relays can be appended in a vector as

$$\mathbf{y} = \sum_{k=1}^{N} \mathbf{h}_k s_k + \mathbf{v} \quad (2)$$

where $\mathbf{y} = [y_1, y_2, \cdots, y_R]^T$, $\mathbf{h_k} = [h_{1,k}, h_{2,k}, \cdots, h_{R,k}]^T$ and $\mathbf{v} = [v_1, v_2, \cdots, v_R]^T$. The received signals are multiplied by a set of complex weights and forwarded as

$$\mathbf{x} = \mathbf{W}^H \mathbf{y} \quad (3)$$

where $\mathbf{x} \in \mathrm{C}^{\mathrm{R}\times 1}$ represents the signals transmitted by the relays, $\mathbf{W}$ is a complex diagonal matrix with its r^{th} diagonal element as the weight $\mathrm{w_r}$ required to multiply the signal received at the r^{th} relay, and $(\cdot)^{\mathrm{H}}$ is Hermitian transpose. If cooperation between relay nodes is possible, a non-diagonal $\mathbf{W}$ could be considered as in [4], [5]. Let $\mathbf{q}_i = [q_{1,i}, q_{2,i}, \cdots, q_{R,i}]^T$ be the vector representing the channel from the relays to the i^{th} destination user terminal, then the signal received by the i^{th} user is given by

$$\begin{aligned} z_i &= \mathbf{q}_i^T \mathbf{x} + n_i = \mathbf{q}_i^T \mathbf{W}^H \sum_{k=1}^{N} \mathbf{h}_k s_k + \mathbf{q}_i^T \mathbf{W}^H \mathbf{v} + n_i \\ &= \underbrace{\mathbf{q}_i^T \mathbf{W}^H \mathbf{h}_i s_i}_{\text{Signal}} + \underbrace{\mathbf{q}_i^T \mathbf{W}^H \sum_{k=1, k\neq i}^{N} \mathbf{h}_k s_k}_{\text{Interference}} + \underbrace{\mathbf{q}_i^T \mathbf{W}^H \mathbf{v} + n_i}_{\text{Noise}} \end{aligned} \quad (4)$$

where $i = 1, 2, \cdots, N$, and n_i is AWGN at the i^{th} destination with variance σ_n^2. We assume there are L other user terminals in the system that are not supposed to receive signals being transmitted from these multiple sources. These L user terminals could be, for example, active users communicating with a different set of source terminals in a separate wireless *ad hoc* network. We call this set of L terminals as neighboring nodes. Let $\mathbf{a}_j = [a_{1,j}, a_{2,j}, \cdots, a_{R,j}]^T$ be the channel from the relays to the j^{th} neighboring user terminal in the system, then the interference and noise leaked to the neighboring user terminal can be written as

$$t_j = \mathbf{a}_j^T \mathbf{x} + m_j = \underbrace{\mathbf{a}_j^T \mathbf{W}^H \sum_{k=1}^{N} \mathbf{h}_k s_k}_{\text{Interference}} + \underbrace{\mathbf{a}_j^T \mathbf{W}^H \mathbf{v}}_{\text{Noise}} \quad (5)$$

where $j = 1, 2, \cdots, L$. In the design, we make the following assumptions:
- Relay noise is spatially white such that $\mathrm{E}\{v_r v_{r'}^*\} = \sigma_v^2$ if $r = r'$, 0 otherwise.
- Symbol power of the k^{th} source is $\mathrm{E}\{|s_k|^2\} = \mathrm{P}_k$.
- Symbols transmitted by different sources are uncorrelated such that $\mathrm{E}\{s_k s_e^*\} = \mathrm{P}_k$ if $k = e$, 0 otherwise.
- Source signal $\{s_k\}_{k=1}^N$, noise at relays $\{v_r\}_{r=1}^R$, desired users noise $\{n_i\}_{i=1}^N$, and all the channels $\{\mathbf{h}_k\}_{k=1}^N$, $\{\mathbf{q}_i\}_{i=1}^N$ and $\{\mathbf{a}_j\}_{j=1}^L$ are independent.
- All the channels are deterministic such that $\mathrm{E}\{\mathbf{h}_k \mathbf{h}_k^H\}_{k=1}^N = \{\mathbf{h}_k \mathbf{h}_k^H\}_{k=1}^N$, $\mathrm{E}\{\mathbf{q}_i \mathbf{q}_i^H\}_{i=1}^N = \{\mathbf{q}_i \mathbf{q}_i^H\}_{i=1}^N$ and $\mathrm{E}\{\mathbf{a}_j \mathbf{a}_j^H\}_{j=1}^L = \{\mathbf{a}_j \mathbf{a}_j^H\}_{j=1}^L$.

