DISTRIBUTED DIFFERENTIAL SCHEMES FOR COOPERATIVE WIRELESS NETWORKS

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ABSTRACT

In cooperative wireless networks, virtual antenna arrays formed by distributed network nodes can provide cooperative diversity. Obviating channel estimation, differential schemes have long been appreciated in conventional multi-input multi-output (MIMO) communications. However, distributed differential schemes for general cooperative network setups have not been thoroughly investigated. In this paper, we develop and analyze two distributed differential schemes using both decode-and-forward (DF) and amplify-and-forward (AF) relaying protocols. For each scheme and relaying protocol combination, we derive the optimum maximum likelihood (ML) decision rule and its low-complexity suboptimum alternative. Simulations confirm that both schemes provide full diversity gain with either DF or AF relaying protocols. In addition, we carry out performance and rate comparisons between the two distributed differential schemes and preliminary investigations on the optimal relay positioning for the DF and AF relaying protocols.

1. INTRODUCTION

Virtual antenna arrays formed by distributed wireless network nodes can provide cooperative diversity (CD), which can improve the error performance and network throughput in fading channels. Unlike space diversity conventional MIMO systems using multiple co-located antennas, cooperative diversity alleviates the antenna array packing limitations [8]. On the other hand, the distributed nature of such cooperative systems impose new research and development challenges. To this end, information-theoretic perspective and outage probability of CD have been studied in [6], user cooperation in a code division multiple access (CDMA) system was considered in [12], coherent maximum likelihood (ML) detection for wireless cooperative systems was introduced in [7] and its amplify-and-forward (AF) format was analyzed in [3, 8]. However, all these works were based on the assumption that the channel state information (CSI) are available at the relays as well as the destination.

Accurate estimation of CSI may be suitable in (quasi-)static channels. However, the channel estimation complexity increases with the number of relay nodes. It can also induce communication overhead or transceiver complexity. More importantly, CSI estimation may not be feasible when the channel is rapidly time-varying. For these reasons, it is desirable to avoid channel estimation and employ transmission techniques that do not require CSI at the transmitter or receiver.

Recently, CD schemes obviating CSI have been introduced, relying on noncoherent or differential modulations, such as frequency-shift keying (FSK) and differential phase-shift keying (DPSK). Using FSK, noncoherent demodulation was analyzed in [2] for binary symbols, and an ML framework for the general noncoherent case was developed in [1]. More recently, a differential modulation scheme for single-relay (i.e., two-user) CD systems was also analyzed [9–11]. In all these works, the relay-destination channels are assumed to be orthogonal so that the single-input single-output (SISO) modulation schemes (e.g., FSK or DPSK) can be directly adopted.

In this paper, we develop two distributed differential (DD) schemes. The first scheme, which we term as DD-I, generalizes the conventional differential modulation to a distributed scenario with an arbitrary number of relays. The second scheme (DD-II) relies on an increased level of user cooperation via the distributed counterpart of the differential space-time codes in [4]; that is, for each data block, a space-time codeword encoded *across* distributed relays is transmitted over a common relay-destination channel. We then adapt both schemes to DF and AF relaying protocols, and derive the optimum ML and suboptimum decision rules for each scenario, without CSI being required at any node. We show that both schemes can achieve full diversity gain. In addition, preliminary results on the optimal location of the relays are provided.

The rest of this paper is organized as follows. The system model and signal representation for two DD schemes are described in Section 2. Their specific modulation and demodulation for corresponding schemes are derived in Section 3. Section 4 presents simulations and discussions. The summarizing remarks are given in Section 5.

Notation: We use bold upper (lower) case letters to denote matrices (vectors). $\boldsymbol{I}_N$ represents an $N \times N$ identity matrix and diag$\{\boldsymbol{a}\}$ stands for a diagonal matrix with $\boldsymbol{a}$ on its diagonal. We use $(\cdot)^*$ and $(\cdot)^{\mathcal{H}}$ for conjugate and Hermitian, $\mathbb{E}[\cdot]$ for expectation, $\Re\{\cdot\}$ for the real part, $\mathcal{CN}(\mu, \sigma^2)$ for the complex Gaussian distribution with mean μ and variance σ^2, $\|\cdot\|$ for Frobenius norm, and $\boldsymbol{A} \odot \boldsymbol{B}$ for the Schur-Hadamard product of $\boldsymbol{A}$ and $\boldsymbol{B}$.

