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# MIMO Communications for Cooperative Networks with Energy and Delay constraints

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**Abstract**

In this paper we consider a cooperative wireless network, where a source node is surrounded by multiple neighbors and all of them are equipped with a single antenna. Its main objectives are to enhance network throughput, conserve energy, and improve network coverage. In order to minimize the bit error rate performance of the system the selection of cooperative nodes and the power allocation among the selected nodes are jointly considered. More specifically, we quantify the energy during the local distribution and for the long haul transmission stage, given a subset of cooperating nodes. 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. Assuming that the source node either has CSI, or has no CSI, Maximal channel gain (MCG) is proposed in order to exploit available system information and to solve the constrained optimization problem.

**Index Terms**: Cooperative/virtual MIMO, power, energy, constellation size, delay, optimization, channel state information (CSI).

## 1. Introduction

The demand for higher data rates is rapidly increasing for the last few decades. Multiple-Input, Multiple-Output (MIMO) techniques constitute a cost effective approach to enhanced spectral efficiency and system performance in wireless communications. Multiple-input multiple-output (MIMO) is an advanced technology that can effectively exploit the spatial domain of mobile fading channels to bring significant performance improvements to wireless communication systems. Since the direct employment of MIMO to each node might not be feasible, due to size, cost and hardware constraint, a class of techniques known as cooperative communication may be considered which allow single-antenna nodes to reap some of the benefits of MIMO systems. Cooperative MIMO [1], also known as virtual or distributed MIMO, aims to utilize distributed antennas to achieve some benefits similar to those provided by conventional MIMO systems. The idea of cooperative MIMO is to group multiple devices into virtual antenna arrays. They can achieve better energy and delay performance compared to a Single Input Single Output (SISO) system [3], even considering the required overhead in a MIMO system. Space-time coded cooperative diversity protocols are used to combat multipath fading.

In this 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.

This paper is organized as follows: in Section II, we present the system description; in Section III, we quantify the energy consumption and delay induced during the local distribution stage and present the cooperative node selection algorithms employed to choose the subset of cooperative nodes under different system conditions; in Section V, we briefly describe the procedure which is used to realize the cooperation; finally, simulation results and discussions are presented in Section VI, followed by a conclusion in Section VII.

## 2. System Description

### 2.1 System model

We assume that the source node cooperating with its neighboring nodes a can form a virtual MIMO where all such nodes, have a single antenna. However, the destination node is assumed to be large enough so that multiple receiver antennas can be implemented.

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 ≥ K. The distance between the source node and the destination node is *D*, and the neighbors of the source node are randomly distributed within a radius of R of the source node. Here, we assume D >>R, so that the distance between each cooperative node and the destination node can be approximated as [4].

The wireless channels between the source node and its neighbors the channel between the cooperative cluster with *N* nodes (source node plus cooperative neighbors) and the destination node are assumed to experience *i.i.d.* frequency-flat Rayleigh fading channel.

For simplicity, we only consider the correlation effect caused by shadowing. Typically, 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]:

$$\rho = \beta^{\frac{d}{D1}} \tag{1}$$

where $\rho$ is the correlation between the two nodes separated by distance $d$, and $\beta$ is the correlation between two nodes separated by distance $D_1$.By field tests, $\beta$ and $D$ can be measured and then can be used to calculate the correlation between any two nodes [10]. The system model is illustrated in Fig. 1, where a source node selects 2 out of its 3 neighbors to form the virtual MIMO system with the destination. We assume that the system is time-slotted, where the time synchronization among the nodes can be achieved through some kind of beaconing (as in IEEE 802.11). At the receiver, the multiple cooperative nodes would typically interfere with one another, and in order to remove the multistream interference, successive interference cancellation (SIC) is used. 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, can be shown to be given by

