Selection Cooperation in Multi-Source Cooperative Networks

Elzbieta Beres and Raviraj Adve

***Abstract*— In a cooperative network with multiple potential relays and multiple simultaneous transmissions, we present selection cooperation wherein each source pairs with a single "best" relay. We analyze the outage probability of a simple and completely distributed selection scheme, requiring some feedback but no centralization, and show that it outperforms distributed space-time codes for networks with more than three relaying nodes. These gains are due to the more efficient use of power in networks using selection. We suggest two other more complex selection schemes based on increasing system intelligence and centralization, and show that for smaller network sizes their performance improvement over the simple selection scheme is not significant.**

***Index Terms*— Cooperative diversity, decode-and-forward, distributed space-time codes, outage probability, selection, user cooperation.**

I. Introduction

IN distributed wireless systems, cooperative diversity and relaying can harness the advantages of multiple-input multiple-output (MIMO) systems without requiring multiple antennas at each receiver and transmitter. For practical networks this is motivated by the need for simple, inexpensive nodes with limited processing power and a single receive antenna. Additional antennas, if available, can be used to provide further performance gains. The system under consideration here is a static mesh network of access points. Such networks are designed for high-throughput and maximum reliability, creating constraints far different from sensor or ad hoc networks. It is expected that as mesh networks mature, they will enter a period of throughput growth characterized by a scarcity of bandwidth [1].

The available research on cooperative diversity has largely focused on a coherent addition of multiple independently-faded copies of the transmitted signal. This combination can be achieved through pre-coding [2], orthogonal transmissions and a maximal-ratio-combiner (MRC) [3]–[5], a RAKE receiver for CDMA-based systems [2], [6], or through distributed space-time codes (DSTC) [7]–[9]. However, the lack of exact channel knowledge for pre-coding, a high bandwidth penalty for orthogonal transmissions (important in bandwidth-limited systems such as those considered here) and synchronization difficulties for DSTC, make these approaches impractical or difficult to implement.

In this paper, we present selection cooperation in cooperative, bandwidth-limited, wireless systems *with multiple sources*. In this scenario we analyze selection cooperation and show that in slow-fading channels and for most network sizes and rates, and with some limited overhead, selection outperforms the DSTC scheme of [9] in terms of outage probability. This advantage arises from a more efficient use of power. In DSTC-based systems, each relay must share its available power between all source nodes; in a selection cooperation system, a relay node divides its power only between the users that have chosen that node as a relay. Throughout this work we compare selection cooperation to DSTC since, with multiple simultaneous transmissions, the DSTC scheme in [9] makes far more efficient use of resources compared to the other published approaches, such as MRC based schemes.

Clearly, selection in diversity is not a new concept. It is arguably the most intuitive way of implementing diversity, and has been thoroughly analyzed in traditional MIMO systems. The novelty of this paper thus lies in the specific application of selection to cooperative diversity systems and analysis in network settings. Interestingly, in a traditional MIMO system, with m transmit antennas, selection requires $\log_2(m)$ bits of feedback while space-time coding does not require feedback. However, as we will show, in a cooperative network, DSTC requires both feedback and synchronization across geographically distributed nodes. To date, there has been little analysis of selection diversity in cooperative networks. Most of the available work focuses on network-layer issues [10]–[13]. To the best of our knowledge, the only other direct application of selection to cooperative diversity systems has been proposed in independent works by Bletsas et al. [14], [15]. The authors consider a selection scheme as an alternative to DSTC and argue for its simplicity of implementation, but consider only a *single source-destination pair*, i.e., a network with a single source with multiple potential relays. The authors assume that the simplicity of the scheme comes at the price of performance loss as compared to MRC-based schemes. As implemented, the scheme of [14] results in a non-zero probability of two relays being selected for the same source and the analysis presented focuses on quantifying this probability. In [15], on the other hand, the selection is performed in a similar manner to this paper but the analysis, apart from not considering a network setting, assumes no connection between a source and its destination. Although this assumption significantly simplifies the analysis (complicated only by the necessity of

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including the potentially strong source-destination channel), it does not provide a framework e.g., for improving reliability only as required (wherein nodes relay only when the source-destination channel is in outage [3], [16]). In our framework, one could first select a relay and then decide exactly how and when to relay, as in [16]. As compared to [14], [15], we complete the analysis for the single source-destination case, and then focus on the implementation of selection in a network setting with multiple sources.

In a distributed network with multiple simultaneous transmissions, our scheme places relay selection at the core of system design. The importance of relay selection derives from a power constraint: the power available at a relay node depends on the number of sources supported by that relay, and the relay selection for one source may impact the choice of another. A large portion of this paper is thus devoted to relay selection: we analyze three different relay selection schemes based on varying degrees of centralization and tolerance for complexity, and show that even the simplest of these schemes outperforms DSTC for most network sizes.

The available literature in partner selection schemes is more extensive [17]–[19]. Where centralized information is available, partners are selected according to average channel conditions and the possibility of a node partnering with more than one user is not considered. The authors of [17] also suggest distributed schemes where relays choose their partners based on instantaneous source-relay channels, but the crucial source-destination channels are not taken into account. Such an approach is not directly comparable to the work presented in this paper. Furthermore, to the best of our knowledge, no other work considers relay selection in a *network* setting, where a node must split its power when relaying for more than one node.

The main contributions of this paper are:

- We derive the high-SNR outage probability approximation of selection cooperation for a single source-destination pair, considering all source-relay, relay-destination, and source-destination channels.
- We consider a network scenario with multiple simultaneous transmissions, where relaying nodes may relay for more than one source node. The use of selection answers an important question - in a *network* setting, how many nodes should one cooperate with? The answer is, apparently, one (best) node.
- The development of selection in network settings with *multiple* flows, an issue largely avoided in the literature. We present three different relay selection schemes based on available centralization and complexity requirements. We show that the simplest scheme, which does not require any centralization, provides excellent performance with minimum implementation overhead and complexity.
- We analyze this simple relay selection scheme, accounting for source-destination, source-relay and relay-destination channels. We show that this scheme significantly outperforms the DSTC which, furthermore, requires synchronization.

This paper is structured as follows. Section II presents and analyzes the selection cooperation algorithm in a system with one source-destination pair. Section III, the core of this paper, extends this work to multiple transmissions, discussing three possible implementations of the scheme in a distributed network with multiple sources. Detailed derivations are deferred to appendices. Section III-D discusses implementation issues of the proposed schemes and the comparisons undertaken. Section IV concludes this work.

II. Single Source-Destination Pair

A. System Model and Selection Cooperation

To introduce selection cooperation, we first consider a single source node s communicating with a destination d with the help of $m-1$ potential relays, $r_1 \ldots r_{m-1}$. The relays satisfy a half-duplex constraint. We note that this is a stepping stone to the selection algorithms presented in Section III. The channel a_{ij} between nodes i and j is modeled as flat and slowly-fading Rayleigh with variance $1/\lambda_{i,j}$, i.e., $|a_{ij}|^2 \sim \lambda_{i,j} \exp\left[-\lambda_{i,j}\,|a_{ij}|^2\right]$. Because nodes are static, inter-node channels change very slowly. Each node has a peak energy constraint of P Joules/symbol. As in [9], we consider decode-and-forward schemes, although the results presented in the paper can be extended to an amplify-and-forward scenario [20].

