DEVICE COLLABORATION IN AD-HOC MIMO NETWORKS

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ABSTRACT

In this paper we consider methods for determining device coalitions for collaborative signal transmission, where different devices act as relay nodes to peers. The problem is to determine for R total number of users and R transmission slots the subsets of at most two devices that are allowed to transmit simultaneously. The subset selection problem is shown to be equivalent to an assignment problem. We consider both optimal assignment and greedy assignment and demonstrate the performance benefit due to device cooperation with simulations in a network model that models path loss between devices.

1. INTRODUCTION

In future networks different devices could potentially help each other in signal transmission, using each others hardware in an opportunistic way. Amplify-forward (AF) relaying is a potential candidate for such systems, since with AF, the relaying node need not know all transport parameters of the source node (as it does not decode the signal). On the other hand, AF relays are known to enhance also noise. Therefore, a randomly selected AF device can amplify noise to the extent that it has detrimental effect on network capacity.

In a practical network there are typically multiple AF-relaying devices and a limited number of orthogonal subchannels (time-frequency slots). The device population needs to be divided into subsets of active devices for each transmission subchannel. In addition, the roles (if a device acts as source or as a relay) for each device in each subset and channel use need to be determined.

Related subset selection and scheduling problems have appeared in uplink MU-MIMO [7], relay scheduling [2, 3], and in sensor networks [5]. Here, the subset selection problem considered from a MIMO relay network viewpoint, where a source and a co-channel relay jointly form a MIMO channel to a common destination node.

In the current application, we allow at most two devices to collaborate in a given channel use. We use sum-throughput (mutual information) of a MIMO relay channel as a performance measure when determining cooperative user coalitions. Unpaired devices are also allowed, if deemed beneficial. Unpaired devices transmit directly to the destination node (no relaying). A paired device transmits a part of its signal to a peer device during one channel use. In the next channel use, the paired devices transmit simultaneously to the destination node.

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2. SYSTEM MODEL

2.1. Relay model

We have a population of R devices each with one transmit antenna. Signal transmission is divided into two hops. In the first hop a source is allowed to communicate with the selected $K < R$ peers. In the second transmission hop the source and the selected peers transmit simultaneously to the destination node, which is assumed to have $N_\mathrm{r} \geq K$ receive antennas. The second hop channel is a Multiple Input Multiple Output (MIMO) channel. Formally, the signal model follows that of a MIMO relay network.

During the first hop, the source device transmits signal vector $\mathbf{x}$ with power P_1 through a $K \times K$ first hop channel $\mathbf{F}$, where K designates the number of active devices in the second hop channel. The off-diagonal terms of $\mathbf{F}$ (i.e. $|f_{k,n}|^2, n \neq k$) designate interference power due to source n at relay k input. Obviously, interference power vanishes for all relays if matrix $\mathbf{F}$ is diagonal. In this case, each device receives and retransmits a fraction $1/K$ of signal vector $\mathbf{x}$ during the second hop.

The $N_\mathrm{r} \times K$ second hop MIMO channel from the (selected) K devices to the destination is given by $\mathbf{H}$. During the second hop, each of the K devices multiply the signal with a relay-specific weighting coefficient w_k to satisfy a transmit power constraint at relay. We let

$$w_k = \sqrt{\frac{P_2/K}{\sum_{n=1}^{K} |f_{k,n}|^2 + \sigma_k^2}} \tag{1}$$

where σ_k^2 designates noise power at kth relay and P_2 is the desired sum transmit power over all K relay nodes. Note that if interference terms and noise power vanish, the relay only modifies the transmit power of the original signal. In the second hop channel, for notational simplicity, the original source device is modelled a special AF relay with zero noise and interference power at relay input.

