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Cooperative MIMO Communication in Constrained Wireless Ad Hoc Networks

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Abstract
In this paper, we investigate the issue of cooperative node selection in MIMO communications for wireless ad hoc networks, where a source node is surrounded by multiple neighbors and all of them are equipped with a single antenna. Given constraints such as energy, delay and data rate, a source node dynamically chooses its cooperating nodes from its neighbors to form a virtual MIMO system with the destination node (which is assumed to have multiple antennas), as well as adaptively allocates the power level and adjusts the constellation size for each of the selected cooperative nodes. In order to optimize system performance, we jointly consider the optimization of all these parameters with given system constraints. We assume that the source node either has CSI, or has no CSI. Heuristic algorithms, such as maximal channel gain (MCG) and least channel correlation (LCC) algorithms are proposed in order to exploit available system information and to solve the constrained optimization problem.
Keywords: *Cooperative/virtual MIMO, ad hoc, correlation, QR decomposition, channel state information (CSI).*

1. Introduction

In modern wireless communications, enhanced spectral efficiency can be achieved by the use of multiple-input - multiple- output (MIMO) systems. Recently, MIMO has attracted extensive attention and various techniques have been proposed for both cellular systems and ad hoc networks [1, 2] to achieve improved system performance. However, in wireless ad hoc networks, direct employment of MIMO to each node might not be feasible, since MIMO might require complex transceiver and signal processing modules, which result in high power consumption. Furthermore, nodes in wireless ad hoc networks are often powered by batteries with limited energy. This makes direct application of MIMO to each node inefficient from a power-efficiency point of view.

As alternatives, cooperative MIMO techniques [3, 4] have been proposed. By the cooperation of multiple nodes, each of which has a single antenna, a virtual MIMO structure can be constructed which supports space-time processing, and thus improved system performance can be expected. In [3, 5], it has been shown that by using this type of cooperation, cooperative MIMO can achieve better energy and delay performance compared to a Single Input Single Output (SISO) system. In [6], space-time coded cooperative diversity protocols are proposed to combat multipath fading. In [7], adaptive spatial multiplexing techniques for distributed MIMO systems are proposed, together with link adaptation based on available channel state information. Further performance gain can be achieved by appropriate power allocation among nodes that join the cooperation [8, 9]. In [8], optimal energy distribution is proposed with an attempt to minimize the link outage probability, while in [9], with only mean channel gain information; a source node jointly selects the cooperative nodes from its neighbors and optimally allocates power to each cooperative node in order to minimize outage probability.

In order to achieve cooperative MIMO, a source node should first distribute data information to other cooperative nodes; this is the first stage or the "local distribution" stage. After each cooperative node receives information from the source node, the second stage is carried out by using a particular cooperative protocol, where the source node and the cooperative nodes collaborate together to form a virtual MIMO system and transmit to the destination node. The second stage is sometimes referred to as "long haul" transmission. Most previous work, such as [4-9], only focused on the second stage, without considering the effects in the first stage. In order to have a complete view of cooperative MIMO in wireless networks, both stages should be jointly considered.

In our paper, for a cooperative MIMO system with uncoded spatial multiplexing, we jointly consider the selection of cooperative nodes and the power/rate allocation among the selected nodes in order to minimize the bit-error rate performance of the system. More specifically, we quantify the energy and delay induced during the local distribution stage; then, for the long haul transmission stage, given a subset of cooperating nodes, we express the system performance as a function of that subset of nodes, and the power/data rate allocated to each node; after that, we form a multi-variable optimization problem to maximize the performance at the destination node, taking into account both stages and the energy/delay/rate constraints.

Finally, we investigate how to select the cooperative nodes and how to solve the optimization problem where the source node either has perfect instantaneous channel state information (CSI), or the source node only knows the channel correlation information.

