SPECTRALLY EFFICIENT RELAY SELECTION PROTOCOLS IN WIRELESS NETWORKS

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ABSTRACT

Relay networks face a fundamental challenge in terms of spectral efficiency, because relays must repeat the source information. To address this key problem, this paper presents two relay selection protocols that salvage spectral efficiency by adroitly leveraging the multiple relays. Both protocols have the feature of letting the source transmit all or most of the time. The diversity-multiplexing tradeoff (DMT) of Zheng-Tse is used to show the advantage of our protocols. The proposed protocols require minimal overhead and feedback, and have similar complexity compared to existing protocols.

Index Terms— Cooperative diversity, diversity-multiplexing tradeoff, outage probability, relay selection, wireless networks.

1. INTRODUCTION

Relaying in delay-limited wireless networks has been seen recently as a promising method that can overcome the deleterious effects of fading channels when the network nodes are of limited size and capability [1]. In this work we propose two relay selection algorithms with improved diversity-multiplexing tradeoff (DMT) compared to the existing relaying protocols in multiple relay networks [2]. Our protocols also require very limited information exchange between the network nodes.

Laneman and Wornell proposed the use of distributed spacetime codes (DSTC) leading to a dominant performance compared to repetition based coding [3]. In [4], the non-orthogonal amplify-andforward (NAF) and the dynamic-decode-and-forward (DDF) show even superior performance compared to the use of DSTC. However, both schemes do not scale with increasing the number of relays in high rate regimes. Bletsas et al. proposed a simple protocol which they termed "opportunistic relaying" (OR) [5]. OR protocol achieves the same DMT performance of DSTC, however without the need for tight symbol synchronization and coordination between the nodes. Recently, it was shown that the same DMT performance of OR can be achieved via limited feedback from the destination and without requiring the relays to know their outgoing channel gains [6].

The above algorithms, as shown by the DMT curves in the sequel, are not suitable for working in the high-rate regimes. This motivates and defines the present work. This paper develops algorithms that achieve DMT performance beyond the above protocols across a large range of spectral efficiencies, but *specially in high rate regimes*. We consider two decode-and-forward (DF) based protocols under half-duplex transmission assumption. The key feature of the proposed protocols is to let the source transmit all (or most) of the time *and* always let its transmission to be relayed by one out of a group of nearby nodes (if needed). Our contributions can be summarized as follows. For a two-hop relay network, we propose a new cooperative communication protocol which we call multi-hop with relay selection (MHRS). We derive upper and lower bounds on the DMT of a two-hop DF relay network with relay selection mechanism. We present an incremental transmission with relay selection (ITRS) protocol for a relay network with an existing direct link that shows dominant DMT superiority over existing protocols. An outage probability expression that is valid at *any* SNR is developed. Moreover, we derive a DMT expression and conclude that it coincides with the MISO upper bound.

Finally, a word about notations. We use $(q)^+$ to mean the $\max\{q, 0\}$. We reserve x_i for transmitted signals and y_j for the received ones. The subscripts $i \in (s, m)$ and $j \in (m, d)$ where s, m and d refer to source node, an intermediate node and destination node, respectively and $m = 1, \dots, M$. The best relay is denoted by m^* and b denotes the transmission block index, $b = 1, \dots, B$.

2. SYSTEM AND CHANNEL MODELS

We consider a wireless network where communication takes place between a source-destination pair with the help of M half-duplex relay nodes. In the first protocol that we propose, the S - D link is assumed to be blocked leading to a two-hop network model. However, in the the second presented protocol the relay nodes leverage the performance of the existing S - D link and perform relaying whenever needed. Throughout the paper it is assumed that a low rate error-free delay-free feedback channel is available from destination to the network nodes. No transmit side channel state information (CSI) is available to the network nodes but receive side CSI availability is assumed. The nodes that listen to the source transmission and can successfully decode its message form a (random) set D(s). Following [3], for simplicity we call D(s) the "decoding set". The error in deciding correct decoding at the relays is assumed negligible.

We assume a quasi-static Rayleigh fading channel model. Each codeword spans just one coherence interval of the channel and random Gaussian codebooks are assumed. All nodes transmit with equal symbol power P. The thermal noise at all receivers z_j is modeled as complex Gaussian random sequences $\sim \mathcal{N}(0, \sigma^2)$. The received SNR without fading at the relays and destination is denoted by ρ , where

$$\rho = \frac{P}{\sigma^2} \tag{1}$$

The channel coefficients $h_{i,j}$ are modeled as zero-mean, independent, circularly symmetric complex Gaussian random variables (R.V.s) with variance $\lambda_{i,j}$. Thus, the effective channel gains are exponential random variables with mean $\lambda_{i,j}$.