This communication between the source and destination targets an end-to-end data rate of R. As in [9], due to the half-duplex constraint, communication is performed in two time slots. The source distributes its data in the first time slot, while the destination and each of the $m-1$ relays decode this information. The decoding set $\mathcal{D}(s)$ for the source is the set of relays that decoded the information correctly, i.e., a node $r_k \in \mathcal{D}(s)$ if the source-relay channel has a capacity above the required rate R:

$$\begin{aligned} &\frac{1}{2}\log\left(1+|a_{s,r_k}|^2\frac{P}{N_0}\right) \\ =\;& \frac{1}{2}\log\left(1+|a_{s,r_k}|^2\mathrm{SNR}\right) \geq R, \end{aligned} \tag{1}$$

where the factor of 1/2 models the two time slots required for relaying given the half-duplex constraint, N_0 is the noise power spectral density and SNR $= P/N_0$ is the non-faded signal-to-noise ratio at a receiving node. This approach of allowing only a subset of all nodes $m-1$ to relay is referred to in [9] as “selection relaying" and ensures full diversity order in decode-and-forward schemes. In [9] the nodes in the decoding set either each forward the source data in a round robin fashion (requiring m time slots and allowing for MRC) or use a DSTC (requiring only two time slots).

Our scheme differs from selection relaying in that only a single relay node, within $\mathcal{D}(s)$, forwards data to the destination. The destination chooses a *single* relay with the best instantaneous relay-destination channel to forward the information to the source in the second time slot. Relaying is thus performed on orthogonal channels, but, as with DSTC, because only one relay is chosen for each source, the required bandwidth is only doubled. Choosing one of $m-1$ relays requires $\log_2(m-1)$ bits of feedback from the destination.

We should note here the potential confusion between the terms “selection relaying" and “selection cooperation". In selection relaying all nodes $\mathcal{D}(s)$ forward data for the source,

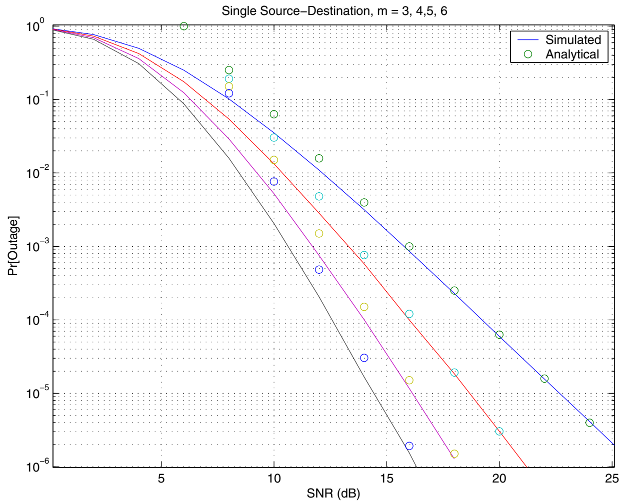

Fig. 1. Outage probability for selection cooperation with a single source-destination pair. $R = 1$ b/s/Hz, $\lambda_{i,j} = 1$, $m = 3, 4, \ldots, 6$.

while *selection cooperation restricts relaying to only one node from this decoding set.*

B. Performance Analysis and Simulation Results

The probability of outage, P_{out}, defined as the probability that the mutual information I_{sel} between source and destination falls below the required rate R, is an important characterization of any cooperation protocol. This paper generally uses outage probability as the figure of merit to compare various cooperation schemes. If node r_j is selected as the relay, the destination combines the transmissions from source and relay and this mutual information is given by

$$I_{\text{sel}} = \frac{1}{2}\log\left(1 + \text{SNR}|a_{s,d(s)}|^2 + \text{SNR}|a_{r_j,d(s)}|^2\right). \quad (2)$$

Proposition: For a single source-destination pair, with $m-1$ potential nodes, the outage probability of the selection scheme in the high-SNR regime, is

$$P_{out} = \left[(2^{2R}-1)/\text{SNR}\right]^m \lambda_{s,d} \sum_{|\mathcal{D}(s)|} \frac{1}{|\mathcal{D}(s)|+1} \times \prod_{r_i \in \mathcal{D}(s)} \lambda_{r_i,d} \prod_{r_i \notin \mathcal{D}(s)} \lambda_{s,r_i}, \quad (3)$$

where $1/\lambda_{i,j}$ is the variance of the channel between node i and j.

Proof: The proof is presented in Appendix A.

Note that, as expected, selection cooperation provides the full diversity order of m. This formulation is similar to that presented in [15], with the important difference that here, the source-destination channel is taken into account. This significantly complicates the analysis and we focus on the high-SNR. The authors of [15] neglect the source-destination channel (decreasing the diversity order by one), and present the exact outage probability.

In Fig. 1, this high-SNR approximation is verified for increasing numbers of m relays with $\lambda_{i,j} = 1$ and $R = 1$ b/s/Hz. The approximation in (3) is very good for SNR levels above 15dB.

In the following section, the central contribution of this paper, the selection scheme is implemented in a network with multiple source-destination pairs. The performance of selection cooperation is compared to the DSTC scheme of [9], chosen as one of the few efficient schemes that specifically analyzes networks with simultaneous multiple flows.

III. Network Implementation

A. System Model

In this section, we extend the concept of selection cooperation to network settings, using the notation of [9]. The network comprises a set $\mathcal{M}$ of m nodes. Each node $s \in \mathcal{M}$ has information to transmit to its own destination, $d(s) \notin \mathcal{M}$, and acts as a potential relay for other nodes in $\mathcal{M}$. While we use the notation s for a source node and r for a relay node, we emphasize that every node in $\mathcal{M}$ is a source node and is potentially also a relay node. The channel between any two nodes is assumed independent of all other channels. This model is appropriate for networks where each node may have its own destination.

Because the network comprises multiple sources, each node can potentially relay for several other nodes. This raises the question of relay selection and power allocation and motivates the various selection schemes discussed below in Section III-B. Each node has a power constraint of P Joules/symbol. In DSTC, every node expects to relay for all other $m-1$ nodes and thus uses $2P/m$ Joules/symbol per source in both phases. In our case, in the first phase, each source sends its data using full power P Joules/symbol. In the second phase, each relay divides its power evenly between the source nodes it is supporting. A relay node supporting n source nodes will thus use P/n Joules/symbol for each source. Note that a relay node does not know *a priori* how many nodes it will relay for and does not know the channel to the destination for these sources; it thus cannot pre-compute a better power distribution. Clearly with additional feedback to the relays, a better power distribution may be possible.

We consider both centralized and decentralized versions of the network. A centralized network is governed by a central unit (CU) with knowledge of all network parameters. A CU makes all assignment decisions. In the absence of a CU, the network is decentralized and decisions are made locally by the nodes, with limited information regarding the rest of the network.