2. System Description

2.1 System Model

Below diagram shows the system model. Here, we assume that the source node has K-1 neighbors, and we want to select N out of the K nodes to form a virtual MIMO system, including the source node. The destination node is assumed to have R receive antennas, where $R \geq K$. The distance between the source node

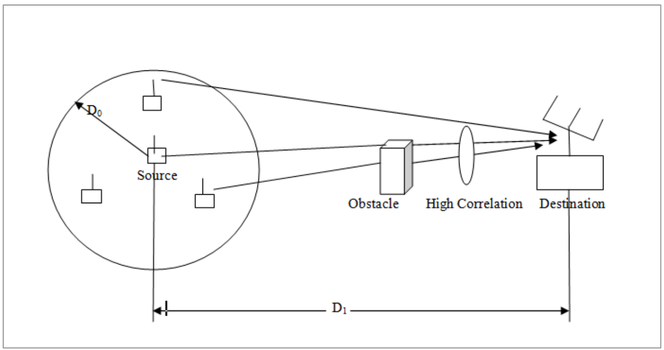

Figure 1: System Model.

and the destination node is D_1, and the neighbors of the source node are randomly distributed within a radius of D_0 of the source node. Here, we assume D_1 >> D_0, so that the distance between each cooperative node and the destination node can be approximated as D_1 [3]. The channel between the cooperative cluster with N nodes (source node plus cooperative neighbors) and the destination node is assumed to experience a combination of frequency-flat Rayleigh fading with parameter σ^2, shadowing, and path loss. In wireless transmission, high correlation can be induced between propagation paths by shadowing if they are blocked by the same obstacle, such as a tree or a building [10]. In this paper, for simplicity, we only consider the correlation effect caused by shadowing. Channel correlation caused by shadowing exhibits distance dependence, and thus we model the channel correlation between any two given cooperative nodes using an exponential model as in [10]:

$$\rho = \beta^{d/D} \tag{1}$$

where ρ is the correlation between the two nodes separated by distance d, and β is the correlation between two nodes separated by distance D. β and D can be measured by field tests and then can be used to calculate the correlation between any two nodes [10].

2.2 Channel Model

Assume we have N cooperative nodes, and let **x**= [x_1,x_2, ...,x_N] denote the transmitted vector, and **y**= [y_1, y_2, ...y_R] denote the received vector at the destination node with R receive antennas. The received signal vector **y**, after matched filtering is given by

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{2}$$

where **H** represents the channel matrix between the cooperative cluster and the destination node, and has dimension R×N, and **n** = $[n_1, n_2, \dots \dots, n_R]^T$ denotes Gaussian noise. Assuming that correlation only resides at the transmitter side, then the channel matrix **H** can be expressed as [11]

$$\mathbf{H} = \mathbf{H}_\omega \mathbf{R}_\mathbf{T}^{1/2} \tag{3}$$

where $\mathbf{H}_\omega$ is an $R \times N$ matrix and $\mathbf{R_T}$ is an $N \times N$ correlation matrix among the cooperative nodes

2.3 Spatial Multiplexing and ZF-SIC

In order to exploit the capacity of a MIMO system, we consider the use of spatial multiplexing, where the source node divides the incoming bit stream into N substreams, and then distributes each of these substreams to one of the N cooperative node. Finally, each cooperative node sends an independent bit stream to the destination node simultaneously with other cooperative nodes via the virtual MIMO structure between the cooperating nodes and the destination node. During the transmission in order to remove the multistream interference, successive interference cancellation (SIC) [11] is used. In this paper, we employ successive interference cancellation with fixed detection order in conjunction with ZF at each detection stage.

2.4 Performance Metric

In our paper we desire to jointly select the optimal subset of cooperative nodes and the per-node power level as well as per-node rate (constellation size) in order to minimize the BER at the receiver. For this, we use the minimum Euclidean distance d_i *as* a performance metric on the i-th subchannel. Suppose an M-ary QAM modulation is employed, and we have N cooperative nodes and N corresponding subchannels, where the i-th subchannel has power level P_i, constellation size B_i and corresponding channel gain $|R_{i,i}|2$. Then, the received minimum squared Euclidean distance of the output constellation of the i-th subchannel is given by [12] as

$$d_i^2 = \frac{6P_{i.}|R_{i,i}|2}{B_i - 1} \tag{4}$$

3. Optimization Problem Formulation

In order to consider the local distribution and long haul transmission together, we need to include the energy consumptions and the delays of the two stages in the optimization problem i.e. for given K possible candidates, the optimization for the optimal subset of cooperative nodes is labeled as ϕ^*, with N nodes, as well as the corresponding power/bit allocations for each of them. We denote by E_{tot} and T_{tot} the total end-to-end energy and the total end-to-end delay, respectively, with maximum allowable values E_0 and T_0 respectively. Then, the overall optimization problem is given by:

