Downlink Node Cooperation with Node Selection Diversity

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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 the "cooperative diversity," a group of receiver nodes are first to form a cluster, which necessitates a node selection algorithm. The operation of such node selection is similar to antenna selection in multiple-input multiple-output (MIMO) systems, except that relaying (or cooperation) cost should be considered. 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

Multiple-input multiple-output (MIMO) wireless communication systems has recently emerged as the one of the most significant technologies. The reason why MIMO communication systems have gained a significant attention is two-fold. The first strength is they can increase wireless link capacity by enhancing the signal-to-noise ratio (SNR) (*spatial multiplexing*). The other advantage is that we can mitigate wireless channel impairments such as fading, delay spread, and co-channel interference (*spatial diversity*). Therefore, work has been done to improve performance of wireless communication systems by utilizing MIMO antenna technologies [1], [2].

Recently the idea of the multiple-input multiple-output (MIMO) antenna system is extended in a distributed fashion where single-antenna nodes can cooperate together to reap some of the benefits of MIMO systems. In a multi-user scenario, single-antenna nodes can share their antenna in a manner that creates a virtual MIMO system. The idea of antenna sharing or cooperation is attractive to wireless networks since a wireless node may not be able to equip multiple antennas due to size and cost limitations. [3] is one of the first studies about cooperative communication. References [7], [8] consider collaborative signal processing in a group of closely-located nodes.

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 [1]. 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.

To realize the "cooperative communication," a group of receiver nodes are first to form a cluster, which necessitates a node selection algorithm. Numerous MIMO antenna selection schemes (e.g. [14], [15]) 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

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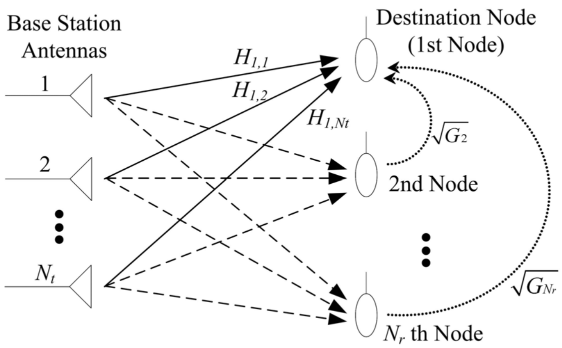

Fig. 1. System model

of receiver node cooperation is an even more crucial issue because relaying cost is significantly dependent on the number of receivers within a receiving 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 distance between receiving nodes.

In order to effectively demonstrate how node selection schemes work, we extend the two-node cluster model of [7] to allow more than two nodes in a cluster. For cooperative transmission/reception in a cluster with more than two nodes, the medium-access control is required to manage orthogonal[2] relaying to ensure that nodes satisfy the half-duplex constraint and do not transmit and receive simultaneously on the same channel [4]. We introduce an intra-cluster multiple access channel (MAC) with optimal multiplexing strategy.

We address a network with an infrastructure, such that, instead of a transmitting cluster, there is a base station, thus we precludes the transmitter cooperation of [7]. More specifically, in our downlink model, the traffic flows from the BS with multiple antennas to the cluster of wireless nodes. Moreover, we assume only a single source-destination pair, i.e., multiple antennas of the BS transmit signals intended to a single node while other receiver nodes cooperate on the reception in behalf of the destination node. The BS may control this cooperative downlink communication and change the destination node turn by turn according to the downlink traffic demand for each node. We believe this simplified cooperative downlink model provides more practical and operative situation.

We begin with section II which outlines the system model in detail. Section III subsequently provides the explanation about the downlink receiver node cooperation with discussion of intra-cluster multiple access mechanisms. Next, we describe the fast node selection schemes, and in section V and Section VI, we present simulation results and conclude our paper, respectively.

[2]physically orthogonal by FDMA or TDMA: virtually orthogonal by CDMA

II. System Model

Now we look more closely into the system model being analyzed. We have a base station with N_t transmitting antennas and a cluster of $N_r(\geq N_t)$ receiving nodes as shown in Fig. 1. Uplink transmit node cooperation is redundant, since we can achieve uplink MIMO rates by allowing multiple mobile nodes to transmit their own messages directly to the base station and by using receiver side MIMO multiplexing technology, such as successive interference cancellation (SIC) or V-BLAST [12] at the base station. Thus, we only consider downlink receiving node cooperation. The base station antennas transmits to the cluster of wireless receiving nodes. The destination node selects N_t-1 nodes out of other N_r-1 nodes to form a cluster (to be discussed in section IV). In order to achieve increased capacity, the receiving cluster can consist of L_r nodes as long as $L_r \geq N_t$ [14], however, we have the size of a cluster as N_t for simplicity.