B. Selection Cooperation Schemes

The concept of selection in a network is identical to that presented in Section II. In phase one, all nodes use orthogonal channels to transmit information to their respective destinations, and each node decodes the information from the other $m-1$ sources. Each node determines if it has decoded the information correctly. If node s_j has decoded the information from source s_i correctly, it declares itself as a member of the decoding set $\mathcal{D}(s_i)$ of nodes eligible to relay for node s_i. Such a decoding set, $\mathcal{D}(s_i)$, is formed for each source node $s_i \in \mathcal{M}$. In phase two, for each source s_i, a relay is chosen from its decoding set $\mathcal{D}(s_i)$, and each relay forwards the information for the source. The activity of a node s_i can thus be summarized as follows: in phase one, it transmits its information and decodes the information of the other $m-1$ nodes; in phase two, it forwards the information of those nodes *for which it was chosen as a relay.*

In this section we present three relay selection schemes based on varying degrees of centralization and tolerance for numerical complexity. While in Section II the relay was selected as the one with the best instantaneous channel to the destination, in a network setting the per-node power constraint motivates search for a more sophisticated scheme. For example, suppose two source nodes, s_1 and s_2, are assigned to the same relay r with the best instantaneous channel to both $d(s_1)$ and $d(s_2)$. The power available at node r for each source is $P/2$. However, performance could potentially be improved by assigning one of the source nodes to a different "free" relay node with available power P. The problem is thus to assign relays to source nodes to minimize some figure of merit which depends on channel conditions as well as available power at the relays. However, as we shall see, the simple assignment scheme of Section II, extended to multiple sources, remains an effective tradeoff between complexity and performance.

1) Optimal Relay Assignment: We state here the optimal relay choice in a network setting. However, this will later be shown to be too complex for practical implementation.

The mutual information between source s_i and destination d_{s_i}, if using r_j as the relay is:

$$I_{\text{sel}} = \frac{1}{2}\log\left(\begin{array}{c} 1+\text{SNR}|a_{s,d(s)}|^2 \\ +\text{SNR}|a_{r_j,d(s)}|^2 \end{array}\right). \tag{4}$$

where N_j is the number of sources that choose node r_j as their relay. One optimal approach, in max-min sense, calculates the mutual information between source and destination of all m transmissions for all possible relay assignments, and picks the relay assignment which maximizes the minimum mutual information of these m transmissions:

$$\{r(s_1),\ldots,r(s_m)\} = \arg\max_{\forall i_1\in\mathcal{D}(s_1),\ldots i_m\in\mathcal{D}(s_m)} \min\{I_{s_1d_{s_1};r_{i_1}},\ldots I_{s_md_{s_m};r_{i_m}}\}, \tag{5}$$

where, for example, $I_{s_1d_{s_1};r_{i_1}}$ denotes the mutual information between source s_1 and its destination $d(s_1)$, with node r_{i_1}, taken from $\mathcal{D}(s_1)$, used as a relay.

This optimal scheme requires a CU with global knowledge of all channels to make m^m comparisons and choose the best one in max-min sense. Hence, though optimal, this scheme is clearly impractical.

2) Sequential Relay Selection: The optimal algorithm described can be simplified considerably by performing this search sequentially for each source node in $\mathcal{M}$. Our sub-optimal algorithm thus works as follows. The relay of the first node, $r(s_1)$, is chosen from $\mathcal{D}(s_1)$, the decoding set of s_1, independently of the other sources. This relay, $r(s_1)$, is the node with the highest channel power to the destination of s_1, $d(s_1)$. For the second source node s_2, two potential relaying nodes from $\mathcal{D}(s_2)$ are picked for consideration: nodes r_j and r_k, with the best and second-best channels to the destination, respectively. If r_j is not already used as a relay for s_1, i.e., $r_j \neq r_{s_1}$, it is automatically chosen as the relay for s_2. If r_j is already relaying, however, the CU decides between r_j and r_k by considering that r_j would need to halve its power to accommodate both source nodes s_1 ands_2. The CU thus compares $I_{s_2d_{s_2};r_k}$ to $\min\{I_{s_1d_{s_1};r_j}, I_{s_2d_{s_2};r_j}\}$, where

$$I_{s_2d_{s_2};r_k} = \frac{1}{2}\log\left(\begin{array}{c} 1+\text{SNR}|a_{s_2,d(s_2)}|^2+ \\ \text{SNR}|a_{r_k,d(s_2)}|^2 \end{array}\right), \tag{6}$$

$$I_{s_1d_{s_1};r_j} = \frac{1}{2}\log\left(\begin{array}{c} 1+\text{SNR}|a_{s_1,d(s_1)}|^2+ \\ \frac{\text{SNR}}{2}|a_{r_j,d(s_1)}|^2 \end{array}\right), \tag{7}$$

$$I_{s_2d_{s_2};r_j} = \frac{1}{2}\log\left(\begin{array}{c} 1+\text{SNR}|a_{s_2,d(s_2)}|^2+ \\ \frac{\text{SNR}}{2}|a_{r_j,d(s_2)}|^2 \end{array}\right). \tag{8}$$

If $I_{s_2d_{s_2};r_k}$ is the larger value, r_k is chosen as the relay for s_2; otherwise, r_j is chosen.

This process repeats until each source has been assigned a relay, with potentially one more relay added to the comparison for each source node considered. For each source node s_i, the CU begins with the relay r_j with the best channel to $d(s_i)$. If that relay is free, it is automatically assigned to s_i. Otherwise, the CU calculates the mutual information for s_i and for all N_j source nodes already supported by r_j, using $P/(N_j+1)$ as the available relay power. The minimum of all the N_j+1 values of mutual information is associated with relaying node r_j. The CU repeats this process for the relay with the next best channel, until it finds a relay that is not claimed by any source node. It then assigns the source s_i to the relay node with the highest relay-destination mutual information.

The iterative scheme is significantly simpler than the exhaustive search of the optimum scheme, but is yet of $O(m!)$ complexity. Also, like the optimum scheme, it requires a centralized node with knowledge of all inter-node channels. Therefore, while more efficient than the optimum scheme, this scheme is also likely to be impractical.

3) Distributed Relay Assignment: The simple selection scheme extends the selection approach in Section II to the network setting considered here. The destination of s_i, $d(s_i)$ picks as its relay the node with the highest instantaneous relay-destination channel power, $r(s_i)$:

$$r(s_i) = \arg\max_{r_k\in\mathcal{D}(s_i)}\{|a_{r_k}|^2\}; \quad k=1\ldots|\mathcal{D}(s_i)|, \tag{9}$$

i.e., each relay is picked independent of the other source-destination pairs. The only penalty is that a node relaying for N_j sources uses power P/N_j for each forwarding link. As the numerical results given below show, this scheme is extremely effective, achieving near optimum performance for small network sizes. The rest of this section is largely focused on this scheme.

This simple scheme is of $O(m^2)$ complexity in the worst case, where each of the m destinations must make $m-1$ comparisons to find a maximum out of (at most) $m-1$ channels. The scheme can also be implemented in fully decentralized manner, as each destination picks its relay independently of all other nodes.