2. SYSTEM MODEL AND SIGNAL REPRESENTATION

Consider a network setup with one source node s, L relay nodes $\{r_k\}_{k=1}^{L}$, and one destination node d, as depicted in Fig. 1. Each node is equipped with a switch that controls its transmit/receive mode to enable half-duplex communications. Multiplexing among the network nodes can be achieved via frequency-division, time-division or code-division. For notational simplicity, we will consider the time-division multiplexing (TDM). The channel (time) assignment of our distributed schemes will be specified later. We consider both the DF and AF relaying protocols. With the former, the relay nodes demodulate the signal from the source node, remodulate and forward to the destination; whereas with the latter, the relay nodes simply amplify the signal from the source node and forward to the destination.

2.1. Distributed Differential Scheme I (DD-I)

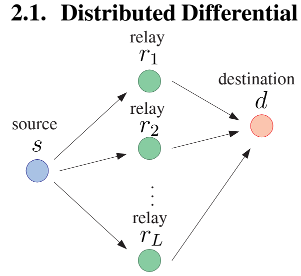


Fig. 1. A wireless system with multiple relays.

In DD-I, the source transmits to all relays via a common channel, while the relay-destination links have mutually orthogonal channels, as in [2, 8]. With TDM, the orthogonality is ensured by assigning non-overlapping time slots to each relay. During the first time slot, the source node broadcasts the first differentially encoded symbol to all relay nodes. Then, each relay transmits the remodulated signal (with DF) or the amplified signal (with AF), to the destination during their distinct time slots. As a result, a total of $(L+1)$ time slots are needed for every symbol transmission.

Denoting the n-th symbol from the source as $x_n^s := x_{n-1}^s s_n = x_{n-1}^s e^{j2\pi c_n/M}, c_n \in \{0, 1, ..., M\}$ with $x_0^s = 1$, the received signal at the k-th relay is given by

$$y_n^{r_k,s} = h_n^{r_k,s} x_n^s + z_n^{r_k}, \ \ k = 1, 2, ..., L, \tag{1}$$

where the fading coefficient of the channel between s and r_k is $h_n^{r_k,s} \sim \mathcal{CN}(0, \sigma^2_{h_{r_k,s}})$, and the noise component $z_n^{r_k} \sim \mathcal{CN}(0, N_r)$. Let $x_n^{r_k}$ denote the n-th transmitted symbol from the k-th relay, $k = 1, 2, ..., L$, then the received signal at the destination corresponding to each relay node is given by

$$y_n^{d,r_k} = h_n^{d,r_k} x_n^{r_k} + z_n^d, \ \ k = 1, 2, ..., L, \tag{2}$$

where the fading coefficient of the channel between r_k and d is $h_n^{d,r_k} \sim \mathcal{CN}(0, \sigma^2_{h_{d,r_k}})$, and the noise component $z_n^d \sim \mathcal{CN}(0, N_d)$. Notice that at the relay nodes, the transmitted signal $x_n^{r_k}$ can be different from the received signal $y_n^{r_k,s}$, depending on the relaying protocols employed. Their relationship will be specified in the ensuing section. Denoting the average energy per symbol for the source and relays as $\mathcal{E}_s := \mathbb{E}[(x_n^s)^* x_n^s]$ and $\mathcal{E}_{r_k} := \mathbb{E}[(x_n^{r_k})^* x_n^{r_k}]$ for $k = 1, 2, ..., L$, we can then define the received instantaneous signal-to-noise ratio (SNR) between the transmitter j and the receiver i as

$$\gamma_{i,j} = (|h_n^{i,j}|^2 \mathcal{E}_j)/N_i, \ \ i, j \in \{s, r_k, d\}.$$

It follows that the average received SNR is $\bar{\gamma}_{i,j} = (\sigma^2_{h_{i,j}} \mathcal{E}_j)/N_i$.

