Performance Improvement Using Receiver Node Selection in Receiver Cooperative Downlink Systems

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Abstract

We examine the downlink of wireless communication systems with receiver cooperation. The cooperative utilization among closely-located receiver nodes is referred to as cooperative receiving, which behaviors similar to multiple-antenna receiving. To realize this, a group of receiver nodes are first to form a cluster, which necessitates a node selection algorithm. The operation of such node selection is conceptually equal to antenna selection in multiple-input multiple-output (MIMO) systems, except that selecting longer distance nodes requires higher cost in cooperation. We propose a few node selection algorithms appropriate for receiver cooperative downlink systems. Simulation results indicate that the performance of the node selection algorithms is significantly dependent on the distances among receiver nodes.

I. Introduction

Recently the idea of the multiple-input multiple-output (MIMO) antenna system is extended in a distributed fashion where a group of closely-located but separate nodes, each of which has its own antenna, can cooperate together to utilize cooperative receiving, similar to multiple-antenna receiving, among themselves [1]–[4].

The co-existence of various wireless communication technologies and their complementary feature is likely to equip a mobile node with multiple wireless communication interfaces. For example, suppose a person carries two mobile equipments that are a cellular phone and a PDA, both of which employ CDMA and Bluetooth interfaces. They can form a wireless personal area network (WPAN) using their Bluetooth interfaces. Now consider how the CDMA cellular interface can be utilized cooperatively. Note that the distance between the CDMA base station (BS) and the group of these nodes is in general much longer than the distance between the cellular phone and the PDA. Then, this group of closely-located WPAN nodes can form a cooperating cluster using their CDMA cellular interfaces and Bluetooth interfaces as well. The intra-cluster channel uses Bluetooth communications, while the BS-to-cluster (between the BS and the cluster) channel uses CDMA cellular communications. That is, the nodes in this cluster can cooperate to utilize their antennas as if their antennas belong to the same node, resulting in advantages of MIMO [6]. Note that intra-cluster communication used for node cooperation allows much higher rate transmission compared to the long-distance BS-to-cluster communication since its relatively short distance. The traffic flows between the cluster of wireless nodes and the BS, although receiver nodes cooperate on their receptions.

References [1], [2] consider node-collaborative signal processing, but with only two cooperating nodes. In our preliminary work [5], we generalize this two-node cooperation model by introducing an intra-cluster multiple access channel (MAC), which is a key factor to realize a cluster of multiple (more than 2) nodes.

Numerous MIMO antenna selection schemes (e.g. [8], [9]) that optimally choose a subset of the available receiver antennas have been proposed in original MIMO systems (multiple antennas in single-node systems) to reduce implementation cost due to multiple RF chains. Node selection (antenna selection in the above case) in the case of receiver node cooperation is an even more crucial issue because relaying cost is significantly dependent on the number of receivers within intra-cluster. That is, the intra-channel is noisy, which affects to cooperation gains compared to the multiple antenna receiving in the above single-node system case, where every antenna is directly and noiselessly connected to each others. Taking lessons from these, we propose a few node selection schemes and investigate their applicability in terms of the BS-to-cluster distance.

II. Downlink Cooperation Model

Now we present the system model being analyzed and derive the cooperative downlink capacity bound based on our previous analysis work [5]. For the sake of illustration, we will consider the infrastructure-mode wireless communications

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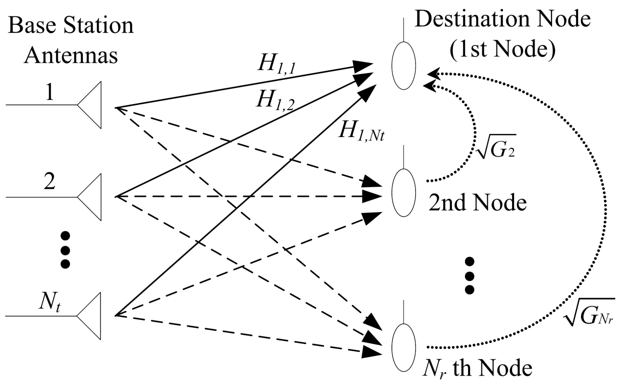

