Opportunistic Relay Selection Based on Interference Nulling in the $K \times N \times K$ Channel With Interfering Relays

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I. Introduction

Recent and emerging work has studied K-user two-hop relay-aided interference channels, consisting of K source-destination (S–D) pairs and N helping relay nodes located in the path between S–D pairs, termed the $K \times N \times K$ channel. Several achievability schemes (e.g., [1]) have been known for the network, but a detailed understanding is still in progress. In [1], however, the system model under consideration assumes that there is no interfering signal between relays and the relays are full-duplex.

In this extended abstract, we study the $K \times N \times K$ channel with interfering relays and introduce an *opportunistic relay selection based on interference nulling (ORS-IN) protocol* that achieves full degrees-of-freedom (DoF) with comparatively easy implementation under the channel model. This work thus focues on the $K \times N \times K$ channel with one additional assumption that N half-duplex relays interfere with each other, which is a more feasible scenario. The scheme adopts the notion of multiuser diversity gain for performing interference management over two hops. In our scheme, the scheduling strategy is presented in time-division duplexing two-hop environments with time-invariant channel coefficients, where a subset of relays is opportunistically selected in terms of producing the minimum total interference level. To improve spectral efficiency, the alternate relaying protocol in [2] is employed with a modification. As our main result, it turns out that in a high signal-to-noise ratio (SNR) regime, the ORS-IN protocol with alternate half-duplex relaying still achieves the min-cut upper bound of K DoF even in the presence of inter-relay interference, provided a certain relay scaling condition is satisfied. Numerical evaluation also indicates that the ORS-IN scheme has higher sum-rates than those of the other relay selection methods at finite SNR regimes. Detailed descriptions are omitted due to the space limitation of this extended abstract.

II. System and Channel Models

Suppose that each source transmits its own message to the corresponding destination only through one of N relays, and thus there is no direct path between an S–D pair. Each relay node is assumed to fully decode, re-encode, and retransmit the source message i.e., decode-and-forward protocol is taken into account. Unlike the work in [1], N relays are assumed to interfere with each other. With alternate relaying, each selected relay node toggles between the transmit and listen modes for alternate time slots of message transmission of the sources.

Now, let us turn to channel modeling. Let $\mathcal{S}_k$, $\mathcal{D}_k$, and $\mathcal{R}_i$ denote the k-th source, the corresponding destination, and the i-th relay node, respectively, where $k \in \{1, \cdots, K\}$ and $i \in \{1, \cdots, N\}$. All the channels are assumed to be Rayleigh, having zero-mean and unit variance, and to be independent across different i, k, n, and hop index.

III. Achievability Result

A. ORS-IN in the $K \times N \times K$ Channel With Interfering Relays

We introduce an ORS-IN protocol, where $2K$ relay nodes among N candidates are opportunistically selected for data forwarding in the sense of having a sufficiently small amount of interference level.

Suppose that $\pi_1(k)$ and $\pi_2(k)$ denote the indices of two relays communicating with the kth S–D pair for $k \in \{1, \cdots, K\}$. In this case, the specific steps of each node during one block are described as follows:

- Time slot 1: Sources transmit their first encoded symbols. A set of K selected relay nodes, $\mathbf{\Pi}_1 = \{\pi_1(1), \cdots, \pi_1(K)\}$, operating in receive mode at each odd time slot, listens to the symbols. Other $N-K$ relay nodes and destinations remain idle.
- Time slot 2: The K sources transmit their second encoded symbols. The K relays in the set $\mathbf{\Pi}_1$ forward their first re-encoded symbols to the corresponding K destinations. Another set of K selected relay nodes, $\mathbf{\Pi}_2 = \{\pi_2(1), \cdots, \pi_2(K)\}$, operating in receive mode at each even time slot, listens to and decodes the second symbols while being interfered with by $\mathcal{R}_{\pi_1(1)}, \cdots, \mathcal{R}_{\pi_1(K)}$. The K destinations receive from $\mathcal{R}_{\pi_1(1)}, \cdots, \mathcal{R}_{\pi_1(K)}$ and decode the first symbols. The remaining $N-2K$ relays keep idle.
- Time slot 3: The K sources transmit their third encoded symbols. The K relays $\pi_2(1), \cdots, \pi_2(K)$ forward their re-encoded symbols to the corresponding K destinations. Another K relays in $\mathbf{\Pi}_1$ receive and decode the third symbols while being interfered with by $\mathcal{R}_{\pi_2(1)}, \cdots, \mathcal{R}_{\pi_2(K)}$. The K destinations receive from $\mathcal{R}_{\pi_2(1)}, \cdots, \mathcal{R}_{\pi_2(K)}$ and decode the second symbols. The remaining $N-2K$ relays keep idle.
- The processes in time slots 2 and 3 are repeated.

Now, let us describe how to choose two types of relay sets, $\mathbf{\Pi_1}$ and $\mathbf{\Pi_2}$ among N relay nodes.

1) Step 1 (The First Relay Set Selection): Let us first focus on selecting the set $\mathbf{\Pi_1} = \{\pi_1(1), \cdots, \pi_1(K)\}$, operating in receive and transmit modes in odd and even time slots, respectively. When $\mathcal{R}_i$ is assumed to serve the kth S–D pair $(\mathcal{S}_k, \mathcal{D}_k)$, it computes the scheduling metric $\tilde{L}_{i,k}$, defined as (i) the sum of interference power received at $\mathcal{R}_i$ for the first hop plus (ii) the sum of interference power generating at $\mathcal{R}_i$ for the second hop.