We collect the relay weights into a diagonal matrix

$$\Lambda = \mathrm{diag}(w_1, ..., w_K).$$

The destination receives

$$\mathbf{y} = \mathbf{H}\Lambda\mathbf{F}\mathbf{x} + \mathbf{H}\Lambda\mathbf{n}_r + \mathbf{n}_d$$

where the elements of complex Gaussian vector

$$\mathbf{n}_r = (n_1, ..., n_K)^T$$

designate noise with variance σ_k^2 at k'th relay node, and elements of

$$\mathbf{n}_d = (n_1, ..., n_{N_\mathrm{r}})^T$$

designate complex Gaussian noise in each destination antenna. We assume that noise power is identical in each receiver antenna, i.e each has variance σ_d^2. The mutual information with i.i.d. Gaussian sources (in terms of bits-per-channel-use (bpcu)) for the considered signal model is [6]

$$\alpha = \frac{1}{2}\log_2 \det(\mathbf{I} + \mathbf{H}\Lambda\mathbf{F}\mathbf{F}^\dagger\Lambda^\dagger\mathbf{H}^\dagger\mathbf{C}_{nn}^{-1}), \tag{2}$$

where the noise correlation matrix is

$$\mathbf{C}_{nn} = (\sigma_d^2\mathbf{I} + \mathbf{H}\Lambda\mathrm{diag}(\sigma_1^2, ..., \sigma_K^2)\Lambda^\dagger\mathbf{H}^\dagger).$$

Factor $1/2$ in model (2) is due to two-hop relaying.

2.2. Subset selection

We consider a special case of the subset selection problem to reduce computational burden of the optimization algorithm. Instead of allowing arbitrary-sized subsets, we determine identities of only $K \leq 2$ second-hop devices for each channel use. We assume that each of the R devices is a source in exactly one of R channel uses. Assuming that $N_\mathrm{r} = 2$, each second hop MIMO channel supports $K \leq 2$ simultaneously transmitting devices. Moreover, each of the devices acts as a relay exactly once in the R channel uses, to incorporate a notion of fairness to relay selection. That is, we determine for R sources and R transmission slots the distinct ordered subsets of at most two devices. We first describe the optimal (in system throughput sense) algorithm used for subset selection and then summarize the reference cases, greedy subset selection and random subset selection.

Since, $K \leq 2$, we need to compute the mutual information α_{r_1,r_2} when device $r_1 \in \{1, ..., R\}$ is the source device and device $r_2 \in \{1, ..., R\}$ is the relay device. In general, $\alpha_{r_1,r_2} \neq \alpha_{r_2,r_1}$ since $\mathbf{F}$,$\mathbf{H}$ and Λ matrices also depend on these indices (omitted to simplify notation). When $r_1 = r_2$ ($K = 1$), the source transmits directly to destination with double power.

Optimal selection: Consider the selection of devices over R channel uses (via the following linear programming problem ([4]):

$$\arg\max_{(z_{r_1,r_2})} \sum_{r_2}^{R}\sum_{r_1}^{R} \alpha_{r_1,r_2} z_{r_1,r_2} \tag{3}$$

subject to

$$\sum_{r_1=1}^{R} z_{r_1,r_2} = 1, \forall r_2 \tag{4}$$

$$\sum_{r_2} z_{r_1,r_2} = 1, \forall r_1, \tag{5}$$

$$z_{r_1,r_2} \geq 0, \forall r_1, r_2, \tag{6}$$

The variables z_{r_1,r_2}, solved from above problem, dictate which devices become active source and relay nodes in each of the R slots. The model implicitly assumes all assignments involve either direct transmission or device pairing. When considering matrix (z_{r_1,r_2}), the solution to problem (3)-(6) dictates that there is exactly one non-zero element in each row and column, thus ensuring that all nodes act as sources equal number of times. When two nodes are active, either node may take the role of a source, while the other functions as a relay node. Whenever the $z_{r_1,r_2} = 1$, and $r_1 < r_2$, r_1 acts as source and r_2 relays. This convention results from the way the indices in eq. 3 are enumerated. When $z_{r_1,r_2} = 1$, with $r_1 = r_2$, only the direct link is activated, and relaying is disabled. Recall that problem (3)-(6) and the resulting permutation matrix can be solved efficiently (with polynomial complexity) applying transportation algorithm [4].

Naturally, considerably simpler subset selection algorithms exist:

Random selection: In random subset selection, the matrix (z_{r_1,r_2}) is defined as a random permutation matrix.

Greedy selection: In the first iteration of a Greedy subset selection the column and row indices of the largest element of (α_{r_1,r_2}) determine an element of the solution matrix. Then, the elements of these rows and columns are set to zero and maximum indices are sought in the following iteration from the modified matrix. This guarantees that the indices are unique for each iteration and that after R iterations a permutation matrix emerges.