2.2. Distributed Differential Scheme II (DD-II)

In DD-I, all L source-relay links share a common channel, whereas the relay-destination links use L orthogonal channels. DD-II assigns the channels (time slots) in the opposite manner: the L source-relay links will occupy non-overlapping time slots, whereas all relay-destination links share a common channel. Clearly, such a channel allocation entails a relaying protocol distinct from DD-I. Notice that since all relay-destination links share a common channel, the relays cooperate at a lifted level. This naturally calls for space-time coding (STC) techniques. To enable signaling in the absence of CSI, we will resort to differential approaches, namely the differential unitary space-time coding (DUSTC) [4, 5]. For simplicity, we will focus on the diagonal designs with the cyclic construction [4]. Then, during the first L time slots of a transmission block, the source transmits the diagonal entries of the DUSTC encoded symbol block to the relays using DPSK modulation, and their differentially decoded (or amplified) signals are broadcasted by the L relays during the L following time slots.

Denote the n-th differentially encoded signal from the source as $\boldsymbol{X}_n^s := \boldsymbol{X}_{n-1}^s \boldsymbol{V}^{(Q_n)}$ with $\boldsymbol{X}_0^s = \boldsymbol{I}_L$, where $\boldsymbol{V}^{(Q_n)}$ is an $L \times L$ diagonal unitary matrix and $Q_n \in \{0, 1, ..., M-1\}$. Then, the n-th received signal block at the relays is given by

$$\boldsymbol{Y}_n^{r,s} = \boldsymbol{H}_n^{r,s} \boldsymbol{X}_n^s + \boldsymbol{Z}_n^r, \tag{3}$$

where the channel matrix between the source and relay is $\boldsymbol{H}_n^{r,s} := \text{diag}\{h_n^{r_1,s}, h_n^{r_2,s}, ..., h_n^{r_L,s}\}$, and the $L \times L$ noise matrix is $\boldsymbol{Z}_n^{r,s} := \text{diag}\{z_n^{r_1}, z_n^{r_2}, ..., z_n^{r_L}\}$. Let $\boldsymbol{X}_n^r$ denote the n-th transmitted signal from the relays, then the corresponding received signal at the destination is given by

$$\boldsymbol{Y}_n^{d,r} = \boldsymbol{H}_n^{d,r} \boldsymbol{X}_n^r + \boldsymbol{Z}_n^d, \tag{4}$$

where channel matrix between the relays and destination is $\boldsymbol{H}_n^{d,r} := \text{diag}\{h_n^{d,r_1}, h_n^{d,r_2}, ..., h_n^{d,r_L}\}$ and the $L \times L$ noise matrix is $\boldsymbol{Z}_n^d := \text{diag}\{z_n^d, z_n^d, ..., z_n^d\}$. Depending on the relaying protocols, $\boldsymbol{X}_n^r$ have different forms at the relays, and its detailed formulation will be discussed the following section.

3. DISTRIBUTED MODULATION AND DEMODULATION

In this section, we will develop the optimum and suboptimum decision rules for the DD-I and II schemes, under DF or AF relaying protocols. For each of these schemes, we will first introduce the general frameworks for the ML decision rule and then specify depending on the relaying protocols.

3.1. Distributed Differential Scheme I

In DD-I, the received signals at the destination (from different relays) are independent, conditioned on the signal transmitted from the source node. Hence, their log likelihood ratio (LLR) functions, conditioned on the signal transmitted from the source node x^m is

$$l_m^{r_k}(y_n) := \ln p_{y_n^{d,r_k}|x_n^s}(y_n|x_n^m) \ . \tag{5}$$

Using this definition at the destination node, the general ML decision rule for scheme DD-I can be expressed as follows

$$\hat{m} = \arg \max_{m \in \{0,1,...,M-1\}} \sum_{k=1}^{L} l_m^{r_k}(y_n). \tag{6}$$

With this structure, we can specify the LLR function in Eq. (5) to the DF and AF relaying protocols.

