Adaptive Broadcast Transmission in Distributed Two-Way Relaying Networks

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***Abstract*—In this paper we consider adaptive, distributed two-way relaying networks using physical-layer network coding (PLNC). In the multiple-access (MA) phase, two sources transmit simultaneously to multiple relays. Depending on the decoding success at the relays, adaptive transmission schemes are investigated to avoid error propagation in the broadcast (BC) phase employing distributed orthogonal space-time block codes (D-OSTBCs). Recently, adaptive schemes have been proposed, where only relays with correct estimates of the network coded message participate in the BC transmission. In this work, we extend the analysis by incorporating also the case, that some relays are able to detect only one source message and propose a corresponding modified adaptive transmission scheme. For performance evaluations we resort to a semi-analytical method in order to examine the outage behavior of the presented schemes. As demonstrated by link-level simulations, the proposed adaptive scheme outperforms the traditional scheme significantly, especially for asymmetric network topology.**

I. Introduction

The application of physical-layer network coding (PLNC) enables enhanced system throughput in two-way wireless relaying networks [1]. In the multiple-access (MA) phase both sources transmit simultaneously to a relay, the relay estimates the network coded message given by the modulo-2 sum of the two source messages and sends this so-called relay message to both sources in the broadcast (BC) phase. For estimating the relay message, several a-posterior probability (APP) based PLNC decoding schemes were presented in [2], [3], [4].

For one-way relaying systems employing several relays it has been recognized, that full diversity can be achieved by utilizing in the second transmission phase only those relays with a positive cyclic redundancy check (CRC), while the erroneous relays keep silent [5]. The corresponding outage probability has been derived assuming space-time codes in [5] and relay selection in [6] for the transmission from the relays to the destination. The analysis has been extended to two-way relaying networks in [7], where only relays with correct estimates of the relay message participate in the BC transmission using relay selection. The same adaptive relaying concept is considered in [8] employing Alamouti code for a network with two relays and a dual-relay selection technique was proposed in [9] that selects two correct relays with respect to both links in the BC phase.

In all previous contributions on adaptive two-way relaying only those relays with correct estimates of the *relay message* participate in the BC transmission. However, this discards the case that some relays are only able to decode *one individual source message* correctly. In this paper, we take this event into account by designing an adaptive approach for the BC transmission using distributed orthogonal space-time block codes (D-OSTBCs). A semi-analytical method is applied to obtain the outage behavior of the presented scheme and link-level simulations are performed to verify the analytical results.

The remainder of this paper is organized as follows. The system model is illustrated in Section II. The traditional and the modified adaptive BC transmission schemes are presented with the derivation of outage probability in Section III and IV, respectively. Numerical results are discussed in Section V and Section VI concludes the paper.

II. System Description

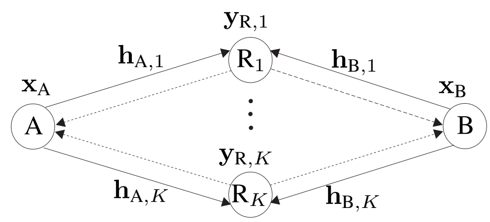

Fig. 1. A two-way relaying network consisting of a MA phase (solid lines) and a BC phase (dashed lines) where two sources A and B exchange messages with each other via K distributed relays R_k, $k = 1, \cdots, K$.

The considered distributed two-way relaying network is shown in Fig. 1, where two sources A and B exchange information with each other via K relays R_k, $k = 1, \cdots, K$. All nodes are equipped with a single antenna. In the MA phase, both sources encode their information words $\mathbf{b}_A$ and $\mathbf{b}_B$ with the same linear code of rate R_C, resulting in *source codewords* $\mathbf{c}_A$ and $\mathbf{c}_B$. These codewords are mapped to symbol vectors $\mathbf{s}_A$ and $\mathbf{s}_B$ of length L, which are transmitted to the relays simultaneously. The l-th received signal at R_k with $l = 1, \cdots, L$ is given by the linear superposition of the transmitted signals $s_{A,l}$ and $s_{B,l}$ weighted by the fading coefficients $h_{A,k,l}$ and $h_{B,k,l}$ as

$$y_{R,k,l} = h_{A,k,l} s_{A,l} + h_{B,k,l} s_{B,l} + n_{R,k,l} \ . \qquad (1)$$

Upon reception, each relay R_k aims to estimate the network coded message $\mathbf{c}_R = \mathbf{c}_A \oplus \mathbf{c}_B$ from $\mathbf{y}_{R,k}$ and transmits this *relay codeword* to the sources in the BC phase. Assuming that all relays decoded $\mathbf{c}_R$ correctly, transmit diversity can be exploited by sending from each relay a spatial component of a corresponding D-OSTBC. Let $\mathbf{s}_{\mathrm{R},k}$ denote the spatial component at relay R_k, the l-th receive signal at source m, $m = \{\mathrm{A}, \mathrm{B}\}$, is given by