$$\max_{(\phi,\, N,\, Pi,\, Bi)} d_0^2$$

$$\text{s.t.} \quad (1) \sum_{i=1}^{N} P_i = P_T \quad (2)\ E_{tot} = E_{tot}^{(2)} + E_{tot}^{(1)} \le E_O$$

$$(3)\ T_{tot} = T_{tot}^{(2)} + T_{tot}^{(1)} \le T_O \quad (4)\ 0 < N \le K \qquad (5)$$

In order to find the optimal ϕ^*, N, P_i and B_i, $i = 1, \ldots, N$, an exhaustive search is necessary, but this type of problem usually has a large search space when K is large.

4. Local Distribution Analysis

In local distribution stage, the transmission from the source node to a given cooperative node is in the form of packets, we assume that the source node has L_i bits within a packet to be transmitted to cooperative node i. During this stage, a fixed M_0-ary QAM is used together with coherent modulation /demodulation. Since a given $M_0 = I \cdot Q$ rectangular QAM signal can be treated as two independent pulse amplitude modulation (PAM) signals and the probability of error for the original QAM signal can be shown to be:

$$SER = 1 - (1 - SER_I)(1 - SER_Q) \qquad (6)$$

where SER_I and SER_Q are the probabilities of symbol error for the two PAM signals. Hence, at relatively high SNR, the symbol error rate SER, can be tightly approximated as [13]

$$SER \approx 4Q\left(\sqrt{\frac{3\zeta}{M_0 - 1}}\right) \qquad (7)$$

where $Q(\cdot)$ is the Gaussian tail function, and ζ is the corresponding signal-to-noise-ratio for the transmission to node i, given by

$$\zeta = \frac{\alpha_i P_i^{(1)}}{N_0} \qquad (8)$$

where α_i is the channel gain (path loss plus fading), $P_i^{(1)}$ is the employed transmission power per symbol, and N_0 is the noise power. The minimal transmission power $P_i^{(1)}$ for the local transmission to node i is given by

$$P_i^{(1)} = \frac{(M_O - 1).N_O}{3\,\alpha_i} \text{ x } \left[Q^{-1}\left(\frac{SER_t}{4}\right)\right]^2 \qquad (9)$$

The energy for the local distribution to each cooperative is consists of the transmission energy & the circuit energy consumption node which ensures reliable communications from the source node to the particular cooperative node. It is given by

$$E_{tot}^{(1)} = \sum_{i=1}^{N} \left(\frac{T_s L_i}{b_o} X\left[P_c + P_i^{(1)}\right] X\, I(i)\right) \qquad (10)$$

where L_i/b_0 is the number of symbols in the packet and P_c is the circuit power for each symbol which is taken constant. Since, when node i is source node itself, there is no power consumption and delay introduced for the local distribution to node i, we thus define the indicator function $I(i)$.

Under the assumption that TDMA is used for the local distribution with fixed symbol duration T_s, the total delay in this stage is the sum of the delays associated with the transmission to each of the N cooperative nodes:

$$T_{tot}^{(1)} = \sum_{i=1}^{N} \frac{L_i}{b_0} \text{ x } T_s \text{ x } I(i) \qquad (11)$$

5. Transmission Optimization and Cooperative Node Selection

5.1 Long Haul Transmission Optimization

Given that N nodes have been chosen for the long haul transmission, the target is to find the power/bit allocations for each of these selected nodes under the transmit power constraint P_T, and the total bit rate constraint, b_T. Therefore, the optimization problem for the long haul transmission stage is given by

$$\max_{(P_i, B_i)} d_0^2$$

$$\text{s.t.} \quad (1) \quad \sum_{i=1}^{N} P_i = P_T; \qquad (2)\ \sum_{i=1}^{N} log_2(B_i) = b_T \qquad (12)$$