3.1.1. Decode-and-Forward Protocol

In the DF protocol, the received signal at the k-th relay, $y_n^{r_k,s}$, is demodulated and remodulated using conventional differential signaling. Then, the regenerated signal $x_n^{r_k}$ is transmitted. The LLR for y_n^{d,r_k}, the received signal at the destination from the k-th relay, given that $x^{m'}$ is transmitted from the *relay*, is

$$\hat{l}_{m'}^{r_k}(y_n) := \ln p_{y_n^{d,r_k}|x_n^{r_k}}(y_n|x_n^{m'}). \tag{7}$$

With this LLR function, we can re-express Eq. (5) by defining the transition probability, which captures the effect of the relay decision (see e.g., [1]) as:

$$P_{m',m}^{r_k} := Pr[x^{r_k} = x^{m'} | x^s = x^m]. \tag{8}$$

Since the transition probability $P_{m',m}^{r_k}$ can not be easily obtained [1], we use empirical data for our results. Using the above equations, Eq. (5) can be re-written as

$$l_m^{r_k}(y_n) = \ln[\sum_{m'=0}^{M-1} P_{m',m}^{r_k} \exp(\hat{l}_{m'}^{r_k}(y_n))]. \tag{9}$$

Consider now the received signal y_n^{d,r_k}, provided that $x_n^{r_k} = x_n^{m'}$. By dropping the superscripts for notational brevity, the differentially modulated signal, y_n, can be written as

$$y_n = h_n(x_{n-1}s_n) + z_n = y_{n-1}s_n + z'_n,$$

where $z'_n = z_n - z_{n-1}s_n$. Since $\mathbb{E}[s_n^* s_n] = 1$, the $y_n^{d,r_k} \sim \mathcal{CN}(s_n^{m'} y_{n-1}^{d,r_k}, 2N_d)$. Then, the LLR can be simplified as

$$\hat{l}_{m'}^{r_k}(y_n) = \Re\{y_n y_{n-1}^* (s_n^{m'})^*\} = \Re\{(y_n)^* y_{n-1} s_n^{m'}\}. \tag{10}$$

We have to note that, though Eq. (10) is linear, substituting Eq. (10) into Eq. (9), $l_m^{r_k}(y_n)$, generally results in a nonlinear operation. Consequently, the ML decision rule is also nonlinear.

3.1.2. *Amplify-and-Forward Protocol*

Under the AF protocol, each relay amplifies its received signal from the source, *i.e.*,

$$x_n^{r_k} = A_{r_k} y_n^{r_k,s}, \;\; k = 1, 2, ..., L, \tag{11}$$

where A_{r_k} is the amplification factor. To maintain a constant average power at the relay output, the amplification factor is

$$A_{r_k} = \sqrt{\frac{\mathcal{E}_{r_k}}{\sigma^2_{h_{r_k,s}}\mathcal{E}_s + N_r}}, \;\; k = 1, 2, ..., L. \tag{12}$$

Notice that the amplification factor is different from the coherent modulation case where the instantaneous fading coefficient $|h_n^{r_k,s}|^2$ is used in lieu of $\sigma^2_{h_{r_k,s}}$. This A_{r_k} is reasonable for either differential or noncoherent modulations, since we can estimate the value of $\sigma^2_{h_{r_k,s}}$ by averaging the received signals without the knowledge of the instantaneous CSI [1, 10, 11].

Using the above amplification factor and differential signaling, the received signal at the destination corresponding to each relay node is given by

$$y_n^{d,r_k} = \tilde{h}_n^{d,r_k} x_n^s + \tilde{z}_n^d = y_{n-1}^{d,r_k} s_n + (\tilde{z}_n^d)', \;\; k = 1, 2, ..., L,$$

where $\tilde{h}_n^{d,r_k} = A_{r_k} h_n^{r_k,s} h_n^{d,r_k}$, $\tilde{z}_n^d = A_{r_k} h_n^{d,r_k} z_n^{r_k} + z_n^d$, and $(\tilde{z}_n^d)' = \tilde{z}_n^d - \tilde{z}_{n-1}^d s_n$. Then, conditioned on the channels, $y_n^{d,r_k} \sim \mathcal{CN}(y_{n-1}^{d,r_k} s_n, \sigma^2_{h_{k,eff}})$, where the effective variance is given by

$$\sigma^2_{h_{k,eff}} = 2A^2_{r_k}\sigma^2_{h_{d,r_k}} N_r + 2N_d, \;\; k = 1, 2, ..., L. \tag{13}$$