III. Formulation of the Cost Function

The objective is to determine the weights of the relays such that the total power transmitted by the relays is minimized while achieving a set of target SINRs for the desired users and maintaining minimum possible interference and noise power leaked to all the neighboring user terminals. The problem can be formulated as

$$\begin{aligned} \min_{\mathbf{w}\in C^{R\times 1}} . \quad & \mathrm{P}_T \\ \text{s.t.} \quad & \mathrm{SINR}_i \geq \gamma_i, \quad i = 1, \cdots, N \\ & \mathrm{IN}_j \leq \beta_j, \quad j = 1, \cdots, L \end{aligned} \quad (6)$$

where P_T is the total power transmitted by the relays, γ_i is the minimum acceptable SINR for the i^{th} desired user, β_j is the maximum acceptable interference and noise power leaked to the j^{th} neighboring user, and SINR_i and IN_j are expressed as

$$\begin{aligned} \mathrm{SINR}_i &= \frac{\mathrm{P}_s^i}{\mathrm{P}_I^i + \mathrm{P}_n^i} \\ \mathrm{IN}_j &= \mathrm{P}_I^j + \mathrm{P}_n^j. \end{aligned} \quad (7)$$

For the i^{th} desired user, P_s^i represents the power of the desired signal component, P_I^i is the interference power, and P_n^i is the noise power. The interference power and noise power at the j^{th} neighboring node are P_I^j and P_n^j, respectively. From (3), the total power transmitted by the relays can be written as

$$\begin{aligned} \mathrm{P}_T &= \mathrm{E}\{\mathbf{x}^H \mathbf{x}\} = \mathrm{E}\{\mathbf{y}^H \mathbf{W} \mathbf{W}^H \mathbf{y}\} \\ &= \mathrm{tr}(\mathbf{W}^H E\{\mathbf{y}\mathbf{y}^H\} \mathbf{W}) \end{aligned}$$

where $\mathrm{tr}(\cdot)$ represents trace operator. Let $\mathbf{R}_y = \mathrm{E}\{\mathbf{y}\mathbf{y}^H\}$ be the correlation matrix of the received signal, then power transmitted is given as [3]

$$\begin{aligned} \mathrm{P}_T &= \mathrm{tr}(\mathbf{W}^H \mathbf{R}_y \mathbf{W}) = \sum_{r=1}^{R} |w_r|^2 \mathbf{R}_y(r, r) \\ &= \mathbf{w}^H \mathbf{D}_y \mathbf{w} \end{aligned} \quad (8)$$

where $\mathbf{D}_y = \mathrm{diag}(\mathbf{R}_y))$ returns a diagonal matrix with diagonal elements of matrix $\mathbf{R}_y$, $[\mathbf{R}_y(1,1), \mathbf{R}_y(2,2), \cdots, \mathbf{R}_y(R,R)]$, along its diagonal, and $\mathbf{w} = \mathrm{diag}(\mathbf{W})$. Using (2), we obtain [3]

$$\begin{aligned} \mathbf{R}_y &= \mathrm{E}\{\sum_{k=1}^{N} \sum_{e=1}^{N} \mathbf{h}_k s_k s_e^* \mathbf{h}_e^H\} + \sigma_v^2 \mathbf{I} \\ &= \sum_{k=1}^{N} \sum_{e=1}^{N} \mathbf{h}_k \mathrm{E}\{s_k s_e^*\} \mathbf{h}_e^H + \sigma_v^2 \mathbf{I} \\ &= \sum_{k=1}^{N} \mathrm{P}_k \mathbf{h}_k \mathbf{h}_k^H + \sigma_v^2 \mathbf{I}. \end{aligned} \quad (9)$$