Analytical results for the optimal and sub-optimal selection schemes are difficult to obtain. Fig. 2 compares the outage probability of all three selection schemes via simulation. Not surprisingly, performance improves with increasing system intelligence. Finally, the difference in performance between the three schemes also increases with increasing network sizes. This is to be expected, since with more nodes there is a

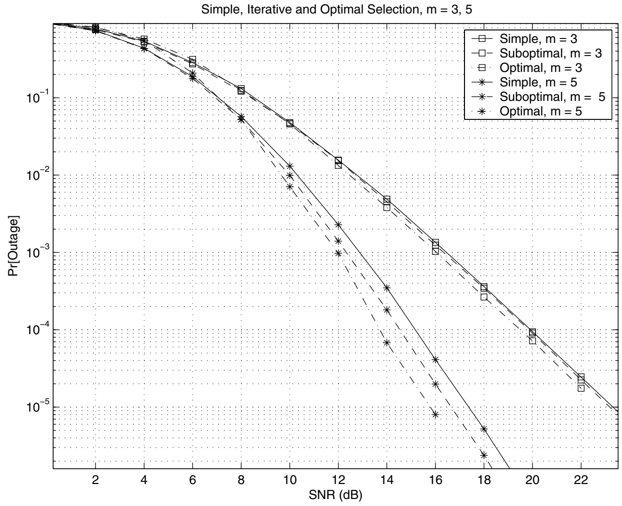

Fig. 2. Outage probabilities of simple, sub-optimal and optimal selection $R = 1$ b/s/Hz, $\lambda_{i,j} = 1$, $m = 3, 5$.

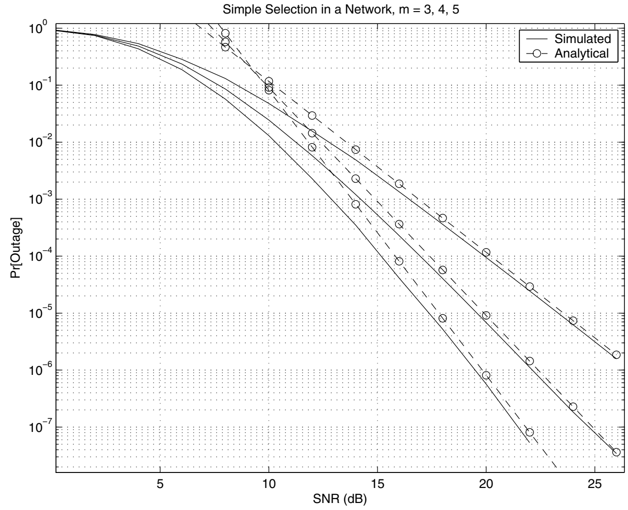

Fig. 3. Simple selection cooperation in a network. $R = 1$ b/s/Hz, $\lambda_{i,j} = 1$, $m = 3, 4, 5$.

higher potential for power splitting, and the optimal and sub-optimal approaches reduce this problem. Note, however, that even for a network size of $m = 5$, the performance loss of the simplest scheme is not very large. This is clarified by (22) in the appendix, the probability that a relay will be chosen by n nodes other than the source node for which it was already chosen. The probabilities of $n = 0$ or 1 (the relay relaying for one and two nodes) is similar and significant, but falls off quickly with increasing n. Most of the time, therefore, a relay will transmit either with full power, or half its power. The power-splitting problem of simple selection is thus not very significant, and the performance of the simple scheme closely tracks that of the optimal scheme. Given the complexity of the selection process, it proves impossible to simulate larger network sizes for the optimal and iterative schemes. Our conclusion is that the simple selection scheme is a very good and practical choice and the rest of this paper focuses on this scheme.

C. Performance Analysis

1) Outage Probability: This section presents the analytical and simulated outage probability for the simple selection scheme described above, including a comparison to the outage probability of the DSTC protocol of [9]. The details of the derivations are deferred to the appendix.

The outage probability is evaluated for a particular source-destination pair, $s_j - d(s_j)$, with arbitrary average channels both between the destination and all other relay nodes, i.e., $r_i - d(s_j)$, $r_i, s_j \in \mathcal{M}$, as well as between all the relay nodes themselves, i.e., $r_i - r_k$, $r_i, r_k \in \mathcal{M}$. To simplify the analysis, we assume equal average channels between all other destinations and relay nodes, i.e., $r_i - d(s_k,)$ $r_i, s_k \in \mathcal{M}$, $r_i, s_k \neq r_j$. (Recall that denoting a node s or r is done purely to highlight its purpose in the second phase, but that in fact $r_k = s_k, \forall s_k, r_k \in \mathcal{M}$. Furthermore, by definition, the destination nodes are not in the set $\mathcal{M}$; thus $r_k \neq d(s_i), \forall r_k, s_i \in \mathcal{M}$).

Proposition: In this scenario, the high-SNR outage probability for a specific source-destination pair using simple selection is

$$\Pr[I_{\text{simple-sel}} < R] = \left[\frac{2^{2R}-1}{\text{SNR}}\right]^m \lambda_{s,d} \sum_{|\mathcal{D}(s)|} \frac{1}{|\mathcal{D}(s)|+1} \times \prod_{r_i \in \mathcal{D}(s)} \lambda_{r_i,d} \prod_{r_i \notin \mathcal{D}(s)} \lambda_{s,r_i} \sum_{n=0}^{m-2} K_m (n+1)^{|\mathcal{D}(s)|}, \quad (10)$$

where

$$K_m = \binom{m-2}{n} \left[\frac{1}{m-2}\right]^n \left[\frac{m-3}{m-2}\right]^{m-2-n}. \quad (11)$$

Proof: See Appendix B.

Following the approach in [9], we bound (10) to eliminate its dependence on the average channels, $\lambda_{i,j}$. See (12) at the top of the next page, where $\underline{\lambda_r} = \min\{\lambda_{r,d(s)}, \lambda_{s,r}\}$, $\overline{\lambda_r} = \max\{\lambda_{r,d(s)}, \lambda_{s,r}\}$, and $\underline{\lambda}$ is the geometric mean of all the $\underline{\lambda_r}$ and $\lambda_{s,d(s)}$, and $\overline{\lambda}$ is the geometric mean of all the $\overline{\lambda_r}$ and $\lambda_{s,d(s)}$. As discussed in the appendix, the upper bound assumes that the relay chosen in the communication between a source and its destination is in the decoding set of all other source nodes. This is a worst-case assumption, since ideally this relay would not be available to relay for other nodes. Clearly, from (12), selection cooperation scheme achieves full diversity order of m for each source-destination pair.

The high SNR approximation in (10) is verified in Fig. 3, which compares the analytical and simulated results for the simple selection scheme. The analytical results are obtained by calculating (10) for increasing network sizes with equal average channels with $\lambda = 1$ and $R = 1$ b/s/Hz. The approximation appears valid at SNR levels above 12dB.