Therefore, the LLR for AF in Eq. (5) can be written as

$$l_m^{r_k}(y_n) = \Re\{y_n y_{n-1}^* (s_n^m)^*\} = \Re\{(y_n)^* y_{n-1} s_n^m\}. \tag{14}$$

By substituting Eq. (14) into Eq. (6), we can obtain the ML decision rule. It is worth mentioning that the ML decision rule only consists of linear operations, which is a major difference from the DF case. By avoiding the nonlinear operations, it provides a simpler ML detection structure. However, the increased noise degrades the overall error performance, as we will see from the simulations.

3.2. Distributed Differential Scheme II

Since DD-II is built on the differential space-time coded transmission, we can apply the corresponding space-time differential demodulation for DD-II. Then, the ML differential demodulation rule [4], given $\boldsymbol{X}_n^s = \boldsymbol{X}_n^m$, is

$$\hat{Q}_n = \arg \max_{m \in \{0,1,...,M-1\}} \|\boldsymbol{Y}_{n-1}^{d,r} + \boldsymbol{Y}_n^{d,r} \boldsymbol{V}_n^{(m)^{\mathcal{H}}}\|. \tag{15}$$

This is the general structure for DD-II. Similar to DD-I, the Frobenius norm part takes different forms depending upon relaying protocols.

3.2.1. *Decode-and-Forward Protocol*

Similar to DD-I, the received signal at the relays, $\boldsymbol{Y}_n^{r,s}$, is decoded, and this signal is re-encoded into $\boldsymbol{X}_n^r$ by differential modulation. Note that each entry of $\boldsymbol{Y}_n^{r,s}$ and $\boldsymbol{X}_n^r$ is demodulated and remodulated *independently*. The received signal for the given relay transmitted signal $\boldsymbol{X}_n^r = \boldsymbol{X}_n^{m'}$ is

$$\boldsymbol{Y}_n^{d,r} = \boldsymbol{H}_n^{d,r} \boldsymbol{X}_{n-1}^r \boldsymbol{V}_n^{(m')} + \boldsymbol{Z}_n^d = \boldsymbol{Y}_{n-1}^{d,r} \boldsymbol{V}_n^{(m')} + \boldsymbol{Z'}_n^d,$$

where $\boldsymbol{Z'}_n^d = \boldsymbol{Z}_n^d - \boldsymbol{Z}_{n-1}^d \boldsymbol{V}_n^{(m')}$. Since $\boldsymbol{V}_n^{(m')}$ is a unitary matrix, $\boldsymbol{Z'}_n^d$ has twice the variance of $\boldsymbol{Z}_n^d$. Given $\boldsymbol{X}_n^r = \boldsymbol{X}_n^{m'}$, the Frobenius norm part of the ML decision rule in Eq. (15) is

$$\|\boldsymbol{Y}_{n-1}^{d,r} + \boldsymbol{Y}_n^{d,r} \boldsymbol{V}_n^{(m')^{\mathcal{H}}}\|. \tag{16}$$

We can represent Eq. (15) in terms of Eq. (16) as we did in DD-I by defining the transition probability, which is defined as

$$P^r_{m',m} := Pr[\boldsymbol{X}^r = \boldsymbol{X}^{m'} | \boldsymbol{X}^s = \boldsymbol{X}^m]. \tag{17}$$

By the independent decoding at each relay, the cardinality of signal $\boldsymbol{X}^{m'}$ equals to M^L. It follows that the true ML decision rule for DD-II with DF is

$$\hat{Q}_n = \arg \max_{m \in \{0,1,..,M-1\}} \left\{ \sum_{m'=0}^{M^L-1} P^r_{m',m} \|\boldsymbol{Y}_{n-1}^{d,r} + \boldsymbol{Y}_n^{d,r} \boldsymbol{V}_n^{(m')^{\mathcal{H}}}\| \right\}. \tag{18}$$