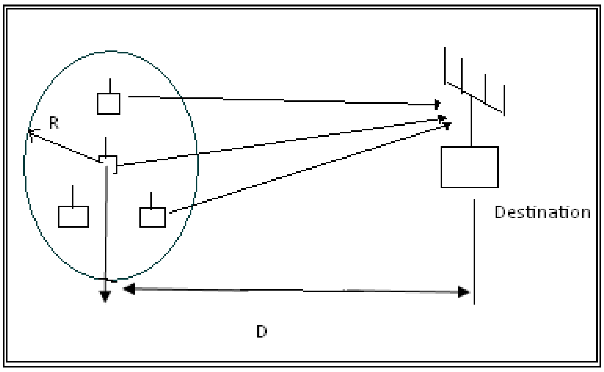


Fig: System model

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

where H represents the channel matrix between the cooperative cluster and the destination node, and has dimension $R\times N$,and n = $[n_1, n_2, ..., n_R]^T$ represents *i.i.d.* Gaussian noise with zero mean and variance $\sigma_n^2$. For simplicity, if we assume that the correlation only resides at the transmitter side, then the channel matrix H can be expressed as [11]

$$H = H_w R_T^{\frac{1}{2}}, \tag{3}$$

where $H_w$ is an $R \times N$ matrix whose elements are *i.i.d.* complex Gaussian random variables with zero mean and unit variance, and $R_T$ is an $N \times N$ correlation matrix among the cooperative nodes, i.e., among the transmit antennas. From (1), $R_T$ can be expressed as follows:

$$R_T = \begin{bmatrix} 1 & \beta^{\frac{d_{12}}{D_1}} & \dots & \beta^{\frac{d_{1N}}{D_1}} \\ \beta^{\frac{d_{21}}{D_1}} & 1 & \dots & \beta^{\frac{d_{2N}}{D_1}} \\ \vdots & \vdots & \vdots & \vdots \\ \beta^{\frac{d_{N1}}{D_1}} & \beta^{\frac{d_{N2}}{D_1}} & \dots & 1 \end{bmatrix} \quad (4)$$

Where $d_{ij}$ is the distance between node I and node j, and $d_{ij}=d_{ji}$.

## 2.2 Local distribution and Long-haul transmission

We assume that, in total, the source node has a bit stream of $L_0$ bits to be sent to the destination. By using the proposed node selection algorithms described in Sec V, $N$ nodes are selected to perform cooperation. Then, during the local distribution stage, the source node forms $N$ different substreams, and distributes the $N$ substreams to the $N$ selected cooperative nodes such that each cooperative node has one distinct substream. During this step, under the assumption that the system is time-slotted with slot duration $Ts$, and that TDMA is employed to distribute the source information, delay is introduced.

We let $T_{tot}$ denote the total delay introduced during the local distribution. Also, the local distribution requires a minimum energy in order to guarantee the transmissions from the source node to its neighbors are reliably received. We let $E_{tot}$ denote the total energy consumed in this stage, and assume it contains both the transmission energy and the circuit energy consumption, as detailed in Section IV. For simplicity, we assume that the source node knows the location of each neighbor and the corresponding channel gain between them.

In the second stage, i.e., the long haul transmission, all the $N$ selected cooperative nodes collaborate together and form a virtual MIMO system with the destination node. The total transmission power for all the cooperative nodes is constrained to be less than or equal to $P_T$ , as in [24, 25]. Further, we let $E_{tot}$ be the total energy used in this stage by all the cooperative nodes and the destination node, where $E_{tot}$ contains both the transmission energy consumption and circuit energy consumption. Lastly, the total delay associated with this stage is given by $T_{tot}$ . All the parameters associated with these two stages will be discussed in more detail in a later section.

## 2.3 Performance Metric

As we discussed previously, 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 simplicity, we use the minimum Euclidean distance $di$ 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 $Pi$, constellation size $Bi$ and corresponding channel gain $|Ri,|^2$. Then, the received minimum squared Euclidean distance of the output constellation of the $i$-th subchannel is given by [13] as

$$d_i^2 = \frac{6P_{i.}|R_{i,i}|^2}{B_i - 1} \tag{5}$$

In other works, such as [16], it was shown that in a MIMO spatial multiplexing system, the system performance is limited by the weakest link. In order to maximize the system performance, we want the output minimum Euclidean distance
for each subchannel to be the same, and then maximize that minimum Euclidean distance, subject to given system constraints. By letting $d_i = d_0$, $i = 1, 2,...,$, the objective becomes maximizing $d_0^2$.