An analytical comparison of the DSTC and simple selection scheme is complicated by the difficulty in writing (10) with m sources in closed-form. The comparisons are thus presented numerically in Figs. 4 and 5, in both cases for channels with $\lambda = 1$. Fig. 4 demonstrates the outage probability of both schemes for $R = 1$ b/s/Hz by calculating (10) and

$$\left[\frac{2^{2R}-1}{\mathrm{SNR}/\underline{\lambda}}\right]^m \sum_{|\mathcal{D}(s)|} \frac{1}{|\mathcal{D}(s)|+1} \sum_{n=0}^{m-2} K_m(n+1)^{|\mathcal{D}(s)|} \leq \Pr[I_{\text{simple-sel}} < R] \leq \left[\frac{2^{2R}-1}{\mathrm{SNR}\ /\overline{\lambda}}\right]^m \sum_{|\mathcal{D}(s)|} \frac{1}{|\mathcal{D}(s)|+1} \sum_{n=0}^{m-2} K_m(n+1)^{|\mathcal{D}(s)|} \quad (12)$$

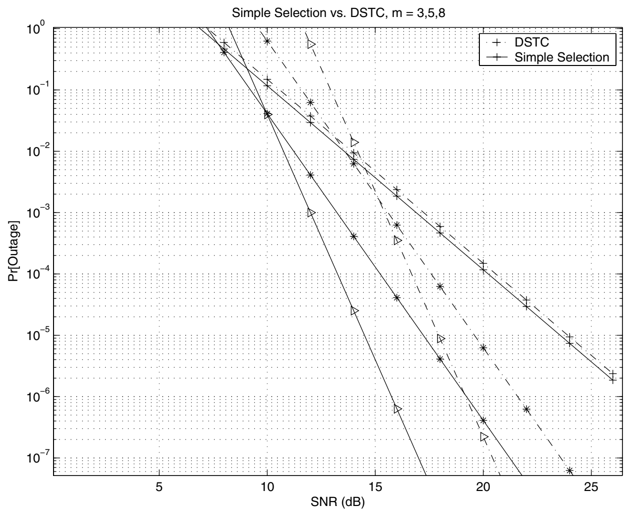

Fig. 4. Outage probabilities of DSTC of [9] and simple selection combining. $R = 1$ b/s/Hz, $\lambda_{i,j} = 1$, $m = 3, 5, 8$.

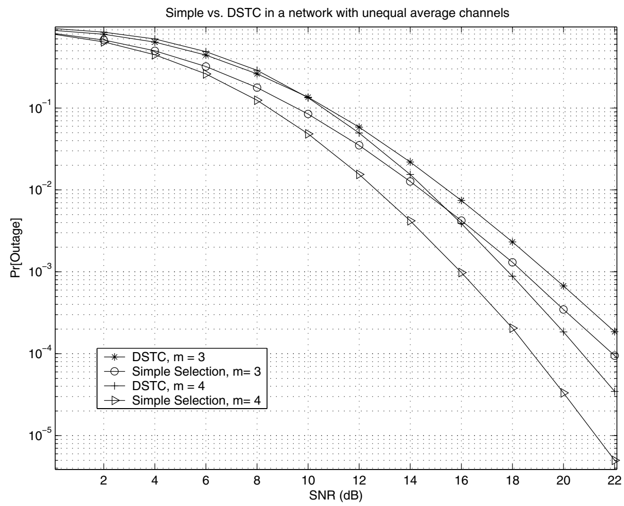

Fig. 6. Outage probabilities of DSTC of [9] and simple selection with unequal average channels and $R = 1$ b/s/Hz, $m = 3, 4$.

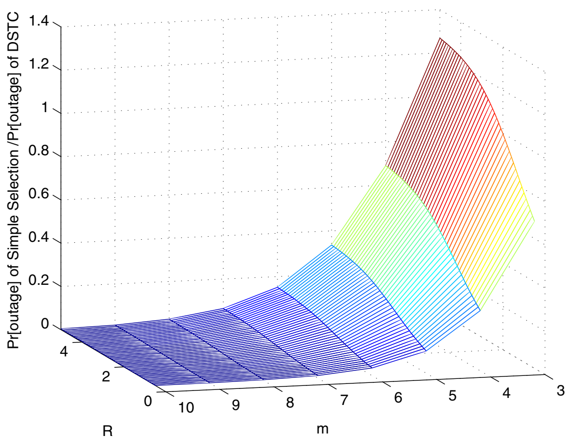

Fig. 5. Ratio of selection outage probability to DSTC outage probability for $R = 1 - 5$ and $m = 3, 4, ..., 10$.

comparing to the outage of DSTC. Note that even the simple scheme always outperforms the DSTC scheme, and that the improvement increases for increasing m. This is due to the increasingly efficient use of power as m increases.

However, due to the coding at the relays, the outage of DSTC is a decreasing function of R [9], and it is not clear how the scheme compares to selection for different rates and network sizes. We thus compute the ratio (independent of SNR) of the outage probability using selection and using DSTC for various R and m, and present the results in Fig. 5. Clearly, selection cooperation outperforms DSTC when this ratio is less than one, as is the case for all shown values of R when $m > 3$. DSTC, on the other hand, perform better for the small network size of $m = 3$ when $R > 2$. We note that the entire function falls sharply with increasing m, while for for larger values of m the dependence on R is negligible.

Equation (10) is valid when the channels between all destinations other than the one being analyzed and the relay nodes are equally strong on average. Clearly, this is not the case in practical systems, where channel power is attenuated by distance and affected by shadowing. Although analytical results for such a case and general network sizes are difficult to obtain for the simple selection cooperation scheme, Fig. 6 presents the results of simulations that compare the simple selection scheme to the DSTC in this scenario.

In this simulation, the average channel power, $E\left\{|a_{ij}|^2\right\}$, is itself an exponential random variable with parameter $\lambda = e^z$, where z is a zero mean normally distributed random variable with unit variance. The simulations demonstrate the improvement in performance of simple selection cooperation over DSTC. Although compared to the equal average channel gain scenario presented in Fig. 4 both selection and DSTC exhibit worse performance, the gap between the two schemes increases. This suggesting that DSTC is more sensitive to scenarios with asymmetrical average channel gains, an unsurprising observation given that space-time codes are designed for and performs best when all channels are independent and have equal average power. Selection, on the other hand, does not inherently have this built-in condition; the performance loss as compared to equal channel gain situation is due only to an uneven distribution of power in a network scenario. It is thus expected that this loss would be smaller than that obtained by DSTC.