The complexity of ML receiver increases exponentially with the number of relays L. Although the cardinality of $\boldsymbol{V}^{(m')}$ is M^L, the M from the transmitted signal set are dominant, especially at medium-to-high SNR. Hence, we can simplify the ML decision rule by approximating Eq. (18) as

$$\hat{Q}_n \approx \arg \max_{m \in \{0,1,..,M-1\}} \left\{ \sum_{m'=0}^{M-1} P^r_{m',m} \|\boldsymbol{Y}_{n-1}^{d,r} + \boldsymbol{Y}_n^{d,r} \boldsymbol{V}_n^{(m')^{\mathcal{H}}}\| \right\}. \tag{19}$$

The above equation is well applicable especially at high SNR. The approximation has stronger effects on systems with large L and at low SNR. These results will be validated in Section 4.

3.2.2. *Amplify-and-Forward Protocol*

In AF, each entry of the received signal from the source , $\boldsymbol{Y}_n^{r,s}$, is amplified and forwarded to the destination node. Therefore, the amplified signal at the relays can be represented as

$$\boldsymbol{X}_n^r = \boldsymbol{A} \odot \boldsymbol{Y}_n^{r,s}, \tag{20}$$

where the amplification matrix $\boldsymbol{A} := \text{diag}\{A_{r_1}, A_{r_2}, ..., A_{r_L}\}$, and A_{r_k} is defined in Eq. (12). Then, using the differential modulation, the received signal at the destination is

$$\boldsymbol{Y}_n^{d,r} = \tilde{\boldsymbol{H}}_n \boldsymbol{X}_n^s + \tilde{\boldsymbol{Z}}_n^d = \boldsymbol{Y}_{n-1}^{d,r} \boldsymbol{V}_n^{(m')} + \tilde{\boldsymbol{Z}}'^d_n,$$

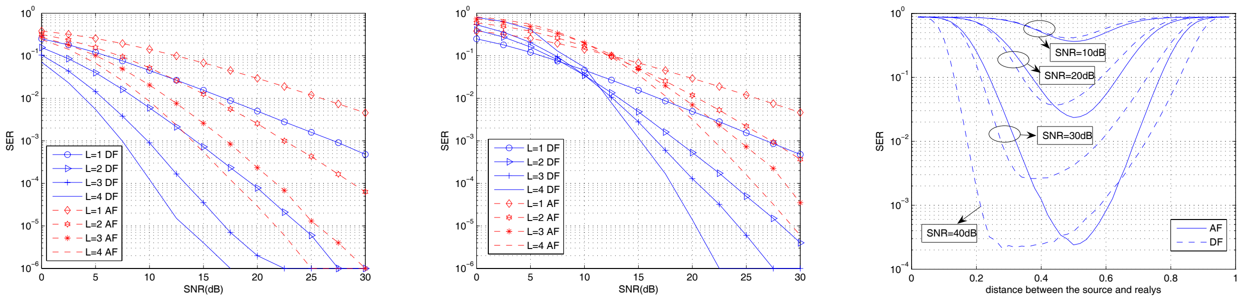
where $\tilde{\boldsymbol{H}}_n = \boldsymbol{A} \odot \boldsymbol{H}_n^{d,r} \odot \boldsymbol{H}_n^{r,s}$, $\tilde{\boldsymbol{Z}}_n^d = \boldsymbol{A} \odot \boldsymbol{H}_n^{d,r} \odot \boldsymbol{Z}_n^r + \boldsymbol{Z}_n^d$, and $\tilde{\boldsymbol{Z}}'^d_n = \tilde{\boldsymbol{Z}}_n^d - \tilde{\boldsymbol{Z}}_{n-1}^d \boldsymbol{V}_n^{(m')}$. The corresponding k-th diagonal entry of the covariance matrix is given by Eq. (13). The ML decision rule given that $\boldsymbol{X}_n^s = \boldsymbol{X}_n^m$ is:

$$\hat{Q}_n = \arg \max_{m \in \{0,1,...,M-1\}} \|\boldsymbol{Y}_{n-1}^{d,r} + \boldsymbol{Y}_n^{d,r} \boldsymbol{V}_n^{(m)^{\mathcal{H}}}\|. \tag{21}$$

We emphasize that this ML decision rule removes the approximation and transition probability as we saw in the DF case. Although the additional noise part can induce performance degradation, it provides an optimal decision rule and alleviates the detection complexity compared with its DF counterpart.