In order to compute SINR for the i^{th} user, we need to determine the expressions for the power of the desired signal component P_s^i, the interference power P_I^i and the noise power P_n^i. Using (4), we obtain the noise power as [3]

$$\begin{aligned}\mathrm{P}_n^i &= \mathrm{E}\{\mathbf{v}^H\mathbf{W}\mathbf{q}_i^*\mathbf{q}_i^T\mathbf{W}^H\mathbf{v}\}+\sigma_n^2\\ &= \mathrm{tr}(\mathbf{W}^H\mathrm{E}\{\mathbf{v}\mathbf{v}^H\}\mathbf{W}\mathbf{q}_i^*\mathbf{q}_i^T)+\sigma_n^2\\ &= \sigma_v^2\mathrm{tr}(\mathbf{W}^H\mathbf{q}_i^*\mathbf{q}_i^T\mathbf{W})+\sigma_n^2\\ &= \mathbf{w}^H\mathbf{D}_q^i\mathbf{w}+\sigma_n^2 \qquad (10)\end{aligned}$$

where $\mathbf{D}_q^i = \sigma_v^2\mathrm{diag}(\mathrm{diag}(\mathbf{q}_i^*\mathbf{q}_i^T))$ is a diagonal matrix with its diagonal elements $[|q_{1,i}|^2, |q_{2,i}|^2, \cdots, |q_{R,i}|^2]$ and σ_n^2 is the noise power present at the receiver. The received signal power at the i^{th} user is computed using (4) as [3]

$$\begin{aligned}\mathrm{P}_s^i &= \mathrm{E}\{\mathbf{q}_i^T\mathbf{W}^H\mathbf{h}_i\mathrm{s}_i\mathrm{s}_i^*\mathbf{h}_i^H\mathbf{W}\mathbf{q}_i^*\}\\ &= \mathbf{w}^H\mathrm{diag}(\mathbf{q}_i)\mathbf{h}_i\mathrm{E}\{\mathrm{s}_i\mathrm{s}_i^*\}\mathbf{h}_i^H\mathrm{diag}(\mathbf{q}_i^*)\mathbf{w}\\ &= \mathbf{w}^H\mathbf{Q}^i\mathbf{w} \qquad (11)\end{aligned}$$

where $\mathbf{Q}^i = \mathrm{P}_i\mathrm{diag}(\mathbf{q}_i)\mathbf{h}_i\mathbf{h}_i^H\mathrm{diag}(\mathbf{q}_i^*)$. The interference power at the i^{th} user is obtained using (4) as [3]

$$\begin{aligned}\mathrm{P}_I^i &= \mathrm{E}\{\mathbf{q}_i^T\mathbf{W}^H\sum_{k=1,k\neq i}^{N}\sum_{e=1,e\neq i}^{N}\mathbf{h}_k\mathrm{s}_k\mathrm{s}_e^*\mathbf{h}_e^H\mathbf{W}\mathbf{q}_i^*\}\\ &= \mathbf{w}^H\mathrm{diag}(\mathbf{q}_i)\sum_{k=1,k\neq i}^{N}\sum_{e=1,e\neq i}^{N}\mathbf{h}_k\mathrm{E}\{\mathrm{s}_k\mathrm{s}_e^*\}\mathbf{h}_e^H\mathrm{diag}(\mathbf{q}_i^*)\mathbf{w}\\ &= \mathbf{w}^H\mathrm{diag}(\mathbf{q}_i)\sum_{k=1,k\neq i}^{N}\mathrm{P}_k\mathbf{h}_k\mathbf{h}_k^H\mathrm{diag}(\mathbf{q}_i^*)\mathbf{w}\\ &= \mathbf{w}^H\mathbf{B}_i\mathbf{w} \qquad (12)\end{aligned}$$