3. NUMERICAL RESULTS

We study the arising collaboration patterns in a simple two-dimensional network. The R devices are placed randomly (uniformly) on a 20×20 rectangular area (meter units) with lower-left corner at coordinate $(0, 25)$. The destination position is $(30, 50)$. We assume $K = 2, N_\mathrm{r} = 2$, so that only

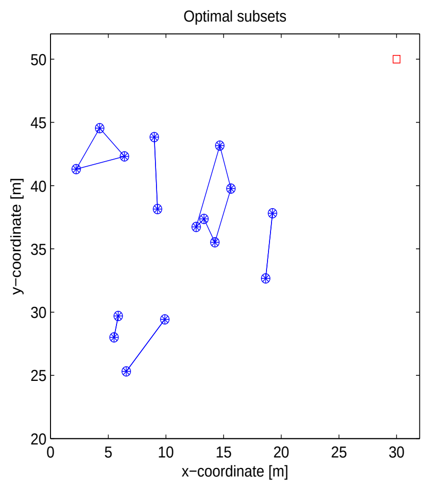

Fig. 1. Example of device collaboration patterns for *optimal subset selection* with $R = 16$. Destination is located on top-right corner, marked with character '□'. Collaboration patterns include 4 cycles of length 2, 1 cycle of length 3, and one cycle of length 5.

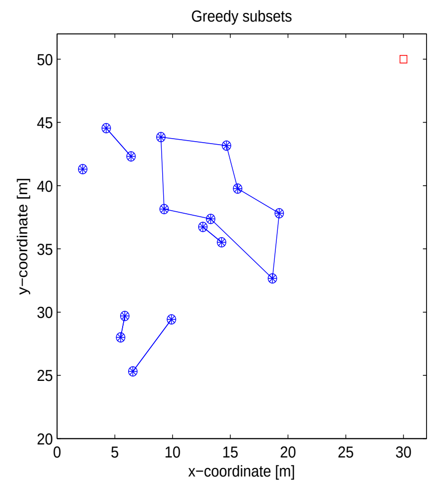

Fig. 2. Example of device collaboration patterns for *greedy subset selection* with $R = 16$. Destination is located on top-right corner, marked with character '□'. Collaboration patterns include 1 cycle of length 1 (no relaying), 4 cycles of length 2, and 1 cycle of length 7.

device pairing or direct transmission is allowed. The 2×2 network matrices $\mathbf{F}$ and $\mathbf{H}$ are computed using a simple path-loss model as follows: the distance between nodes r_1 and r_2 is d_{r_1,r_2} meters and the first-hop link matrix is set to

$$\mathbf{F} = \mathrm{diag}(1, \sqrt{P}_1/d_{r_1,r_2}^{2.3/2})$$

when devices r_1 and r_2, $r_1 \neq r_2$ are paired. The transmit power $P_1 = 27$ dB. For direct transmission ($r_1 = r_2$) the path-loss model is obviously neither applicable or relevant due to the weighting method given in eq. 1. Thus, to model direct transmission in the relay framework, we set $\mathbf{F} = \mathrm{diag}(1, 1)$.

Due to applied weighting, the total second-hop transmit power is identical for direct and paired transmission. The second-hop matrix is of form

$$\mathbf{H} = \mathrm{diag}(\sqrt{P}_2/d_{r_1,d}^{2.3/2}, \sqrt{P}_2/d_{r_2,d}^{2.3/2})\tilde{\mathbf{H}},$$

where $d_{r_1,d}$ and $d_{r_2,d}$ is the distance device r_1 and r_2 and the destination node, respectively, and P_2 is the transmit power on second hop. We set $P_2 = 31.7$ dB. Matrix $\tilde{\mathbf{H}}$ is an i.i.d. complex Gaussian-distributed MIMO matrix, where each element has unit power.

3.1. Collaboration patterns

The optimization schemes in previous section each determine a permutation of matrix of dimension R. The non-zero value on the rth row of the permutation matrix is mapped to element $\sigma(r)$, i.e. $z_{r,\sigma(r)} = 1$ in terms of notation in section 2.2. We say that devices $(r, \sigma(r))$ form a collaboration pair. The permutation matrices arising from optimal, greedy or random subset selection can each be mapped to a permutation σ of R elements of the form

$$\sigma : \begin{pmatrix} 1 & 2 & \cdots & R \\ \sigma(1) & \sigma(2) & \cdots & \sigma(R) \end{pmatrix}. \quad (7)$$

If $r = \sigma(r)$, device r is unpaired. The unpaired devices correspond to the fixed elements of the permutation. In our relay model, this corresponds to the case, where a device transmits directly to the destination node.