Fig. 1. System model

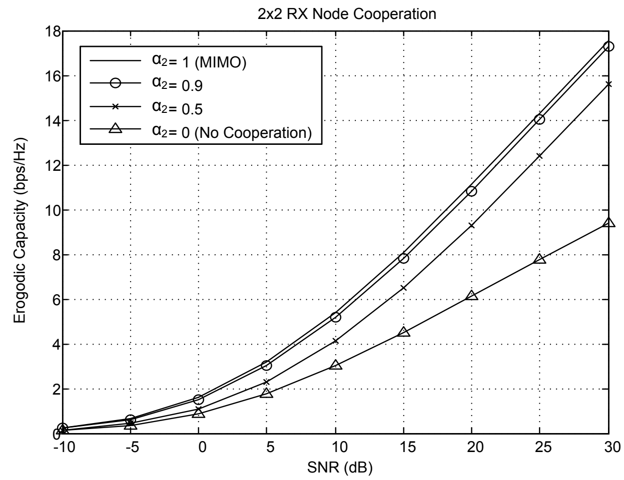

Fig. 2. Performance of cooperative receiving with different α_2

such as cellular networks. Under these circumstances, receiver node cooperation matters only in downlink since the BS (as a single-node receiver in uplink) can readily harness the power of the MIMO system in uplink. Let us assume that a BS is equipped with N_t transmitting antennas and there is a cluster of $N_r(\geq N_t)$ receiving nodes as shown in Fig. 1. BS wishes to serve only one specific node, say destination node, where the assistance of adjacent receivers enhances the receiving performance using cooperative receiving. The destination node selects $N_t - 1$ nodes out of $N_r - 1$ neighbor nodes to form a cluster. In order to achieve increased capacity as much as the number of transmit antennas, N_t, in general the receiving cluster must have L_r nodes such that $L_r \geq N_t$ [8], so $L_r = N_t$ is sufficient condition, which is the size of a cluster in this paper. Noting that letting the number of receiver nodes, L_r, be larger than the number of transmit antennas, N_t, increases capacity a little bit, while probably much significantly increasing the cost of relaying.

The BS first converts a single data stream (intended to the destination node) into N_t parallel sub-streams. On the receiver side, the destination node forms a receiving cluster by selecting the best $N_t - 1$ relaying nodes out of $N_r - 1$ neighboring nodes in terms of the given node selection criterion. Then the selected cooperating nodes will cooperate by forwarding their received streams to the destination node that would then decodes them. So, the decoding and signal processing is done at the destination node while the other nodes are involved in relaying cooperation.

The above clustering scenario allows us to assume that the distance between the BS and the receiving cluster is sufficiently large so that the distance between any antenna in the BS and any node in the receiving cluster can be assumed to be equal. The channel gain amplitudes between these two sets (N_t transmitting antennas and N_r receiving antennas) are then normalized to one, meaning that $|h_{i,j}| = 1$ where $h_{i,j}$ is the channel between the ith transmit antenna and the jth receiver node. The BS-to-cluster channel and the intra-cluster channel are assumed to be orthogonal, so there is no interference between each other (e.g., by use of frequency division multiplexing (FDM) or time division multiplexing (TDM) [7]). The bandwidth of them is assumed to be 1 Hz each.

We first consider the BS-to-cluster channel, which is characterized by the $N_r \times N_t$ matrix, elements of which are $h_{i,j}$. Let $\mathbf{x}$ denote the $N_t \times 1$ transmit vector and $\mathbf{y}$ is the $N_r \times 1$ receive vector at the receiving nodes. Then the channel equation may be expressed by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{1}$$

where each element of the vector $\mathbf{n}$ is an identically and independently distributed (i.i.d.) circularly symmetric $\mathcal{CN}(0, 1)$ noise. Each element of the channel matrix is given by just a phase change, i.e, $h_{i,j} = e^{j\theta_{i,j}}$.