For the definitions of "exponential equality", "diversity gain" and "multiplexing gain", the reader is referred to [2]. Due to space limitations, proofs of the theorems are omitted.

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3. MULTI-HOPPING WITH RELAY SELECTION

When a direct path is unavailable, the relays must repeat the signal in a two-hop fashion to establish communications between the source and the destination. The problem is that repeating the source transmission limits the spectral efficiency. However, when multiple nodes can correctly decode the message of the source, the following protocol has minor rate loss compared to direct transmission.

3.1. MHRS Protocol Description

- 1. The source transmits alone in the first time slot. Then, in each time slot:
- 2. Relays that successfully decode the source packet, declare their status to the destination via a one-bit RTS packet.
- 3. The destination picks the best relay and broadcasts its index [6]. The best relay retransmits its decoded packet, which the destination attempts to decode. At the same time, the source transmits a new packet.
- 4. The source packet and relayed packet combine at other relays. Relays attempt to decode new source packet in the presence of interference. Then continue to Step 2.

Notice that whenever a relay transmits, due to the half-duplex constraint, it cannot receive. Therefore, in the following time interval, it is operating at a disadvantage since it cannot peel-off the interference signal from the source transmission. The overhead for control in the MHRS protocol is $1 + \frac{\log(M-1)-1}{M}$ bits per node per packet.

3.2. Performance Analysis

3.2.1. DMT Upper Bound

Consider a source-destination pair communicating via a single MIMO relay. At each transmission block, the antenna with the best channel gain to the destination is selected to transmit the previously decoded message of the source while other antennas are used to receive the current source signal. This model is equivalent to having perfect information exchange between the relay nodes and thus provides an upper bound on the DMT of our protocol.

Theorem 1 The DMT of the multi-hop with relay selection (MHRS) protocol is upper-bounded by:

$$d^*(r) = (M-1)(1 - \frac{B+1}{B}r)^+$$
(2)

3.2.2. Achievable DMT

In the following, we present two decoding schemes at the relays and derive their respective achievable DMT. The first decoding protocol is based on successive cancellation at the relays. The key result in successive cancellation is that, after each relay's transmission, due to interference it cannot recover its own decoding diversity, thus it cannot contribute to the overall diversity any longer. It follows that across time, a family of DMT curves are produced with varying diversity. The interesting outcome of the family of DMT curves is that it allows variable error-protection.

If the relays have enough computational power, they may be able to jointly decode the two interfering signals. We show that a hybrid strategy, incorporating both successive cancellation and joint decoding, in part meets the DMT upper bound, and is superior to successive cancellation. Achievable DMT under Succesive Decoding

Theorem 2 For the MHRS protocol under successive cancellation decoding at the relays, the following diversitymultiplexing tradeoff is achievable for the packet b, where $b \in \{1, ..., B\}$.

$$d(r,b) = (M-b+1)^{+} \left(1 - \frac{B+1}{B}r\right)^{+}$$
(3)

In some applications, we may not be interested in a multiplicity of DMT's, thus the diversity across different packets b is dominated by the smallest diversity gain, i.e.,

$$d_{SC}(r) = \min_{b} d(r, b) = (M - B + 1)^{+} \left(1 - \frac{B + 1}{B}r\right)^{+}$$

Note that in this expression, B + 1 is a *refresh cycle* of the system, i.e., the period after which the source will transmit alone and will reset all the interferences at the relays.

• Achievable DMT under Joint Decoding

Successive cancellation in the MHRS protocol leads to error propagation and a gradual loss of diversity with increasing packet index. This loss arises from the reduced ability of the relays, after their own transmission, to correctly estimate and subtract the interference caused by other relays.