If two devices, say r_1 and r_2, use each other as their respective relays, these devices form a pair (r_1, r_2). If in addition, r_2 uses r_1 as a relay, the corresponding permutation includes columns (7) $(r_1, r_2 = \sigma(r_1))^T$ and $(r_2, r_1 = \sigma(r_2))^T$.

In terms of [1, 7], unpaired devices correspond to cycles of length 1, while paired users that use each other as relays correspond to cycles of length 2. Naturally, an arbitrary permutation σ, e.g.

$$\sigma : \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 5 & 2 & 3 & 1 & 4 \end{pmatrix}$$

can have longer cycles. Above we have a cycle $(1, 5, 4)$ of length 3. In the relay model, device 1 uses devices 5 as relay in the first channel use, device 2 is unpaired in the second channel use, and so on. The collaboration pattern is thus $\{(1,5)(2,2)(3,3)(4,1)(5,4)\}$ in 5 channel uses, and it includes two unpaired users.

We first illustrate the emerging cooperation patterns using one realization of device locations and channels. In Fig. 1 the optimal device collaboration patterns for each transmission slot are computed by solving problem (3)-(6). In Fig. 2 the same is done for greedy heuristics. In both figures, the destination receiver is located on top-right corner with character '□'. In the two figures a line is drawn between two devices cooperative devices. For cycles of length 2, the two devices act as source and relay nodes for each other in alternate channel uses. For cycles with length 3 or higher, a device acts as source and relay for two different devices in separate channel uses. For example, in Fig. 1 a cycle of length 3 appears in top-left corner. It takes three channel uses to serve all three devices.

3.2. Performance

Fig. 3 depicts the ergodic performance (average mutual information) for four different subset selection schemes (optimal, greedy, random, direct/no pairing) with $R \in \{2, 4, 8, 12, 16\}$ single-antenna devices and one dual-antenna destination node. The results are averaged for each R over 1000 device locations each with independently generated MIMO channel. For optimal subset selection, the device collaboration patterns for each are computed from problem (3)-(6) and related mutual information is recorded. The mutual information arising from optimal subsets are shown in figures with legend 'Optimal'. For comparison, we also depict the performance with random subsets - these results are associated with legend 'Random'. The following observations are in order:

- Channel-aware subset selection provides a substantial capacity gain over both direct transmission and random device pairing, thanks to its ability to select network-optimal MIMO relays for the second-hop channel.
- The gain due to optimal subset increases with increasing number of devices. This is in part due to the fact that network is denser and cooperation occurs with devices that are closer.

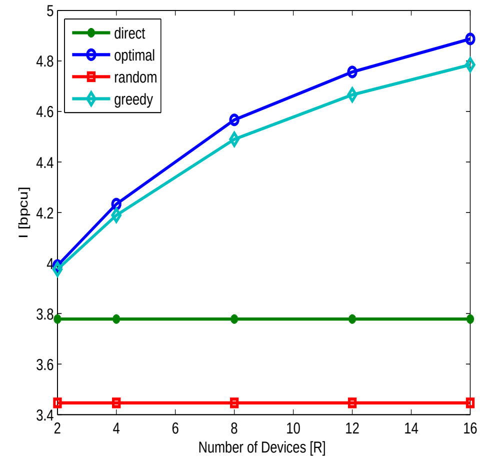

Fig. 3. Average mutual information (I) at destination node with different number of devices (R) and different pairing schemes. Direct transmission is depicted as reference.

4. CONCLUSIONS

We have considered device cooperation as means to form relay-based MIMO uplink. In the considered scheme optimal device collaboration patters (device subsets) are computed (up to pairs) using optimal and greedy matching algorithms. The subset selection algorithms determine which of the R devices should be paired and which should transmit directly to the destination in R channel uses. We demonstrated the performance gain (in terms sum mutual information) with simulations. It is observed that the device subsets have cyclic structure. If the cycle length is three, three devices need to form a coalition when forming source-relay pairs. A topic for future work is to consider subset selection from the point of view of cooperative game theory.

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