2) Diversity Multiplexing Trade-off: The discussion so far has dealt with outage probability exclusively. In this section we compare the diversity multiplexing trade-off curves of selection cooperation and DSTC. Using the standard definitions of diversity order Δ and normalized rate R_{norm} [21], this trade-off can easily be derived from (12) as

$$\Delta_{simple-sel} R_{\text{norm}} = m(1 - 2R_{\text{norm}}). \tag{13}$$

In [9], the authors determine the lower and upper bounds for the trade-off as

$$m(1 - 2R_{\text{norm}}) \le \Delta_{DSTC} R_{\text{norm}} \le m(1 - \left[\tfrac{m-1}{m}\right] 2R_{\text{norm}}). \tag{14}$$

The selection diversity-multiplexing trade-off is thus exactly the lower bound of the DSTC trade-off. This difference comes from the coding at the relays: because in selection the data is simply repeated by the relay, the corresponding mutual information is a logarithmic function of the sum of the source-destination and relay-destination channels. For DSTC, the lower bound is achieved in this manner. If the relays use an independent codebook the upper bound is achieved. In this paper we do not explore the use of independent codebooks at the relay in the context of selection. For increasing network sizes m, however, the upper and lower bound converge, as does the performance of selection cooperation and DSTC. Furthermore, the flat curves as a function of R for higher m in Fig. 5 suggests that DSTC reach only the lower bound of the trade-off curve for higher m, and the performance difference between the two schemes is dominated by the SNR-gain of their outage probabilities.

D. Overhead and System Requirements

Due to the geographical distribution of nodes, any cooperative transmission scheme suffers some overhead. In this section, we discuss the overhead, centralization and complexity requirements of selection cooperation.

After the first time slot, each of the m relays attempts to decode $m-1$ messages. For each message, the relay must indicate its success or failure with one bit, resulting in a total of $m(m-1)$ feed-forward bits. For each source, the destination (or the CU) must select one of the $m-1$ relays using $\log(m-1)$ feedback bits, resulting in a total of $m\log(m-1)$ feedback bits. The overhead is thus $m\left[\log(m-1) + (m-1)\right]$ bits per network, and $\left[\log(m-1) + (m-1)\right]$ bits per source-destination pair.

The simple selection scheme is fully decentralized (i.e. the destination only needs to know the channels from its relays) and thus the above calculated overhead is sufficient to implement this scheme. The transmission of the overhead bits must occur on orthogonal channels, decreasing the available bandwidth for the transmission and affecting system performance. We assume, however, that cooperation will be implemented in low-mobility environments, such as mesh networks, where channels change slowly in time. In such a case, the channel coherence time spans many code blocks, and the $m[\log(m-1) + (m-1)]$ overhead bits are assumed negligible in comparison to the transmitted information bits.

It is difficult to compare the implementation overhead of DSTC and selection cooperation. In both schemes, only the relay nodes that have correctly decoded the message proceed to encode and transmit the data. Because the relays must inform each other whether they have correctly decoded the message of each of the sources, a feed-forward overhead also exists in DSTC systems, and is identical to that of selection cooperation: $(m-1)$ bits per source-destination pair. The incremental overhead of the simple selection scheme is thus only $\log(m-1)$ bits.

In a traditional MIMO system, space-time coding may be preferable to selection diversity because its implementation does not require feedback. In a distributed system, however, DSTC incurs a significant overhead, generally not accounted for in the analysis. DSTC requires overhead for synchronization and, although the quantification of this overhead is beyond the scope of this paper, it is likely that it will be larger than the $\log(m-1)$ bits required to implement simple selection cooperation. The performance comparison of selection cooperation and DSTC thus becomes fair in terms of overhead requirements. Additionally, there may be feedback required to organize the participating nodes into indexes of the DSTC matrix. Given that the overhead for synchronization and this organization is difficult to quantize, for this purposes of this paper, we do not assume any further centralization or overhead requirements of DSTC. In summary, the network requirements of each scheme are shown in Table 1 at the top of the next page.

E. Discussion

The superior performance of selection cooperation over DSTC in network setting is not surprising: with m transmit antennas, selection transmit diversity (with $\log_2(m)$ bits of feedback) also outperforms space-time codes (no feedback required) in traditional MIMO systems. The performance loss of space-time codes (STC) results from the power constraint: with m antennas, the received signal power in each time slot with STC is $\left(|h_1|^2 + |h_2|^2 + \ldots + |h_m|^2\right)/m$, while the received power with selection is $|h_{\max}|^2$, where $|h_{\max}|^2 = \max\left(|h_1|^2, |h_2|^2 \ldots, |h_m|^2\right)$. Note that, as described above, in a distributed network DSTC also requires significant feedback.

Although it could be deduced that selection will outperform DSTC, the extent and the region of this performance gain is not clear a priori since, as previously stated, simple selection carries a power penalty. Furthermore, although in a decode-and-forward system with a single source-destination pair the optimal solution is clearly beamforming, this is not necessarily true in a network setting where each node has a peak power constraint. In this scenario, the optimal solution and the trade-offs involved in suboptimal solutions is still an unexplored problem. Finally, it is worth stating that the selection scheme described here could be extended in several ways. At the cost of additional overhead in channel feedback, the performance of the selection scheme could be improved by optimal power allocation across the $(n+1)$ relay-destination channels. Alternatively, selection cooperation may be implemented in conjunction with incremental (or opportunistic) relaying wherein a relay transmits only if required [3], [16].

TABLE I

COMPLEXITY AND CENTRALIZATION REQUIREMENTS FOR THE SIMPLE, SUB-OPTIMAL AND OPTIMAL SELECTION SCHEMES AND DSTC

Scheme	Complexity	Centralization	Overhead
Simple	m^2	No	$m[\log(m-1)+(m-1)]$
Sub-Optimal	$m!$	Yes	$m[\log(m-1)+(m-1)]+Lm^m$
Optimal	m^m	Yes	$m[\log(m-1)+(m-1)]+Lm^m$
DSTC	$--$	No	$m(m-1)$

IV. CONCLUSIONS

In this paper, we have presented selection cooperation in distributed, multi-source networks. Through analysis and simulation, we have shown that selection cooperation achieves full diversity order and significantly outperforms DSTC in a distributed system for all networks with more than three potential relays. This is because the relays do not have to “waste" energy transmitting to destinations over poor channels. Furthermore, simulations show that this improvement is greater in the practical case of geographically distributed nodes with channel qualities impacted by distance attenuation and shadowing.

The one significant drawback with selection cooperation, in a network setting, is the overhead involved in choosing a relay. Relay nodes must declare themselves eligible to cooperate and the destination must feedback the choice of relay. The analysis in this paper neglects the small overhead to choosing a relay on the overall throughput. However, it does not change the straight-forward manner in which the scheme could be applied or the central claims made here.

APPENDIX

A. Outage Probability: Single Transmission

In this section, we develop the outage probability $\Pr[I_{sel} < R]$ for selection cooperation in a single user system. As in [9], the derivation uses the total probability law:

$$\Pr[I_{sel} < R] = \sum_{\mathcal{D}(s)} \Pr\left[\mathcal{D}(s)\right] \Pr\left[I_{sel} < R|\mathcal{D}(s)\right]. \quad (15)$$

1) Probability of the Decoding Set: This derivation is given in [9] and is summarized here for completeness. Relays are in the decoding set if the source-relay channel satisfies

$$\begin{aligned}\Pr\left[r \in \mathcal{D}(s)\right] &= \Pr\left[|a_{s,r}|^2 > (2^{2R}-1)/\mathrm{SNR}\right] \\ &= \exp\left[-\lambda_{s,r}(2^{2R}-1)/\mathrm{SNR}\right].\end{aligned}$$

Because each relay makes independent decisions and the channel fading realizations are independent, the probability of a specific decoding set is

$$\begin{aligned}\Pr[\mathcal{D}(s)] &= \prod_{r_i \in \mathcal{D}(s)} \exp[-\lambda_{s,r_i}(2^{2R}-1)/\mathrm{SNR}] \\ &\quad \times \prod_{r_i \notin \mathcal{D}(s)} \left(1-\exp[-\lambda_{s,r_i}(2^{2R}-1)/\mathrm{SNR}]\right) \\ &\simeq \left[\frac{2^{2R}-1}{\mathrm{SNR}}\right]^{m-|\mathcal{D}(s)|-1} \times \prod_{r_i \notin \mathcal{D}(s)} \lambda_{s,r_i}, \quad (16)\end{aligned}$$

where the final approximation in (16) is valid at high-SNR.