For better performance, we can employ a more powerful decoding technique at the relay. The relays attempt joint decoding of the two arriving signals. To calculate the DMT of MHRS with joint decoding, we use certain recent results on the so-called Z-channel. Our system model is a special case of the Z-channel, since the source is heard only by the relays, while the best relay in each interval is heard by both the destination *and* relays. Recently, the DMT of the Z channel under general decoding was reported in [7]. Specializing the result of [7] to our channel model gives in the following relay outage diversity for a single-block decoding:

$$d_Z(r) = (\min\{(1-r), 2(1-2r)\})^+$$
(4)

When all relays use joint decoding for detecting the message of the source and using the DMT of the Z-channel given above in (4), one arrives at the following result:

Theorem 3 The DMT of MHRS protocol under joint decoding is lower bounded by

$$d_{JD}(r) = \left(\min\left\{(M-1)(1-\frac{B+1}{B}r),\right.\\ \min_{t=0,\dots,M-1}(2M-2-t) - \frac{B+1}{B}r(4M-4-3t)\right\}\right)^+$$
(5)

Achievable DMT under Hybrid Joint Decoding

At low spectral efficiencies, the above expression shows a distinct improvement over successive cancellation. However, at high spectral efficiencies, successive cancellation DMT outperforms that of joint decoding. This calls for the use of an adaptive method. Whenever possible, the relays decode by successive cancellation, but whenever that is not possible, the relays attempt joint decoding of the two arriving signals. The more powerful method, denoted *MHRS with hybrid*



Fig. 1. Diversity-multiplexing tradeoff of different protocols in a two-hop network with ten relays.

joint decoding, improves the DMT of the MHRS protocol, and meets the DMT upper bound up to a certain multiplexing gain. Since hybrid MHRS, for each packet detection, chooses the better of successive cancellation or joint decoding, the hybrid method must perform strictly better than either of its components.

Theorem 4 The DMT of hybrid joint decoding is bounded below by:

$$d_{MHRS}(r) = \max\left\{ (M - B + 1)^{+} \left(1 - \frac{B + 1}{B} r \right)^{+}, \\ \min\left\{ (M - 1)(1 - \frac{B + 1}{B} r)^{+}, \\ \min_{t=0,\dots,M-1} [(2M - 2 - t) - \frac{B + 1}{B} r(4M - 4 - 3t)]^{+} \right\} \right\}$$
(6)

Figure 1 compares the diversity-multiplexing tradeoff of several DFbased protocols in a two-hop relay network with M = 10 and B = 6. Also, shown the MHRS protocol upper bound derived in Section 3.2.1. The hybrid MHRS protocol attains better DMT performance, across a large range of spectral efficiencies, compared with distributed space-time codes and opportunistic relaying.

4. INCREMENTAL TRANSMISSION WITH RELAY SELECTION

This section considers the relay selection problem under a slightly different system model, where (unlike the last section) a direct path is available between the source and destination. Since we now can utilize a direct path for the initial transmission, and since a feedback between the destination and relays already exists (for selection purposes), then it stands to reason that this existing feedback path can also be used for retransmission requests (also known as incremental relaying [8]) to further improve the spectral efficiency. This section proposes a hybrid technique known as incremental transmission with relay selection (ITRS) and analyzes its performance.

4.1. ITRS Protocol Description

- 1. The source transmits at the beginning of block *b*. Intermediate nodes will try to decode the signal.
- The destination tries to decode the source transmission. If successful, it broadcasts an ACK signal and the source moves on to transmit new packet. However, if unsuccessful decoding is detected at the destination, a NACK signal is broadcasted.
- 3. Consequently, the relay nodes declare their decoding success to the destination. A relay selection process is performed similar to MHRS protocol. The node with best instantaneous uplink channel gain is selected for relaying from all the available nodes (the nodes in the decoding set *plus* source). The destination combines both packets and tries to decode again. If unsuccessful, packet is dropped and outage is declared.

Unlimited retransmissions would remove outage, but also incur unbounded delay. In general, wireless applications that are modeled in quasi-static channels are delay-sensitive. We study the case of maximum one round of retransmission which incurs modest delay and yet captures the biggest part of the gains available through retransmissions. Including the source in the competition in the second phase guarantees that the channel will not remain idle if no relay correctly decoded the source message. This in turn improves the effective rate and the diversity order.

4.2. Performance Analysis

4.2.1. Outage Probability and Effective Rate

The received signals at the intermediate nodes and the destination during normal source transmission are respectively given by:

$$\mathbf{y}_m[b] = h_{s,m} \mathbf{x}_s[b] + \mathbf{z}_m[b] \tag{7}$$

$$\mathbf{y}_d[b] = h_{s,d} \mathbf{x}_s[b] + \mathbf{z}_d[b]$$
(8)

During relayed transmissions, the received signal at destination is,

$$\mathbf{y}_d[b'] = h_{m^*,d} \mathbf{x}_{m^*}[b'] + \mathbf{z}_d[b']$$
(9)

Where b' stands for the relayed transmission block.