**2.4 Cooperative node selection**

In what follows, we describe the algorithm when perfect instantaneous CSI is available at the source node or only the channel correlation information is available at the source node. As shown below, the algorithm 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. It is worth noting that, compared to the exhaustive search, the proposed heuristic algorithm result in only marginal performance degradation.

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×K, and the correlation information among all the nodes. In order to maximize the target function, given N, we want the product of those channel gains,$\prod_{i=1}^{N}|R_{i,i}|^2$,to be as large as possible. Due to the fact that the eigenvalues of R are equal to $R_{i,}$, we have the following properties:

$$\prod_{i=1}^{N}|R_{i,i}|^2 = \prod_{i=1}^{N}|\gamma_i(R)|^2 = det(R^H R)$$

$$= \det(R^H Q^H Q R) = det(H^H H) \text{ ..............} \qquad \text{....(6)}$$

where $(\cdot)$ is the eigen value of the argument. Therefore, as shown in above equation, it is clear that in order to maximize the product of the channel gains, $|R_{1,1}|^2 . |R_{2,2}|^2 .... |R_{N,N}|^2$, we only need to maximize the determinant of the corresponding channel matrix ($H^H$H).To accomplish this, consider the use of a maximal channel gain (MCG) algorithm as follows: at the (k+1)-th step, 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

$$s^{*} = argmax_{s*\in s}\left[det\left(\left(H^{(k+1)}\right)^{H}\left(H^{(k+1)}\right)\right)\right] \quad (7)$$

We repeat this until all the $K$ nodes are chosen. Therefore,at each step, we obtain a selected combination of nodes, $\phi$, 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 $d_{20}$ 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, however, the performance degradation as shown later is only marginal, which demonstrates the effectiveness of the proposed MCG algorithm.

## 3. Numerical Results and Discussions

In this section, we provide the performance of the proposed node selection algorithms under the system constraints, such as the delay and energy consumption constraints.

Simulation parameters:

| S. No | Parameter | Value |
|---|---|---|
| 1 | No.of cooperative nodes | 6 |
| 2. | No.of antennas at destination node | 6 |
| 3 | D(distance between source and destination node) | 100m |
| 4 | R(radius of the cooperative cluster) | 10m |
| 5. | system bandwidth | 10KHz |
| 6 | Data rate chosen | 14bps/Hz |
| 7 | B | 0.3 |

First of all, we demonstrate the necessity for selection of cooperative nodes in a constrained environment. In Figs. 2 and 3, we let the system constraints $Eo$ and $To$ be infinite, i.e., no constraints, and the MCG algorithm with perfect CSI is employed. As we can see from Fig. 2 and Fig. 3, if we have delay and energy constraints present, it is clear that the more stringent the constraints are, the fewer cooperative nodes we can choose. As a result, it turns out that the two system constraints, i.e., $Eo$ and $To$, play important roles for the selection of cooperative nodes. On the other hand, it is also clear that the overall system performance is somehow dependent on the system constraints, i.e., $Eo$ and $To$, which determine the number of cooperative nodes that can participate the cooperation. For example, if $Eo$ and $To$ 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. As can be seen, when no delay constraint is present, i.e., $To$ 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, we cannot always choose the optimal set of nodes that can achieve the best performance.

In Fig. 5, we show the performance comparison among the proposed algorithms under different channel correlation levels. Fig. 6, 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.