2) Outage Probability Conditioned on the Decoding Set: This section develops the outage probability for a single source node s communicating with destination d using a relay chosen among $m-1$ relays from the decoding set. The chosen relay has the best relay-destination channel, i.e., largest $|a_{r,d}|$. Define the random variables X and Y as

$$X = \max_{r_i \in \mathcal{D}(s)} \left\{|a_{r_i,d}|^2\right\}; \quad i = 1\ldots|\mathcal{D}(s)|, \quad (17)$$

$$\Rightarrow F_X(x) = \prod_{i=1}^{|\mathcal{D}(s)|} (1-\exp[-\lambda_{r_i,d}y]), \quad (18)$$

and

$$Y = |a_{s,d}|^2, \quad (19)$$

$$\Rightarrow f_Y(y) = \lambda_{s,d}\exp[-\lambda_{s,d}y], \quad (20)$$

where the cumulative distribution function of X in (18) is derived using the independence of $|a_{r_i,d(s)}|^2 \ \forall\ i$. For the proposed selection scheme, the channel mutual information is thus

$$I_{sel} = \frac{1}{2}\log(1+\mathrm{SNR}(X+Y)). \quad (21)$$

Let $b = \left(2^{2R}-1\right)/\mathrm{SNR}$. Since $b \to 0$ as $\mathrm{SNR} \to \infty$, coupled with the approximation $e^x \simeq (1+x)$ as $x \to 0$, using the binomial expansion yields (see (22) at the top of the next page), where $\binom{n}{p} = \frac{n!}{p!(n-p)!}$. After solving the integral, some manipulations and the use of identity 0.155 from [22], this expression reduces to

$$\begin{aligned}\Pr[I_{sel} &< R|\mathcal{D}(s)] \\ &= b^{|\mathcal{D}(s)|+1}\lambda_{s,d}\left[\frac{\sum_{j=0}^{|\mathcal{D}(s)|}\binom{|\mathcal{D}(s)|}{j}}{\frac{(-1)^j}{j+1}\prod_{i=1}^{|\mathcal{D}(s)|}\lambda_{r_i,d}}\right] \\ &= b^{|\mathcal{D}(s)|+1}\lambda_{s,d}\frac{1}{|\mathcal{D}(s)|+1}\prod_{i=1}^{|\mathcal{D}(s)|}\lambda_{r_i,d}. \quad (23)\end{aligned}$$

3) Outage Probability: The total outage probability is obtained by substituting (16) and (23) into (15)

$$\begin{aligned}\Pr[I_{sel} < R] &= b^m\lambda_{s,d}\sum_{|\mathcal{D}(s)|}\frac{1}{|\mathcal{D}(s)|+1} \\ &\quad \times \prod_{r_i \in \mathcal{D}(s)}\lambda_{r_i,d}\prod_{r_i \notin \mathcal{D}(s)}\lambda_{s,r_i} \\ &= \left[\frac{2^{2R}-1}{\mathrm{SNR}}\right]^m\lambda_{s,d}\sum_{|\mathcal{D}(s)|}\frac{1}{|\mathcal{D}(s)|+1} \\ &\quad \times \prod_{r_i \in \mathcal{D}(s)}\lambda_{r_i,d}\prod_{r_i \notin \mathcal{D}(s)}\lambda_{s,r_i}. \quad (24)\end{aligned}$$

Hence the proposition in Section II is proved. ■

$$\begin{aligned}\Rightarrow \Pr\left[I_{sel} < R|\mathcal{D}(s)\right] &= \Pr\left[(X+Y) < b\right] \\ &= \int_0^b \prod_{i=1}^{|\mathcal{D}(s)|} \left(1-\exp[-\lambda_{r_i,d}(b-y)]\right)\lambda_{s,d}\exp[-\lambda_{s,d}y]dy \\ &= \lambda_{s,d}\prod_{i=1}^{|\mathcal{D}(s)|}\lambda_{r_i,d}\int_0^b (b-y)^{|\mathcal{D}(s)|}(1-\lambda_{s,d}y)dy \\ &= \lambda_{s,d}\prod_{i=1}^{|\mathcal{D}(s)|}\lambda_{r_i,d}\times\int_0^b\sum_{j=0}^{|\mathcal{D}(s)|}\binom{|\mathcal{D}(s)|}{j}b^{|\mathcal{D}(s)|-j}(-y)^j(1-\lambda_{s,d}y)dy\end{aligned} \tag{22}$$

B. Outage Probability of Simple Selection: Network Settings

In this section, we develop the outage probability bounds of selection cooperation in network where the relay node is chosen in a "simple" manner - the chosen relay is the one that can decode the source message correctly and has the best relay-destination channel.

We consider a source node $s_j \in \mathcal{M}$ communicating with its destination $d(s_j)$ using a relay r_j. We use the random variable N to denote the number of *other* source-destination pairs that have also selected relay r_j. We assume that all other destination nodes have equal average channels to all the relay nodes. This assumptions makes N independent of the average channel values and consequently of the node selected by $d(s_j)$, thus significantly simplifying the analysis.

The outage probability for this source-destination pair is again obtained by using the total probability law, averaged over N.

$$\Pr[I_{sel} < R] = \sum_{n=0}^{m-2}\Pr[I_{sel} < R|N=n]p(N=n), \tag{25}$$

where $p(N=n)$ denotes the probability of relay r_j supporting n nodes other than the chosen source node s_j.