The base station converts a single bitstream (intended to the destination node) into N_t parallel streams of complex symbols. These all streams have independent symbol streams. On the receiver side, the destination node and the other selected N_t-1 nodes would cooperate by amplifying and forwarding their received streams to the destination node which would then decode them. Thus the encoding and signal processing is done at the destination node while the other nodes are involved in relaying cooperation. Employing amplify-and-forward at the nodes in the receiving cluster has been proved to be a promising cooperative strategy [5], [6]. It was shown that amplify-and-forward achieves the asymptotic capacity in an network with a single source-destination pair [5].

Aforementioned scenario with CDMA and Bluetooth enabled WPAN allow us to assume that the distance between a base station and a receiving cluster is sufficiently large so that the distance between any antenna in the base station and any node in the receiving cluster can be considered to be equal. The channel gain amplitudes between these two sets are then normalized to one. Therefore, each channel between a transmitter-receiver pair contributes only a random phase change to the signal. This is being denoted by θ_i which are assumed to be uniformly distributed in $[0, 2\pi]$. For simplicity and to gain intuition, the channel between base station antennas and receiving nodes (inter-cluster channel) and the channel between nodes of the receiving cluster (intra-cluster channel) are assumed to be orthogonal. The bandwidth of the inter-cluster channel and the intra-cluster channel at the receiver side is assumed to be 1 Hz each.

We first consider the inter-cluster channel. Let x_i denote the signal transmitted by the ith transmitting antenna and y_i the received signal at the ith receiving node. Then the channel equation would be

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \mathbf{y}_{N_r} \end{bmatrix} = \mathbf{H} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \mathbf{x}_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ \mathbf{n}_{N_r} \end{bmatrix} \quad (1)$$

where, n_i are independent $\mathcal{N}(0,1)$ noises. Each element of the channel matrix is given by just a phase change i.e, $H_{i,j} = e^{j\theta_k}$, where $H_{i,j}$ denotes the channel from the jth transmitting antenna to the ith receiving node.

Now, we look at the intra cluster channel at the receiving end. Among all N_r *receiving* nodes in a receiving cluster, the node 1 or 1st node indicates the *destination* node and the other $N_r - 1$ nodes are *relaying* nodes. We express the intra channel gain from the kth relaying node to the destination node (node 1) as G_k where $2 \leq k \leq N_r$. Since the inter-channel gain amplitudes are normalized to one, this is equivalent to a situation where the distance between the base station and the receiving cluster is $(G_k)^{1/l}$ times as large as the distance between the destination node and the kth relaying 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'_k and the forwarded signal at the destination node due to each node is y'_k, then we have the channel equation as $y'_k = \sqrt{G_k}x'_k + n'_k$ where $2 \leq k \leq N_r$ and n'_k are independent $\mathcal{N}(0,1)$ Gaussian noises. Now the signals x'_k are constrained to be functions of the signals received from the transmitting antennas.

The cost of receiver cooperation is an overhead which is limited to power P_r and the total base station power is constrained to P

$$E\left[\sum_{k=1}^{N_t} {x_k}^2\right] \leq P, \quad E\left[\sum_{k=2}^{N_r} {x'_k}^2\right] \leq P_r.$$

III. Downlink Cooperation Model

In this section, we describe a method which allows the N_r receivers to cooperate while a base station is transmitting with N_t antenna elements.

Now the amount of signal gathered at each of the receiving nodes (including the destination node) is the same, as the channels between base station antennas and receiving nodes are equivalent except for the phase differences and also the transmitters send independent messages. The relaying node amplifies and forwards all signals to the destination node (node 1). With perfect node cooperation, the destination node would get to see the received signals $y_2 \ldots y_{N_r}$ in addition to its own signal y_1. As each received signal gets amplified and forwarded to the destination node, it also results in some noise amplification. Each of $(N_r - 1)$ relaying nodes uses the fraction of receiver power $P_r/(N_r - 1)$ to amplify-and-forward its received signal to the destination receiver. Since the base station antennas transmit independent symbol streams, the signals $x_1 \ldots x_{N_r}$ are independent and are chosen to $\mathcal{N}(0, \frac{P}{N_t})$. The expected received power at y_k $(k = 1, ..., N_r)$ is given by $E[y_k^2] = (\sum_{i=1}^{N_t} E[x_i^2]) + E[n_k^2] = (P) + 1$. Thus, the kth $(k = 2, ..., N_r)$ node relays to the destination node [7]

$$\sqrt{\frac{P_r/(N_r-1)}{P+1}}y_k = \sqrt{\frac{P_r/(N_r-1)}{P+1}}\left(\sum_{i=1}^{N_t} H_{i,k}x_i + n_k\right). \tag{2}$$

Then, $(N_r - 1)$ relaying nodes relay to the destination node and, eventually, the channel used for receiver side cooperation is multiple access channel shared by $(N_r - 1)$ users. Ideally $N_r - 1$ different channels would be convenient but such a case is impractical. Thus we must consider multiple access channels in the system. Under realistic assumptions, we would have to use only one channel with multiple access such as CDMA, TDMA or FDMA etc. We consider a multiple access scheme which allocates optimal rates without any multiplexing overhead such as guard time in TDMA etc.