Now, we look at the intra-cluster channel at the receiving end and then see the model of the aggregated signal channel. We denote by G_i the intra-channel gain from the ith node to the destination node (1st node) where $2 \leq i \leq N_r$. Since the amplitudes of BS-to-cluster channels are all normalized to one, this is equivalent to a situation where the distance between the BS and the receiving cluster is $(G_i)^{1/l}$ times as large as the one between the destination node and the ith receiving node where l is the path loss exponent. In the receiving cluster if the signals from the nodes to the destination node is denoted by x'_i and the forwarded signal at the destination node due to each node is y'_i, then we have the channel equation as $y'_i = \sqrt{G_i}x'_i + n'_i$ where $2 \leq i \leq N_r$ and n'_i are i.i.d circularly symmetric $\mathcal{CN}(0, 1)$ noises.

The total power cost of receiver cooperation is P_r and the total BS transmission power is constrained to P. Assuming that the node selection is performed and so $L_r = N_t$, the aggregated signal at the destination receiver is then given by [5]:

$$\tilde{\mathbf{y}}_1 = \mathbf{H}'\mathbf{x} + \mathbf{n} \tag{2}$$

where $\mathbf{n}$ is the intra-channel noise vector and has the same distribution as the noise vector in (1). Also, $\mathbf{H}' = \mathbf{A}\mathbf{H}$ where $\mathbf{A} = \mathrm{diag}\{1, \alpha_2, \ldots, \alpha_{L_r}\}$ and the noise amplification factor

α_i is

$$\alpha_i = \frac{\beta_i}{1+\beta_i}, \quad \beta_i = \sqrt{G_i' \frac{P_r/(L_r-1)}{P+1}} \tag{3}$$

where

$$G_i' = \frac{N-1}{P_r}\left((1+P_rG_i)^{\frac{1}{N-1}} - 1\right)$$

and $L_r = N_t$. Note that $\tilde{\mathbf{y}}_1$ differs from $\mathbf{y}$ only due to α_i in $\mathbf{A}$, which is caused by noise amplification during intra-channel relaying and is a parameter less than 1. We see that if we can use the sufficiently large cooperation power, i.e., $P_r \to \infty$, while other parameters are constant, α_i goes to 1. On the contrary, α_i goes to 0 if $P_r \to 0$. This fact notices that using higher relaying power less increases noise, which is relevant to the previous discussion. More generally, changing of β_i shows the similar behavior of the α_i varied by changing of P_r, which means that larger cooperation power P_r is required for smaller $G_i'/(P+1)$ to obtain the equal α_i. On the other hands, larger number of cooperation nodes constrained to the total cooperation power P_r reduces the cooperation power for each node, i.e., $P_r/(L_r-1)$, so that each α_i is decreased. Fig. 2 illustrates the performance of cooperative receiving with different α_2 in the system having two transmit antennas and two cooperative receiver nodes, showing that the capacity is quite dependent on α_2 (especially in higher SNR regime) as we expected.

The sum rate decodable at the destination receiver is given by:

$$\begin{aligned} R_d &= \log\left|\mathbf{I} + \frac{P}{N_t}\mathbf{H}'\mathbf{H}'^H\right| \\ &= \log\left|\mathbf{I} + \frac{P}{N_t}\mathbf{A}\mathbf{H}\mathbf{H}^H\mathbf{A}^H\right| \end{aligned} \tag{4}$$

where the superscript ^{H} denotes the Hermitian transpose. We easily understand that the capacity achieved by receiver cooperation in (4) is the shifted version of the capacity achieved by multiple-antenna receiving along with the x-axis representing the input power as much as $10\log_{10}(L_r/\sum_{i=1}^{L_r} 1/\alpha_i^2)$ (dB) where $\alpha_1 = 1$. Note again that such loss come from the noise enhancement by cooperative receiving.