4. SIMULATIONS

In this section, we present the simulation results for DD-I and DD-II with different relaying protocols. We assign equal energy among the source and relays, *i.e.*, $\mathcal{E}_s = \mathcal{E}_{r_k}, \forall k$. Figs. 2(a) and 2(b) depict the simulated symbol error rate (SER) of DD-I and DD-II with $L = 1, 2, 3,$ and 4, under both DF and AF protocols. We use binary DPSK signaling for DD-I. We can see that the diversity benefit is increasing for both schemes as the number of relays increases. For unitary space-time constellation, we use the parameters in [4] for $\eta = 1$ bit/sec/Hz. We can see that DD-II scheme is more effective for a high SNR case. This is the same result as observed in the conventional DUSTC. Simulations show that DF has better performance than AF for both schemes because of the noise enhancement in AF. Notice that this performance advantage in DF is achieved by sacrificing the complexity in DD-I and the optimality in DD-II as we saw



(a) (b) (c)

Fig. 2. (a) Average SER vs. SNR for DD-I (SNR $= \bar{\gamma}_{r_k,s} = \bar{\gamma}_{d,r_k}$); (b) Average SER vs. SNR for DD-II (SNR $= \bar{\gamma}_{r_k,s} = \bar{\gamma}_{d,r_k}$); and (c) Average SER vs. relay location for DD-II ($L = 3$, SNR $= \bar{\gamma}_{r_k,s} + \bar{\gamma}_{d,r_k}$).

in section 3. Comparisons of the two schemes show that DD-I outperforms DD-II. However, we note that DD-II can support a higher transmission rate, and this rate advantage increases as the number of relays increases. Using the same parameters of above, we can transmit $1/(L+1)$ and $1/2$ symbols per time slot with DD-I and DD-II, respectively, since we need $(L+1)$ time slots for 1 symbol transmission with DD-I and $2L$ time slots for L symbols transmission with DD-II.

To capture the effect of the relay positioning, we consider different relay locations at a given average SNR, for both AF and DF. For simplicity, one dimensional coordination is assumed. The source is assumed to be located at $(0, 0)$, the destination located at $(D_d, 0)$, and the relays located at $(D_r, 0)$, where $0 < D_r < D_d$. The fading variance $\sigma^2_{h_{i,j}}$ is assigned depending on D_r and the path-loss exponent d, in the form of $\sigma^2_{h_{i,j}} \propto D_r^{-d}$. We choose $d = 4$ and $L = 3$ and use DD-II for our simulations. As shown in Fig. 2(c), the optimum relay locations under the AF protocol is always the middle point between the source and the destination, regardless of the SNR. This observation is the same as the coherent AF case [8] and agrees with the differential scheme in [10]. For the DF protocol, the results indicate that the optimum relay location is roughly the middle point ($D_r = D_d/2$) at low SNR, but moves towards the source as SNR increases. Similar trends were also observed in the simulations with noncoherent modulations [1, 2]. Intuitively, this is because the error probability at the relays is decreasing as the relays are close to the source.

5. CONCLUSIONS

This paper explores two distributed differential schemes for cooperative wireless networks. We developed two such schemes (DD-I and DD-II) for a wireless relay network with arbitrary number of relays, and derived the modulation and demodulation with both DF and AF relaying protocols. Simulations confirm that both DD-I and DD-II are capable of collecting full diversity gains, under both relaying protocols, and without CSI at the source, relays or destination. We observe that DD-II relies on lifted user cooperation to exploit the space-time processing benefit such as increased bandwidth efficiency. The overall performance of DF is better than AF because the latter induce noise enhancement. Although AF under-performs DF, it entails low-complexity ML detection with DD-I, as well as enjoys the optimality and simplicity with DD-II. Our preliminary results on relay positioning show that the optimal relay location depends upon the relaying protocol. In our future work, we plan to carry out performance analysis of the differential systems, and explore jointly the optimum relay positioning and optimum power allocation.

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