In the code division multiple access (CDMA) manner with an optimal decoder [9], the destination node decodes all $(N_r - 1)$ signals jointly followed by successive stripping of signals. From the discussion in [10], we can observe that at the optimal equal rate point (equal rate for all users) we also have equal rates with CDMA, FDMA (and the analogous TDMA). Thus, we introduce the optimal CDMA effective gain (G'_k) $(2 \leq k \leq N_r)$ in order for all $(N_r - 1)$ relaying nodes to have optimal rate. As shown in [10], this optimal point on the capacity region is applicable to the optimal FDMA and TDMA as well. In order keep the assumption of same bandwidth, 1Hz, for all transmitted signals, we choose the optimal CDMA formula. So the achievable rate for each $(N_r - 1)$ node of optimal FDMA and CDMA system are described as follows

$$R_{FDMA} = \frac{1}{N_r - 1}\log(1 + P_r G_k) \tag{3}$$

$$R_{CDMA} = \log\left(1 + \frac{P_r}{N_r - 1}G'_k\right) \tag{4}$$

where interference caused by other signals are ignored in (4), but instead, received signal power is adjusted to meet effective (corresponding) SNR value with the unit noise variance in the CDMA system. Because R_{CDMA} must be equal to R_{FDMA},

$$G'_k = \frac{N_r - 1}{P_r}\left((1 + P_r G_k)^{\frac{1}{N_r - 1}} - 1\right). \tag{5}$$

Thus, the corresponding signal received at the destination receiver, transmitted from the kth relaying node, is given by

$$\sqrt{\frac{G'_k \frac{P_r}{N_r - 1}}{P+1}}\left(\sum_{i=1}^{N_t} H_{ik}x_i + n_k\right) + n \tag{6}$$

where $n \sim \mathcal{N}(0,1)$. Thus, we consider interference caused by other signals in the equivalent optimal CDMA system by utilizing G'_k. The aggregate signal at the destination node is given by

$$\widetilde{\mathbf{y}_1} = \mathbf{H}'\mathbf{x} + \mathbf{n}' \tag{7}$$

where $\mathbf{n}'$ is the intra-channel noise vector and

$$\mathbf{H}' = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1N_t} \\ \alpha_2 H_{21} & \alpha_2 H_{22} & \cdots & \alpha_2 H_{2N_t} \\ \cdots & & & \\ \alpha_{N_r} H_{N_r 1} & \alpha_{N_r} H_{N_r 2} & \cdots & \alpha_{N_r} H_{N_r N_t} \end{bmatrix}.$$

where $\mathbf{n}$ is the intra-channel noise vector and has the same distribution as the noise vector in (1). And the noise amplification factor α_k is

$$\alpha_k = \frac{\beta_k}{1 + \beta_k}, \quad \beta_k = \sqrt{G'_k \frac{P_r/(L_r - 1)}{P+1}} \tag{8}$$

. Note that $\tilde{\mathbf{y}}_1$ differs from $\mathbf{y}$ only due to α_k which is caused by noise amplification during intra-channel relaying and is a parameter less than 1. The sum rate decodable at the destination node is given by:

$$R_{downlink} = \log \left| \mathbf{I} + \frac{P}{N_t} \mathbf{H}' \mathbf{H}'^H \right| \tag{9}$$

where the superscript ^{H} denotes the Hermitian transpose.

IV. 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 [16]), 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 (7).

A. Optimum Node Selection Criterion

Since the sum achievable rate or the capacity bound of a downlink node cooperation is defined as (9), the destination now selects those neighbor nodes that allow the maximization of the rate, so that

$$R_{sel} = \max_{\tilde{\mathbf{H}}' \subset S(\tilde{\mathbf{H}}')} \left(\log \left| \mathbf{I} + \frac{P}{N_t} \tilde{\mathbf{H}}' \tilde{\mathbf{H}}'^H \right| \right) \tag{10}$$

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 [15].