III. Node Selection Algorithms

Prior to the transmission from the BS to the destination node, the destination node forms a receiving cluster by selecting the *best* $N_t - 1$ relaying nodes out of $N_r - 1$ neighboring nodes in terms of the given criterion. Similar to receiver antenna selection in MIMO system (in which it reduces the cost due to the requirement of multiple RF chains [10]), node selection reduces the size, complexity, and thus cost of cooperation. One big difference we should keep in mind is that there are no cooperation cost in multiple-antenna receiving while in receiver node cooperation such cost is one of key factors to analysis the performance. In that sense, we must not use directly the channel matrix $\mathbf{H}$ in (1) for node selection. So, we propose a few new selection criterions as well as optimal criterion, which are based on the effective channel matrix in (2).

A. Optimum Node Selection Criterion

Since the sum achievable rate or the capacity bound of a downlink node cooperation is defined as (4), the destination now selects those neighbor nodes that allow the maximization of the rate, so that

$$R_{sel} = \max_{\tilde{\mathbf{H}}' \subset S(\tilde{\mathbf{H}}')}\left(\log\left|\mathbf{I} + \frac{P}{N_t}\tilde{\mathbf{H}}'\tilde{\mathbf{H}}'^H\right|\right) \tag{5}$$

where $\tilde{\mathbf{H}}'$ is created by deleting $N_r - N$ rows from $\mathbf{H}'$, and $S(\tilde{\mathbf{H}}')$ denotes the set of all possible $\tilde{\mathbf{H}}'$ whose cardinality is $\binom{N_r}{N_t}$.

The optimum selection of nodes requires knowledge of the complete channel matrix and $\binom{N_r}{N_t}$ computations of determinants, which is computationally burdensome. Therefore, suboptimal algorithms are needed to achieve lower complexity at the expense of optimum selection.

B. Channel Information Based Selection

One of the suboptimal algorithms is correlation based method (CBM). If there are two rows of the $\mathbf{H}'$ that are identical, we can delete any row of these two rows without losing any information about the transmitted signal. In addition if they have different powers, we delete the row with lower power. When there are no identical rows we select next two rows for the deletion whose correlation is the next highest. If we repeat this deletion until $N_r - N_t$ rows are eliminated, we can have the $N_t \times N_t$ channel matrix $\tilde{\mathbf{H}}'$ whose rows are maximally uncorrelated and have maximum powers. Somewhat similar approach is to delete one of two rows whose mutual information has maximum value. This correlation based method (CBM) and mutual information based method (MIBM) require less than ${N_t}^2$ vector multiplications while providing comparable performance. For original MIMO antenna selection versions of MIBM and CBM see [9].

C. Relaying Power Based Selection

Although [8] showed that simply choosing the antennas that instantaneously receive the most energy does not give good performance in MIMO antenna selection, it is worthwhile to consider power based selection in the case of node selection. We do not use the signal power from the BS antennas, but use the received signal power from relaying nodes at the destination node. In particular, if the BS-to-cluster distance is not so much larger than the distance between the destination and relaying nodes, the distribution of G_i has a large effect on the downlink rate. sum rate of the destination node than the correlation between channel vectors. If relaying nodes use equal power to transmit to the destination node, the received signal power from the ith relaying node is directly mapped to G_i at the destination node and eventually to the intra-cluster distance. Thus, relaying power based method (RPBM) that selects $N_t - 1$ nodes with highest received signal power can be effective despite its simplicity.