where $\mathbf{B}_i = \mathrm{diag}(\mathbf{q}_i)\sum_{k=1,k\neq i}^{N}\mathrm{P}_k\mathbf{h}_k\mathbf{h}_k^H\mathrm{diag}(\mathbf{q}_i^*)$. The interference power leaked to the j^{th} neighboring user P_I^j is computed using (5) as

$$\begin{aligned}\mathrm{P}_I^j &= \mathrm{E}\{\mathbf{a}_j^T\mathbf{W}^H\sum_{k=1}^{N}\sum_{e=1}^{N}\mathbf{h}_k\mathrm{s}_k\mathrm{s}_e^*\mathbf{h}_e^H\mathbf{W}\mathbf{a}_j^*\}\\ &= \mathbf{w}^H\mathrm{diag}(\mathbf{a}_j)\sum_{k=1}^{N}\sum_{e=1}^{N}\mathbf{h}_k\mathrm{E}\{\mathrm{s}_k\mathrm{s}_e^*\}\mathbf{h}_k^H\mathrm{diag}(\mathbf{a}_j^*)\mathbf{w}\\ &= \mathbf{w}^H\mathrm{diag}(\mathbf{a}_j)\sum_{k=1}^{N}\mathrm{P}_k\mathbf{h}_k\mathbf{h}_k^H\mathrm{diag}(\mathbf{a}_j^*)\mathbf{w}\\ &= \mathbf{w}^H\mathbf{T}_j\mathbf{w} \qquad (13)\end{aligned}$$

where $\mathbf{T}_j = \mathrm{diag}(\mathbf{a}_j)\sum_{k=1}^{N}\mathrm{P}_k\mathbf{h}_k\mathbf{h}_k^H\mathrm{diag}(\mathbf{a}_j^*)$. The noise power leaked to the j^{th} neighboring user P_n^j is computed using (5) as

$$\begin{aligned}\mathrm{P}_n^j &= \mathrm{E}\{\mathbf{v}^H\mathbf{W}\mathbf{a}_j^*\mathbf{a}_j^T\mathbf{W}^H\mathbf{v}\}\\ &= \mathrm{tr}\{\mathbf{W}^H\mathrm{E}\{\mathbf{v}\mathbf{v}^H\}\mathbf{W}\mathbf{a}_j^*\mathbf{a}_j^T\}\\ &= \sigma_v^2\mathrm{tr}\{\mathbf{W}^H\mathbf{a}_j^*\mathbf{a}_j^T\mathbf{W}\}\\ &= \mathbf{w}^H\mathbf{D}_a^j\mathbf{w} \qquad (14)\end{aligned}$$

where $\mathbf{D}_a^j = \sigma_v^2\mathrm{diag}(\mathrm{diag}(\mathbf{a}_j^*\mathbf{a}_j^T))$ is a diagonal matrix with elements $[|a_{1,j}|^2, |a_{2,j}|^2, \cdots, |a_{R,j}|^2]$. The optimization problem can be written as

$$\begin{aligned}&\min_{\mathbf{w}\in C^{R\times 1}}.\ \mathbf{w}^H\mathbf{D}_y\mathbf{w}\\ &\text{s.t.}\quad \frac{\mathbf{w}^H\mathbf{Q}^i\mathbf{w}}{\mathbf{w}^H(\mathbf{B}_i+\mathbf{D}_q^i)\mathbf{w}+\sigma_n^2}\geq\gamma_i,\quad i=1,\cdots,N\\ &\qquad \mathbf{w}^H(\mathbf{T}_j+\mathbf{D}_a^j)\mathbf{w}\leq\beta_j,\ j=1,\cdots,L\end{aligned} \qquad (15)$$