Since $d_i = d_0$, from (4), we have B_i given by

$$B_i = \frac{6P_i \,.\, |R_{i,i}|2}{d_0^2} + 1 \qquad (13)$$

Plugging (13) into the second constraint in (12), we obtain the following equation:

$$\sum_{i=1}^{N} log_2\left(\frac{6P_i \,.\, |R_{i,i}|2}{d_0^2} + 1\right) = b_T$$

$$\Rightarrow log_2\left(\prod_{i=1}^{N}\left[\frac{6P_i \,.\, |R_{i,i}|2}{d_0^2} + 1\right]\right) = b_T \qquad (14)$$

$$\max_{\{P_i\}}\left\{\prod_{i=1}^{N} 6\, P_i \,.\, |R_{i,i}|2\right\} \quad \text{s.t}(1) \sum_{i=1}^{N} P_i = P_T \qquad (15)$$

It is clear that in order to maximize (15), we need to maximize the product of P_i. Moreover, due to the constraint in (15), where the summation of P_i is equal to the total power P_T, the maximization is achieved when the total power P_T is equally distributed to all the cooperative nodes, which means $P_i = P_T/N$, $i = 1, \ldots, N$.

5.2 Cooperative Node Selection

In what follows, we describe the heuristic algorithms in two different scenarios, i.e., perfect instantaneous CSI is available at the source node or only the channel correlation information is available at the source node. As shown below, each of these two algorithms will only need to search a subspace with K possible cooperative node combinations, which is much less than that required by an exhaustive search. Among the K combinations, only the one achieving the best end to-end performance while meeting the specified total end-to-end delay and energy constraints will be used for the transmission.

Perfect Full CSI is Available. In this case, the source node knows the instantaneous CSI between all the K cooperative nodes and the destination node, i.e., the channel gain matrix H with dimension $R\ X\ K$, and the correlation information among all the nodes. To accomplish this, consider the use of a maximal channel gain (MCG) algorithm as follows: at the (k+1)-thstep, where k nodes have already been chosen, and the corresponding channel matrix $H^{(k)}$are known, where $H^{(k)}$ is the channel matrix when k nodes are chosen, we want to select one additional node s^* from the set S containing the remaining $K-k$ nodes such that

$$s^* = \text{argmax}_{s^* \in S}\left\{\det\left(\left(H^{(k+1)H}\, H^{(k+1)}\right)\right)\right\} \qquad (16)$$

We repeat this until all the K nodes are chosen. Therefore, at each step, we obtain a selected combination of nodes, ϕ, with an increasing number of nodes in it. In total, the algorithm runs K steps, thus the search space for the previous optimization problem has only K combinations. Finally, we choose the optimal subset $\phi*$ which results in the largest $d_0^2$for the cooperative transmission while meeting the specified total end-to-end delay and energy constraints. Since the MCG algorithm only searches a small subset of possible combinations instead of searching all combinations, it would induce performance drop, and however, the performance degradation as shown later is only marginal, which demonstrates the effectiveness of the proposed MCG algorithm.

In this case, the source node only knows the correlation information among the potential cooperative nodes. Therefore, the MCG algorithm proposed above should be modified as follows, due to the lack of CSI. Thus, the modified MCG algorithm is as follows: at the (k + 1)-th step, where nodes have been chosen, and the corresponding correlation matrix $\left(R_T^{1/2}\right)^{(k)}$ are known, we want to select one additional node s^* from the set S which contains the remaining $K-k$ nodes such that

$$S^* = \text{argmax}_{s^* \in S}\left\{det\left(\left(\left(\left(R_T^{\frac{1}{2}}\right)(+1)H\left(\left(R_T^{1/2}\right)(k+1)\right)\right)\right)\right)\right\} \qquad (17)$$

Hence, when full CSI is not available, we still can significantly reduce the search space by exploiting the channel correlation information, and thus the optimization problem can be solved.