The mutual information across the S-D channel during the transmission by the source is given by,

$$I_{s,d} = \log(1 + \rho g_{s,d}) \tag{10}$$

Conditioned on D(s), the mutual information between the channel inputs from the source and "best" relay and channel outputs is,

$$I_{itrs}^* = \frac{1}{2} \log(1 + \rho(g_{s,d} + g_{m^*,d}))$$
(11)

The probability of outage can be expressed as:

$$P_{out,ITRS} = \sum_{D(s)} Pr\left(I_{itrs}^* < \frac{R}{2} | I_{s,d} < R, D(s)\right)$$
$$\times Pr\left(I_{s,d} < R\right) Pr\left(D(s)\right),$$
$$= \sum_{D(s)} Pr\left(I_{itrs}^* < \frac{R}{2} | D(s)\right) Pr\left(D(s)\right) \quad (12)$$

Where in (12) outage is computed for rate R in case of successful direct transmission and for rate $\frac{R}{2}$ in case of incremental transmission due to information repetition. By calculating the probability of

a decoding set D(s) with cardinality t and obtaining the CCDF of I_{itrs}^{*} one can find a closed form expression for the overall outage probability ($M \ge 1$):

$$P_{out,ITRS} = \sum_{D(s)} F_W(\gamma) \times {\binom{M}{t-1}} \exp\left(-\frac{\gamma}{\lambda_{s,m}}\right)^{t-1} \left(1 - \exp\left(-\frac{\gamma}{\lambda_{s,m}}\right)\right)^{M-t+1}$$
(13)

Where

$$F_W(\gamma) = \left[t \sum_{k=1}^{t-1} {\binom{t-1}{k}} \frac{(-1)^k}{k} \left(1 + \frac{\exp(-\mu(k+1)\gamma) - 1}{(k+1)} - \exp(-\mu\gamma) \right) \right] + t \left(1 - (\mu\gamma + 1)\exp(-\mu\gamma) \right)$$
(14)

 $\gamma = \frac{2^R - 1}{\rho}$ and for simplicity we let $\lambda_{s,d} = \lambda_{m^*,d} = \frac{1}{\mu}$. We now calculate the throughput (expected rate) η . This value

We now calculate the throughput (expected rate) η . This value has two terms, for packets that are received in one try, or in two tries.

$$\eta = R \exp\left(-\frac{2^{R}-1}{\rho \lambda_{s,d}}\right) + \frac{R}{2} \left[\left(1 - \exp\left(-\frac{2^{R}-1}{\rho \lambda_{s,d}}\right) \right) (1 - P_{out}) \right]$$
(15)

We note that a somewhat similar notion of expected spectral efficiency was developed in [8] for a single-relay Amplify and Forward (AF) incremental relaying. The mapping $R \to \eta$ is highly nonlinear and one may choose R to maximize the throughput η .

On average, ITRS protocol requires $1 + \frac{\log(M+1)}{M+1} \left[1 - \exp(-\frac{2^R - 1}{\rho \lambda_{s,d}})\right]$ bits of overhead per transmitting node.

4.2.2. DMT Analysis

Theorem 5 The ITRS protocol achieves the optimal DMT of a system with one source node and M relay nodes given by

$$d_{ITRS}(r) = (M+2)(1-r)^{+}$$
(16)

Figure 2 depicts the DMT of ITRS protocol and compares it with DSTC, OR and DDF [4, Theorem 6] in a network with four relays. For fairness, we have compared our algorithm to a slightly modified version of DSTC [8] and OR [5] by allowing the source to participate in the second phase of transmission. For the non-cooperative benchmark, the DMT of a HARQ signaling is shown, where a maximum diversity order of two is possible via packet combining [9, Corollary 3]. We see that ITRS has improved performance over previous protocols across all r, while requiring only limited feedback.

5. CONCLUSIONS

In this paper, we propose two new cooperative communication protocols in wireless networks. For a two-hop relay network without a direct link, where repetition of source information by relays is unavoidable, the new MHRS protocol minimizes the deleterious effects of these retransmissions on overall spectral efficiency. It is shown that the MHRS protocol has superior DMT performance at high multiplexing gains over existing protocols.

For a relay network with a direct link, we propose the ITRS protocol, which achieves the MISO DMT bound. Both protocols are designed to be as simple as possible and to use limited feedback from the destination.



Fig. 2. Diversity-multiplexing tradeoff of different protocols with four relays and S-D link exists

6. REFERENCES

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