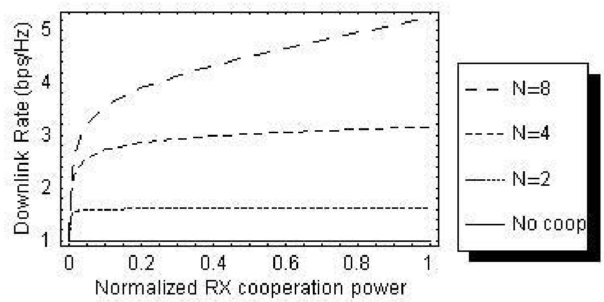

Fig. 2. Downlink rate($R_{downlink}$)

C. Relaying Power Based Selection

Although [14] 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_k has a large effect on the downlink rate than the correlation between channel vectors. If relaying nodes use equal power to transmit to the destination node, the received signal power from the kth relaying node is directly mapped to G_k at the destination node and eventually to the distance between the destination node and the kth relaying node. Thus, relaying power based method (RPBM) that selects $N_t - 1$ nodes with highest received signal power can be effective despite its simplicity.

V. Numerical Results

Fig. 2 deal with achievable downlink rate (9) for a random channel drawn against the receiver cooperation power P_r, which is normalized by the base station power P. $N_r = N_t = N$ and SNR is set to 0 dB, which give a value for P as 1 as noise is normalized to one. Intra-channel gain for every node is equally set to 30 dB ($\forall k, G_k = 1000$). We have assumed a path loss exponent of 3 as it corresponds to the practical case of urban area cellular radio [13]. This implies that the distance between the base station and the cluster is 10 times the distance between each relaying node and the destination node. It was seen that the rates of the cooperation model with optimal multiplexing exceeded the rate achieved without cooperation. The rate achieved without cooperation implies the base station use the total power P to send its messages to the destination directly without cooperation.

According to (9), $R_{downlink}$ is an logarithmic increasing function of α and α converges to 1 as P_r increases. Since increasing of sum rate is a tradeoff of additional cooperation

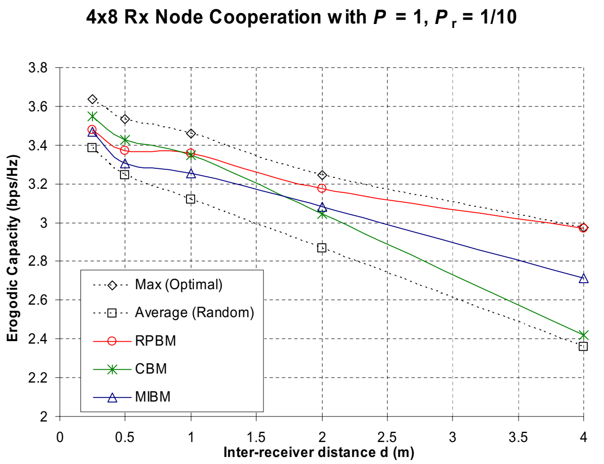

Fig. 3. Performance of node selection when $P = 1,\ P_r = 1/10$

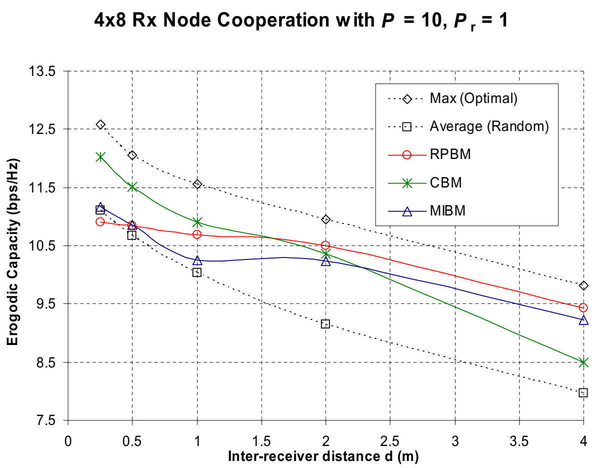

Fig. 4. Performance of node selection when $P = 10,\ P_r = 1$

power consumption P_r, we have a freedom of choice between them. As show in Fig. 2, with appropriate choice of P_r, we can obtain high increase in rate at the expense of very small increase in P_r, for instance, with an increase in P_r from 0 to 0.05, the rate increases by 2 bps/Hz when $N = 8$.

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 distance between BS-to-cluster is fixed to $d_{BS} = 100m$. That is, intra-channel gain for every node is not equal. 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. N_t is set to 4 and N_r is set to 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 $P/10$. For comparison purposes, we add the results of the random node selection algorithm denoted as Average (Random). Random selection means that the destination selects $N_t - 1$ relaying nodes randomly. 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 as d increases, 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.

VI. 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.

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