Consider now an alternative to the use of the modified MCG algorithm, namely, the least channel correlation (LCC) algorithm, which only makes use of the channel correlation information at the source node and tries to minimize the correlation among the cooperative nodes. Compared to the modified MCG algorithm, the LCC algorithm has less complexity. Therefore, the algorithm can be described as follows: at the (k + 1)-th step, where k nodes have been chosen, we want to select one additional node s^* from the set S which contains the remaining K−k nodes such that the average distance $D_{ave}^{(k)}$ to all the previous k nodes can be maximized:

$$s^* = \text{argmax}_{s^* \in S}\left\{D_{ave}^{(k)}\right\} \qquad (18)$$

where the average distance $D_{ave}^{(k)}$ can be computed as

$$\left\{D_{ave}^{(k)}\right\} = \frac{1}{k}\sum_{i=1}^{k}\sqrt{(X_i - X_{k+1})^2 + (Y_i - Y_{k+1})^2} \qquad (19)$$

and (X_i, Y_i) is the axis-position of the i-th node. More specifically, at the first step, the source node is chosen; at the second step, one additional node is chosen such that $D_{ave}^{(1)}$ is maximized; we then repeat the same process. The algorithm ends when all the nodes are chosen.

6. Simulation Results

In order to verify our theoretical analysis above and show the performance of the proposed node selection algorithms under the system constraints, such as the delay and energy consumption constraints, we carry out simulations. We choose K = R = 6, which means 6 potential cooperative nodes including the source node, and the destination node has 6 receive antennas. The distance between the source node and the destination node, D_1, is 100 m, and the radius of the cooperative cluster, D_0, is 10 m. The path loss exponent is set to be 4, system bandwidth be 10 KHz and the circuit power is set to be 250 mw [3]. The fixed data rate is chosen to be b_T = 14 bps/Hz. During the local distribution, the fixed modulation size is assumed to be b_0 = 4. The maximum QAM constellation size used for each node is 256-QAM. Finally, the correlation caused by shadowing uses parameters β = 0.3 and D = 10 m [10].

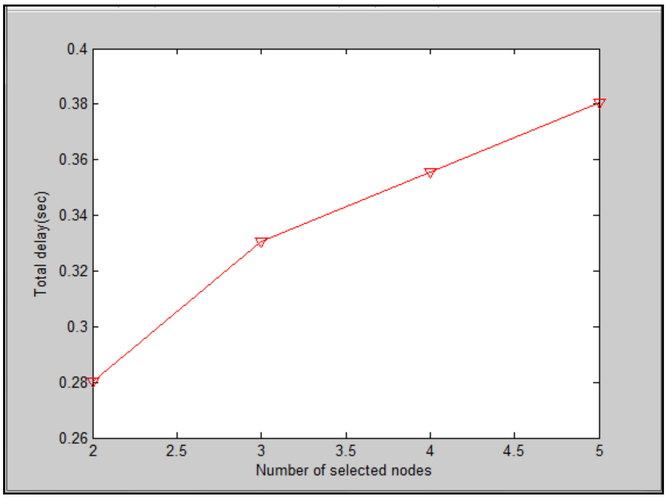

Figure 2: MCG algorithm with perfect CSI; no constraints; average SNR = 21 dB.

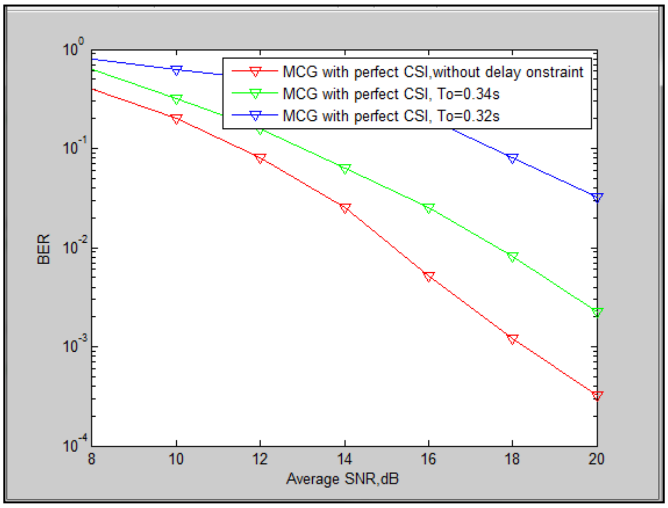

Figure 4: MCG algorithm with perfect CSI; with different delay constraints; E_0 = 0.8 J.