According to the computed metrics $\tilde{L}_{i,k}$, a timer-based method is used for relay selection. At the beginning of every scheduling period, the relay $\mathcal{R}_i$ computes the set of K scheduling metrics, $\{\tilde{L}_{i,1}, \cdots, \tilde{L}_{i,K}\}$, and then starts its own timer with K initial values, which are proportional to the K metrics. Thus, there exist NK metrics over the whole relay nodes, and we need to compare them so as to determine who will be selected. The timer of the relay $\mathcal{R}_{\pi_1(\hat{k})}$ with the least one $\tilde{L}_{\pi_1(\hat{k}),\hat{k}}$ among NK metrics will expire first, where $\pi_1(\hat{k}) \in \{1, \cdots, N\}$ and $\hat{k} \in \{1, \cdots, K\}$. The relay then transmits a short duration RTS (Request to Send) message, signaling its presence, to the other $N-1$ relays. Thereafter, the relay $\mathcal{R}_{\pi_1(\hat{k})}$ is first selected to forward the $\hat{k}$th S–D pair's packet. All the other relays are in listen mode while waiting for their timer to be set to zero (i.e., to expire). At the stage of deciding who will send the second RTS message, it is assumed that the other relays are not allowed to communicate with the $\hat{k}$th S–D pair, and thus the associated metrics $\{\tilde{L}_{1,\hat{k}}, \cdots, \tilde{L}_{\pi_1(\hat{k})-1,\hat{k}}, \tilde{L}_{\pi_1(\hat{k})+1,\hat{k}}, \cdots, \tilde{L}_{N,\hat{k}}\}$ are discarded with respect to timer operation. When such K RTS messages are sent out in consecutive order, $\mathbf{\Pi_1} = \{\mathcal{R}_{\pi_1(1)}, \cdots, \mathcal{R}_{\pi_1(K)}\}$ is chosen, the timer-based algorithm for the first relay set selection terminates.

2) Step 2 (The Second Relay Set Selection): Now let us turn to choosing the set of K relay nodes (among $N-K$ candidates), $\mathbf{\Pi_2} = \{\pi_2(1), \cdots, \pi_2(K)\}$, operating in receive and transmit modes in even and odd time slots, respectively. Using K RTS messages broadcasted from the K relay nodes in the set $\mathbf{\Pi_1}$, it is possible for relay node $\mathcal{R}_i \in \{1, \cdots, N\} \setminus \mathbf{\Pi_1}$ to compute the sum of inter-relay interference power generated from the relays in $\mathbf{\Pi_1}$. When $\mathcal{R}_i$ is again assumed to serve the kth S–D pair $(\mathcal{S}_k, \mathcal{D}_k)$, it computes the metric $L_{i,k}$, termed *total interference level*, defined as (i) $\tilde{L}_{i,k}$ (used in Step 1) plus (ii) the sum of inter-relay interference power.

According to the computed metric $L_{i,k}$, we also apply the timer-based method used in Step 1 for the second relay set selection. The relay $\mathcal{R}_i \in \{1, \cdots, N\} \setminus \mathbf{\Pi_1}$ computes the set of K interference levels, $\{L_{i,1}, \cdots, L_{i,K}\}$, and then starts its timer with K initial values, proportional to the K interference levels. Thus, we need to compare $(N-K)K$ metrics over the relay nodes in the set $\{1, \cdots, N\} \setminus \mathbf{\Pi_1}$ in order to determine who will be selected as the second relay set. The rest of the relay set selection protocol (i.e., RTS message exchange among relay nodes) almost follows the same line as that of Step 1. The timer-based algorithm for the second relay set selection terminates when K RTS messages are sent out in consecutive order. Then, K relay nodes having a sufficiently small amount of $L_{i,k}$ are selected as the second relay set $\mathbf{\Pi_2}$.

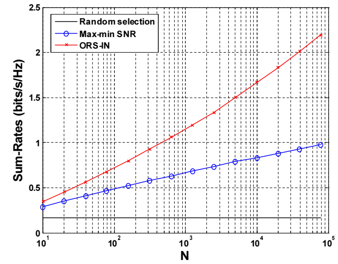

Fig. 1. The sum-rates versus N when $K = 3$, SNR $=$ 20dB, and $\text{INR}_\text{R} =$ 30dB.

B. The Analysis of Achievable DoF

Using the scaling argument bridging between the number of relays, N, and the received SNR [3], we analyze the achievable DoF of the $K \times N \times K$ channel with interfering relays and the minimum N required to guarantee the achievability result.

Theorem 1: Suppose that the ORS-IN scheme with alternate relaying is used for the $K \times N \times K$ channel with interfering relays. Then, the total DoF are bounded by K if N scales faster than SNR^{3K-2} and the number of transmission symbols in one block is sufficiently large.

IV. Numerical Evaluation

For comparison, two baseline relay selection schemes are shown: 1) a random relay selection scheme and 2) a max-min SNR scheme that is well-suited for relay-aided systems if interfering links are absent. Alternate relaying is also used for each of the compared schemes. Figure 1 illustrates the achievable sum-rates versus N when $K = 3$, SNR $=$ 20dB, and $\text{INR}_\text{R} =$ 30dB, where INR_R denotes the inter-relay interference-to-noise ratio (INR). For the max-min SNR scheme, the desired channel gain grows as N increases while the interference level remains the same. In consequence, it is seen that the rate of increase in the sum-rates of the ORS-IN scheme with respect to N is much higher than that of the max-min SNR scheme.

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