or, equivalently, as

$$\begin{aligned}&\min_{\mathbf{w}\in C^{R\times 1}}.\ \mathbf{w}^H\mathbf{D}_y\mathbf{w}\\ &\text{s.t.}\quad \mathbf{w}^H(\mathbf{Q}^i-\gamma_i(\mathbf{B}_i+\mathbf{D}_q^i))\mathbf{w}\geq\gamma_i\sigma_n^2,\quad i=1,\cdots,N\\ &\qquad \mathbf{w}^H(\mathbf{T}_j+\mathbf{D}_a^j)\mathbf{w}\leq\beta_j,\qquad j=1,\cdots,L.\end{aligned} \qquad (16)$$

IV. Convex formulation using semidefinite programming (SDP)

To this end, we aim to solve the optimization problem (16) by converting it to a SDP form that can be solved using interior-point algorithms [6]–[8]. We define a new variable $\mathbf{X} = \mathbf{w}\mathbf{w}^H$ and formulate the problem in (16) as

$$\begin{aligned}&\min_{\mathbf{X}\in C^{R\times R}}.\ \mathrm{tr}(\mathbf{D}_y\mathbf{X})\\ &\text{s.t.}\quad \mathrm{tr}(\mathbf{X}(\mathbf{Q}^i-\gamma_i(\mathbf{B}_i+\mathbf{D}_q^i)))\geq\gamma_i\sigma_n^2,\quad i=1,\cdots,N\\ &\qquad \mathrm{tr}(\mathbf{X}(\mathbf{T}_j+\mathbf{D}_a^j))\leq\beta_j,\qquad j=1,\cdots,L\\ &\qquad \mathrm{rank}(\mathbf{X})=1,\ \mathbf{X}\succeq 0,\ \mathbf{X}=\mathbf{X}^*.\end{aligned} \qquad (17)$$

Using standard techniques of semidefinite relaxation [9], the problem in (17) can be relaxed into a convex form by dropping the constraint $\mathrm{rank}(\mathbf{X})= 1$. Due to the relaxation, the problem is not always guaranteed to have a solution with rank 1 matrix. However, extensive simulation results revealed that the rank of the matrix $\mathbf{X}$ is always one, and $\mathbf{W}$ can be extracted from $\mathbf{X}$ as its principal eigenvector.

V. Simulation Results

The performance of the proposed scheme is investigated for a relay network with three sources, three desired users, two neighboring users and a relay layer comprising of ten relays, R = 10. The channels $\{\mathbf{h}_k\}_{k=1}^N$, $\{\mathbf{q}_i\}_{i=1}^N$ and $\{\mathbf{a}_j\}_{j=1}^L$ are generated using zero-mean unity variance complex Gaussian variables. The power of the information symbols is set to unity and the variance of AWGN at the relays and all the users is kept to -20 dB. Simulations have been drawn for 1 million monte-carlo iterations. Fig. (2) shows the power requirement for the relays to achieve the target SINR at the desired users and to maintain interference and noise power below the maximum acceptable level at the neighboring users. At low SINR values the interference and noise leaked to the neighboring users is mostly less than the maximum acceptable level and the corresponding constraints on interference and noise power become inactive. Therefore, the total power transmitted by the relays remains the same for the cases with different threshold limit on interference and noise leaked to the neighboring users. However, for large SINR values, the total

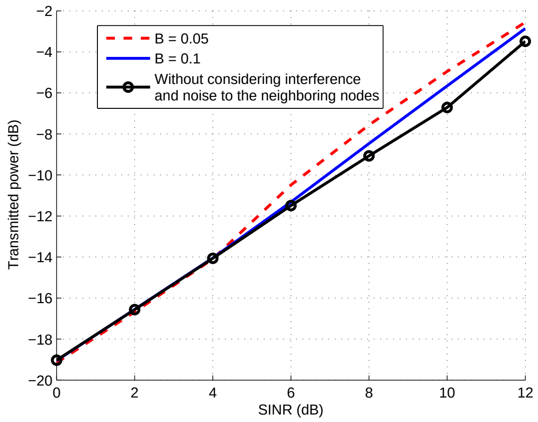

Fig. 2. Total power transmitted by 10 relays with 3 desired users and 2 neighboring users (B is the maximum acceptable interference and noise power leaked to the j^{th} neighboring user, β).