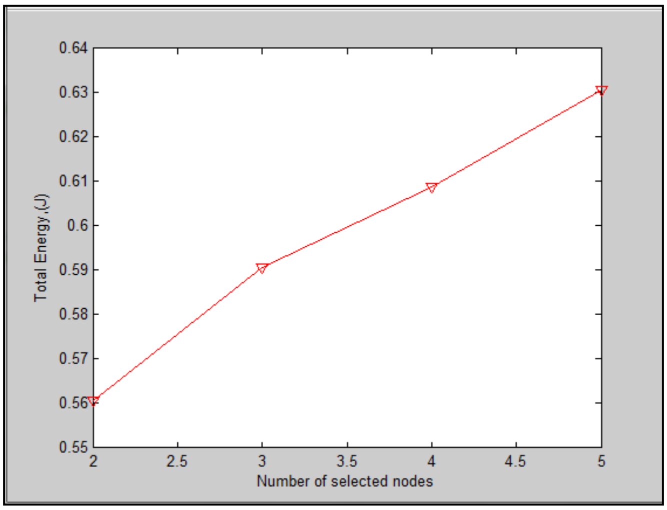

Figure 3: MCG algorithm with perfect CSI; no constraints; average SNR = 21 dB.

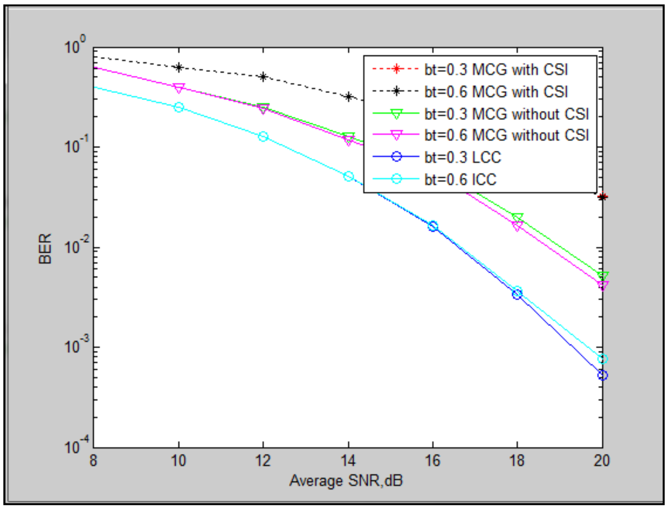

Figure 5: Performance comparison between MCG with perfect CSI, MCG w/o CSI, and LCC; T_0 = 0.41 s and □□ = 0.8 J.

In Figs. 2 and 3, we let the system constraints E_0 and T_0 be infinite, i.e., no constraints, and the MCG algorithm with perfect CSI is employed. It is clear that the more stringent the constraints are, the fewer cooperative nodes we can choose. As a result, the two system constraints, i.e., E_0 and T_0, play important roles for the selection of cooperative nodes as well as the overall system performance, which determine the number of cooperative nodes that can participate the cooperation. For example, if E_0 and T_0 are small, it may not be able to choose the optimal number of nodes, and will result in degraded overall system performance.

In Fig. 4, we show the performance of the MCG algorithm with perfect CSI as a function of the average SNR with distinct delay constraints. When no delay constraint is present, i.e., T_0 is infinite, the best system performance can be achieved. However, when the delay constraint becomes stringent, the system performance degrades substantially, as shown in the figure. This is because when a delay constraint is present, we cannot always choose the optimal set of nodes that can achieve the best performance, and as the constraint becomes more stringent, fewer nodes can be chosen, thus worse performance is expected.

In Fig. 5 we show the performance comparison among the proposed algorithms under different channel correlation levels. For the same channel correlation level, the MCG algorithm with perfect CSI can achieve the best performance since it exploits the perfect instantaneous CSI to achieve the cooperative node selection. Compared to an exhaustive search, the MCG algorithm with perfect CSI only incurs a small drop in performance, which demonstrates the effectiveness of the proposed algorithm.