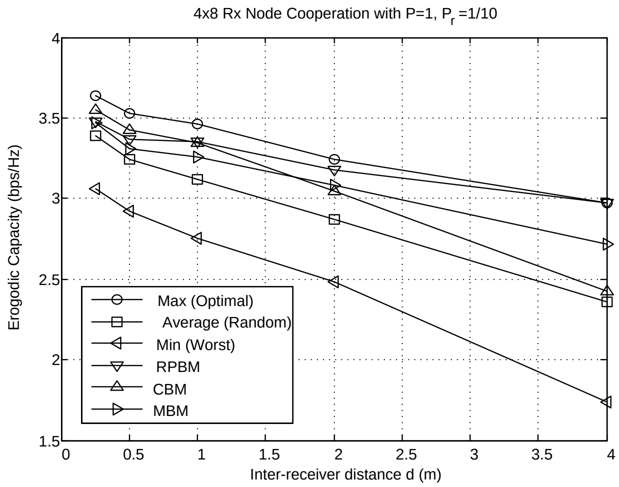

Fig. 3. Performance of node selection when $P = 1,\ P_r = 1/10$

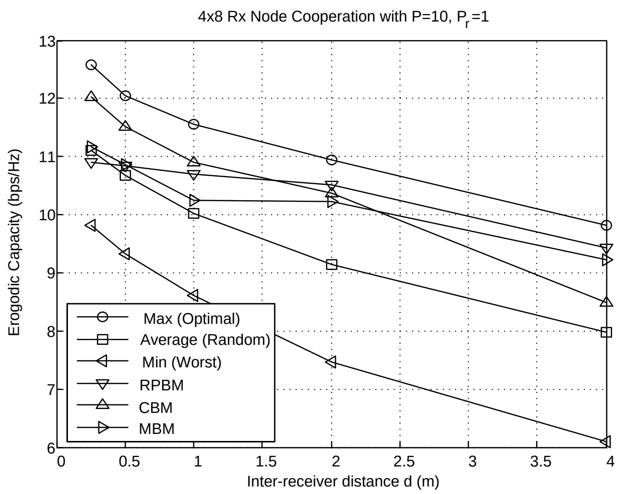

Fig. 4. Performance of node selection when $P = 10,\ P_r = 1$

IV. Numerical Results

Fig. 3 and 4 show the performance of node selection algorithms versus the distance between two receiver nodes, denoted as inter-receiver distance d, when the distance between BS-to-cluster is fixed to $d_{BS} = 100m$, $N_t = 4$, and $N_r = 8$. SNR is set to 0dB and 10dB for two figures, respectively, which gives a value for P as 1 and 10, and the noise is normalized to one. Also, P_r is set to $P/10$. We set the intra-cluster channel gain of each ith relaying node as $G_i = (d(i-1)/d_{BS})^{-3}$ where the numerator $d(i-1)$ denotes the distance between the destination node and the ith relaying node, and 3 is the path loss exponent. For comparison purposes, we add the results of the random, and the minimum group selection algorithm, denoted as Average (Random) and Min (Worst), respectively. The downlink rate of each RPBM, CBM, MIBM and the random selection is compared with optimal selection, denoted as Max (Optimal). RPBM outperforms other methods when $d = 4m$, i.e., the relaying nodes in the cluster is located relatively far from the destination node. CBM outperforms others in the short intra-cluster distance case ($d = 0.25m$). MIBM shows steady capacity enhancement regardless of the distance d.

We observed that this relationship between the performance of algorithms and the distribution of G_i (eventually the network topology) is preserved with different path loss exponent values and various d settings.

V. Conclusions

We have devised a practical infrastructure-based network downlink model for cooperation of multiple receiver nodes. The receiver cooperation gives the same advantage gains to multiple-antenna receiving in MIMO system, except that the cost due to relaying received signals to the target node must be taken into account. To reduce this cost effectively, the node selection is needed. In addition to proposing new optimal selection criterion appropriate for this situation, we found that the performance of suboptimal selection algorithms such as power-based node selection and channel correlation-based node selection acts much differently as it is applied to multiple antennas.

For the future work, more various combinations of the number of transmit antennas and the number of the receiver nodes need to be considered, such as the case where the number of transmit antennas is larger than the number of receiver nodes.

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