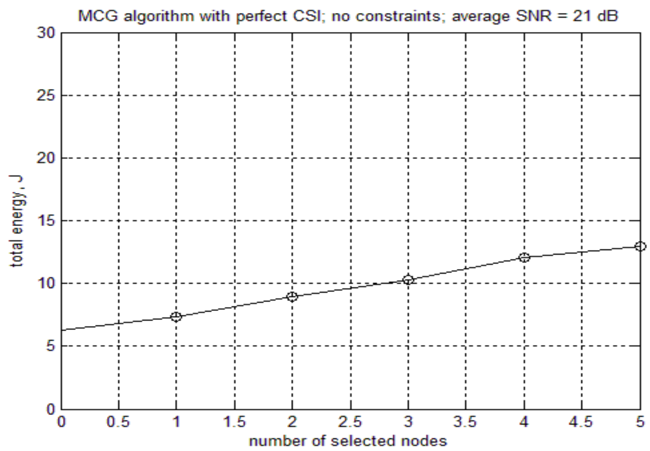


**Fig 2**: MCG algorithm with perfect CSI; no constraints; average SNR = 21dB.

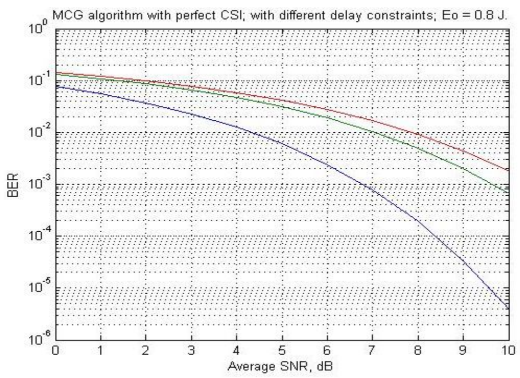


**Fig. 3**: MCG algorithm with perfect CSI; no constraints; average SNR = 21 dB.

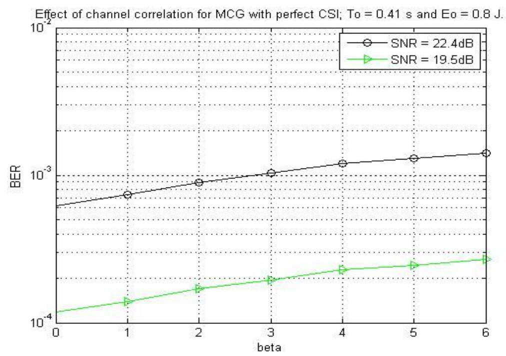


**Fig. 4**: MCG algorithm with perfect CSI; with different delay constraints; $Eo$ = 0.8 J.

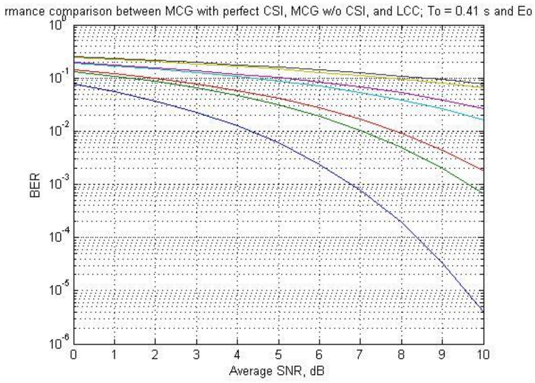


**Fig. 5**: Performance comparison between MCG with perfect CSI, MCG w/o CSI, and LCC; *To* = 0.41 s and *Eo* = 0.8 J.

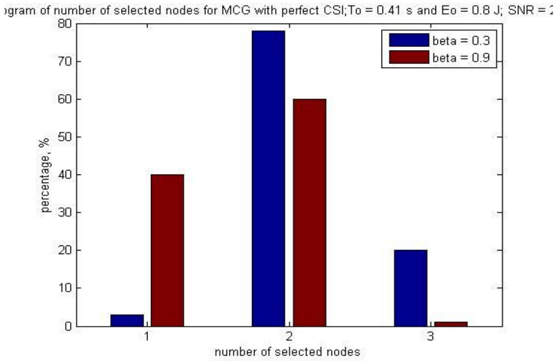


**Fig. 6**: Histogram of number of selected nodes for MCG with perfect CSI; □□ = 0.41s and □□ = 0.8 J; SNR = 22.4 dB.

## 4. Conclusion

In this paper, we investigated the cooperative and constrained virtual MIMO communications. 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. 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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