When no CSI is available, we still can implement the proposed node selection algorithm by the proposed modified MCG algorithm with no CSI and the LCC algorithm. Since the two algorithms exploit the same channel correlation information, they result in similar performance which is not distinguishable from the figure. As shown in Fig. 5, the MCG algorithm with no CSI and LCC algorithm would result in degraded system performance compared to that of MCG with perfect instantaneous CSI. Lastly, we also observe that when the channel correlation increases, system performance is degraded for all the algorithms. On the other hand, it is worth noting that when the correlation level increases, the performance gap between MCG with perfect instantaneous CSI and either the MCG without CSI or the LCC decreases. That means, the proposed MCG without CSI and the LCC algorithms can result in more performance gain in scenarios with high channel correlation.

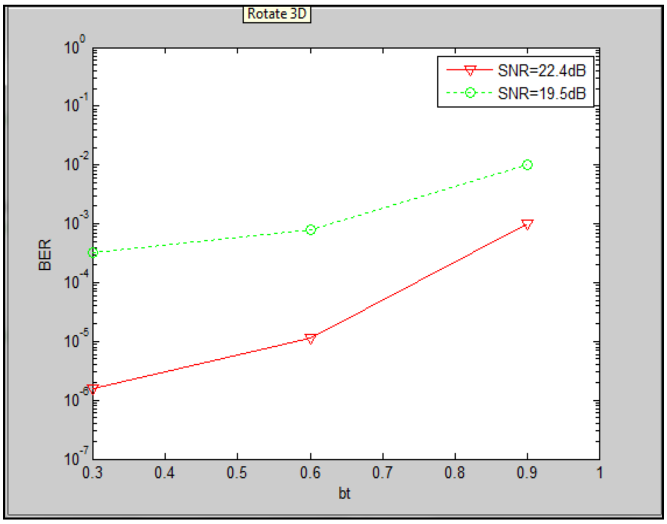

Figure 6: Effect of channel correlation for MCG with perfect CSI; T_0 = 0.41s and E_0 = 0.8 J.

In Fig. 6, we present the effect of correlation on the system performance. As can be seen, when channel correlation increases, the system performance degrades accordingly.

In Fig. 7, we illustrate the frequency distribution of the number of selected nodes under different correlation levels. As shown, it is clear that the system does not need to use all the K nodes in the cooperation, and when the correlation level increases, the system tends to choose fewer cooperative nodes due to the negative effect of correlation.

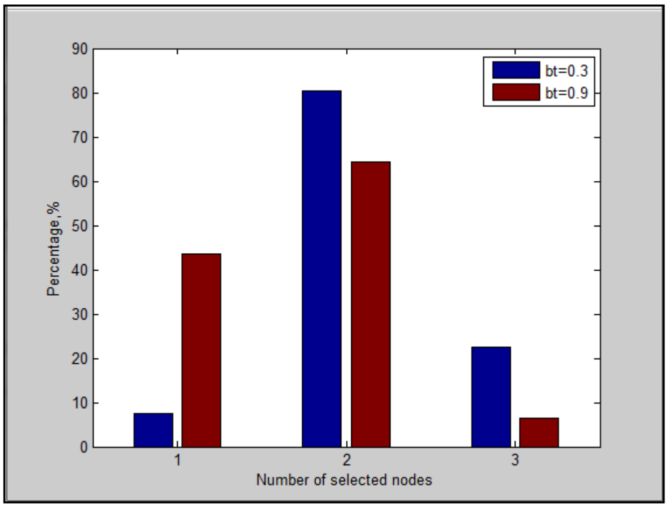

Figure 7: Histogram of number of selected nodes for MCG with perfect CSI; T_o = 0.41 s and E_o = 0.8 J; SNR = 22.4 dB.

7. Conclusion

In this paper, we investigated the cooperative and constrained virtual MIMO communications in ad hoc or sensor networks. More specifically, we have taken into account a complete view of the node cooperation procedure, under the specified system constraints, such as the energy and delay constraints. Then, we quantified the energy consumption and delay incurred during the local distribution stage, and jointly combined the local distribution stage and the long haul transmission stage. Finally, the subset of cooperative nodes participating in the virtual MIMO communication is chosen by considering the overall system constraints and the power level and data rate for each selected cooperative node are adaptively assigned in order to optimize the system performance.

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