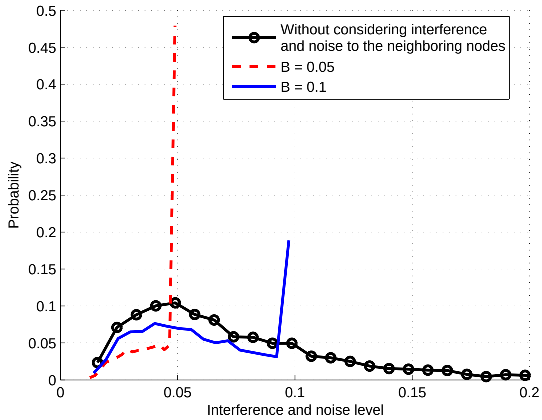

Fig. 3. Probability distribution of interference and noise leakage to neighboring users with 6 dB SINR to desired users (B is the maximum acceptable interference and noise power leaked to the j^{th} neighboring user, β).

power transmitted by the relays increases as the maximum allowed interference and noise power to the neighboring users is decreased. When the maximum interference and noise level at the neighboring users is set to β_j, any interference and noise values that cross the limit are forced by the algorithm to fall with in the acceptable range. As a result, a peak is occurred in the probability density function of interference and noise at β_j values as shown in Fig. (3). Also, when the maximum allowable interference and noise level is increased, the peak of the impulse at the end of the distribution decreases. This is because as β_j is increased, the constraint becomes inactive most of the times. In the simulation, the solutions corresponding to the matrix $\mathbf{X}$ with rank not equal to one and infeasible solutions are discarded. Fig. (4) shows infeasibility of the problem in terms of outage probability (i.e. probability of the problem becoming infeasible). When the target SINR at the desired users is increased or the acceptable interference and noise level at the neighboring users is decreased, this outage probability increases. There is a tradeoff between fairness to neighboring nodes in the system and QoS achieved for the

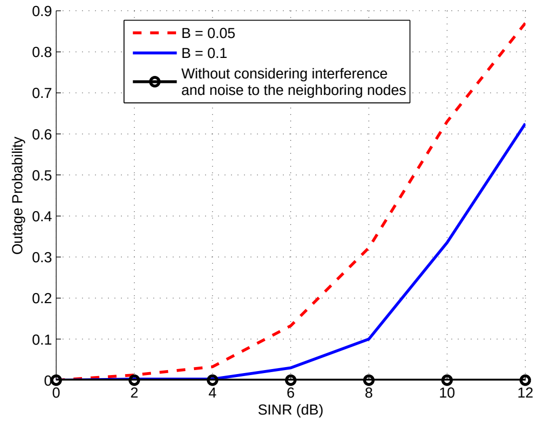

Fig. 4. Outage probability of the distributed wireless relay network (B is the maximum acceptable interference and noise power leaked to the j^{th} neighboring user, β).

desired users. For example, at 0.20 outage probability one needs to sacrifice target SINR of the desired users by 2 dB in order to reduce interference leaked to other active users by a factor of 2.

VI. Conclusion

We have proposed a multiple relaying strategy for wireless networks with user discretion. The proposed scheme achieves a set of target SINRs at the desired user destination nodes while minimizing the interference and noise power leaked to the active neighboring user terminals. Semidefinite programming is used to obtain optimal weight vectors to satisfy the required criterion. A tradeoff between fairness to other active users and QoS for desired users has also been observed.

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