To further simplify the analysis, we use the high-SNR approximation that all relay have correctly decoded the data of all source nodes except for source s_j. The relay r_j is thus included in the decoding set of all source nodes (note that this approximation will give an upper bound on the outage probability, as it increases the average value of N). At best, no other source-destination pairs have selected relay r_j and $N = 0$. At worst, all other source-destination pairs have selected r_j, in which case $N = m-2$ (a source cannot relay for itself, and thus r_j cannot relay its own data). Thus $0 \le N \le m-2$. In the case of equal average channels between all destination nodes other than $d(s_j)$ and the relay nodes, the random variable N has binomial density independent of the average channels

$$p_N(n) = \binom{m-2}{n}\left[\frac{1}{m-2}\right]^n\left[1-\frac{1}{m-2}\right]^{m-2-n}. \tag{26}$$

The other term in (25), $\Pr[I_{sel} < R|N=n+1]$, is the outage probability of the $s_j - d_j$ communication aided by relay r_j, which is also supporting N other source nodes, and thus expending $P/(N+1)$ Joules/symbol for each supported source node. The mutual information, given that $N=n$, is thus

$$I_{sel} = \frac{1}{2}\log\left(1+\mathrm{SNR}\times Y+\frac{\mathrm{SNR}}{n+1}X\right), \tag{27}$$

where Y and $f_Y(y)$ are defined in (19) and (20) and

$$\begin{aligned}X &= \frac{1}{(n+1)}\max_{r_i\in\mathcal{D}(s)}\{|a_{r_i,d}|^2\}; \quad i=1\dots|\mathcal{D}(s)| \\ F_X(x) &= \prod_{i=1}^{|\mathcal{D}(s)|}\left(1-\exp[-(n+1)\lambda_{r_i,d}y]\right).\end{aligned} \tag{28}$$

The development of $\Pr[I_{sel} < R|N=n]$ is very similar to that shown in Sections A.2 and A.3 and we thus give only the final result:

$$\begin{aligned}&\Pr[I_{sel} < R|N=n] \\ &\quad= \left[\frac{2^{2R}-1}{\mathrm{SNR}}\right]^m\lambda_{s,d}\sum_{|\mathcal{D}(s)|}\frac{(n+1)^{|\mathcal{D}(s)|}}{|\mathcal{D}(s)|+1} \\ &\quad\times \prod_{r_i\in\mathcal{D}(s)}\lambda_{r_i,d}\prod_{r_i\notin\mathcal{D}(s)}\lambda_{s,r_i}, \\ &\quad= \left[\frac{2^{2R}-1}{\mathrm{SNR}}\right]^m\lambda_{s,d}\sum_{|\mathcal{D}(s)|}\frac{(n+1)^{|\mathcal{D}(s)|}}{|\mathcal{D}(s)|+1} \\ &\quad\times \lambda_{r_i,d}^{|\mathcal{D}(s)|}\prod_{r_i\notin\mathcal{D}(s)}\lambda_{s,r_i}.\end{aligned} \tag{29}$$

where the $n+1$ sources supported by the relay account for the factor of $(n+1)^{|\mathcal{D}(s)|}$ within the summation, and the last simplification stems from the assumption that all nodes have equal average channels to their destinations, i.e., $\lambda_{r_i,d} = \lambda_{r_k,d} = \lambda_{r,d}, \forall i,k$.

Combining (25), (26) and (29), using the binomial expression yields (22) at the top of next page, where

where

$$K_m = \binom{m-2}{n}\left[\frac{1}{m-2}\right]^n\left[\frac{m-3}{m-2}\right]^{m-2-n}. \tag{31}$$

Hence the proposition in Section III-C is proved. ■

References

[1] M. Sikora, J. N. Laneman, M. Haenggi, D. J. Costello, and T. E. Fuja, "Bandwidth- and power-efficient routing in linear wireless networks," *IEEE Trans. Inform. Theory*, vol. 52, pp. 2624–2633, June 2006.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I, II," *IEEE Trans. Commun.*, vol. 51, pp. 1927–1948, Nov. 2003.

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, pp. 3062–3080, Dec. 2004.

$$\Pr[I_{\text{simple-sel}} < R] = \left[\frac{2^{2R}-1}{\text{SNR}}\right]^m \lambda_{s,d} \sum_{|\mathcal{D}(s)|} \frac{1}{|\mathcal{D}(s)|+1} \prod_{r_i \in \mathcal{D}(s)} \lambda_{r,d} \prod_{r_i \notin \mathcal{D}(s)} \lambda_{s,r_i} \sum_{n=0}^{m-2} K_m (n+1)^{|\mathcal{D}(s)|}, \tag{30}$$

[4] J. Boyer, D. Falconer and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. Commun.*, vol. 52, pp. 1820–1830, Oct. 2004.

[5] P. Herhold, E. Zimmermann, and G. Fettweis, "Co-operative multi-hop transmission in wireless networks," *Computer Networks J.*, vol. 49, pp. 229–324, Oct. 2005.

[6] A. Ribeiro, X. Cai, and G. B. Giannakis, "Opportunistic multipath for bandwidth-efficient cooperative multiple access," *IEEE Trans. Wireless Commun,*, vol. 5, pp. 2321–2327, Sep. 2006.

[7] S. Barbarossa and G. Scutari, "Distributed space-time coding for multi-hop networks," in *Proc. IEEE International Conf. Commun., ICC 2004*, June 2004, pp. 916–920.

[8] M. Uysal and O. Canpolat, "On the distributed space-time signal design for a large number of relay terminals," in *Proc. IEEE Wireless Commun. Networking Conf.*, Mar. 2005, pp. 990–994.

[9] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, pp. 2415–2425, Oct. 2003.

[10] S. Hares, H. Yanikomeroglu, and B. Hashem, "A relaying algorithm for multihop TDMA TDD networks using diversity," in *Proc. IEEE Veh. Technol. Conf.*, Oct. 2003, pp. 1939–1943.

[11] P. Larsson and N. Johansson, "Multiuser diversity forwarding in multi-hop packet radio networks," in *Proc. IEEE Wireless Commun. Networking Conf.*, Mar. 2005, pp. 2188–2194.

[12] B. Zhao and M. C. Valenti, "Practical relay networks: A generalization of hybrid-ARQ," *IEEE J. Select. Areas Commun.*, vol. 23, pp. 7–18, Jan. 2005.

[13] P. Liu, Z. Tao, and S. Panwar, "A cooperative MAC protocol for wireless local area networks," in *Proc. IEEE International Conf. Commun.*, May 2005, pp. 2962–2968.

[14] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Select. Areas Commun.*, vol. 24, pp. 659–672, Mar. 2006.

[15] A. Bletsas, H. Shin, and M. Z. Win, "Outage-optimal cooperative communications with regenerative relays," in *Proc. Conf. Information Sciences Syst. (CISS 2006)*, Mar. 2006, pp. 632–637.

[16] D. Gunduz and E. Erkip, "Opportunistic cooperation by dynamic resource allocation," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 1446–1454, Apr. 2007.

[17] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 283–289, Feb. 2006.

[18] T. E. Hunter and A. Nosratinia, "Grouping and partner selection in cooperative wireless networks," *IEEE J. Select. Areas Commun.*, vol. 25, pp. 369–378, Feb. 2007.

[19] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative regions and partner choice in coded cooperative systems," *IEEE Trans. Commun.*, vol. 54, pp. 1323–1334, July 2006.

[20] Y. Zhao, R. S. Adve, and T. J. Lim, "Improving amplify-and-forward relay networks: Optimal power allocation versus selection," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 3114–3123, Aug. 2007.

[21] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inform. Theory*, vol. 49, pp. 1073–1096, May 2003.

[22] I. S. Gradshteyn, I. M. Ryzhik, A. Jeffrey, and D. Zwillinger, *Table of Integrals, Series and Products*. Boston, MA: Academic Press, 1984.

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