$$y_{m,l} = \sum_{k=1}^{K} h'_{m,k,l} s_{\mathrm{R},k,l} + n_{m,l} \ . \tag{2}$$

Consequently, each source performs space-time linear detection with respect to the applied D-OSTBC, estimates $\hat{\mathbf{c}}_{\mathrm{R}}$, and determines the message from the counterpart by network decoding. We assume in general, that the transmission channels are non-reciprocal, i.e., $h'_{m,k,l} \neq h_{m,k,l}$, and no channel state information (CSI) is available at transmitter side. The additive white Gaussian noise (AWGN) terms $n_{\mathrm{R},k,l}$ and $n_{m,l}$ have zero mean and variance σ_n^2. Additionally, the transmit power at each source and the transmitting relay cluster is normalized to 1, yielding the signal-to-noise-ratio (SNR) defined as $\mathrm{SNR} = 1/\sigma_n^2$.

For estimating the relay message $\mathbf{c}_{\mathrm{R}}$ based on $\mathbf{y}_{\mathrm{R},k}$, different APP-based PLNC decoding schemes have been discussed in, e.g., [2], [3], [4]. In case of separated channel decoding (SCD), both source messages $\hat{\mathbf{c}}_{\mathrm{A}}$ and $\hat{\mathbf{c}}_{\mathrm{B}}$ are estimated either in parallel (P-SCD) or successively (S-SCD), followed by network coding $\hat{\mathbf{c}}_{\mathrm{R}} = \hat{\mathbf{c}}_{\mathrm{A}} \oplus \hat{\mathbf{c}}_{\mathrm{B}}$. In contrast, the relay codeword is directly estimated from the receive signal by joint channel decoding and physical-layer network coding (JCNC). Furthermore, generalized JCNC (G-JCNC) applies a non-binary decoder exploiting the channel codes of both sources in parallel with a subsequent PLNC step leading to superior performance compared to the other schemes [3], [4].

III. Traditional Adaptive BC Transmission

A. Traditional Adaptive Relaying

Assuming the application of the same CRC code in both sources, each relay R_k can determine its decoding success. In order to prevent scarifying the BC phase from decoding errors, adaptive relaying has been proposed where only relays with correct network coded message $\mathbf{c}_{\mathrm{R}}$ participate in the BC transmission [7], [8], [9]. Specifically, denoting $\mathcal{D}_{\mathrm{R}}$ the decoding set that contains the error-free relays in the MA phase, only relays $\mathrm{R}_k \in \mathcal{D}_{\mathrm{R}}$ transmit their corresponding layer of the D-OSTBC to exploit spatial diversity. Applying this adaptive scheme, the BC transmission in (2) is adapted to

$$y_{m,l} = \sum_{\mathrm{R}_k \in \mathcal{D}_{\mathrm{R}}} h'_{m,k,l} s_{\mathrm{R},k,l} + n_{m,l} \ . \tag{3}$$

If no relay is able to decode correctly, i.e., $\mathcal{D}_{\mathrm{R}} = \emptyset$, a *MA outage* occurs resulting in an end-to-end (e2e) outage.

B. Outage Analysis

Extending the analysis in [5], the *e2e outage* probability P_{out} of the distributed two-way relaying system using the total probability law is given by

$$P_{\mathrm{out}} = \sum_{\mathcal{D}_{\mathrm{R}}} \Pr\{\mathcal{D}_{\mathrm{R}}\} \left(1 - \prod_{m=\{\mathrm{A},\mathrm{B}\}} \left(1 - \Pr\{R > I_m | \mathcal{D}_{\mathrm{R}}\} \right) \right) , \tag{4}$$

where $\Pr\{\mathcal{D}_{\mathrm{R}}\}$ represents the probability that a certain decoding set $\mathcal{D}_{\mathrm{R}}$ occurs. Furthermore, $\Pr\{R > I_m | \mathcal{D}_{\mathrm{R}}\}$ denotes the probability that source m is in outage as the rate R in the BC phase is larger than the mutual information I_m between active relays and source m. Assuming the application of D-OSTBC while ignoring the rate loss in the orthogonal code design, I_m can be written as [5]

$$I_m = \log_2 \left(1 + \frac{\mathrm{SNR}}{|\mathcal{D}_{\mathrm{R}}|} \sum_{\mathrm{R}_k \in \mathcal{D}_{\mathrm{R}}} |h'_{m,k}|^2 \right) , \tag{5}$$

where the transmit power at the relay cluster is normalized among the $|\mathcal{D}_{\mathrm{R}}|$ active relays involved in the BC transmission. Compared to one-way relaying, the system is in outage, when at least one source fails to decode the relay message as indicated by the product in (4).

C. Outage Analysis in Symmetric Networks

In the sequel we examine the special case, where all channels in the two-way relaying system obey Rayleigh distribution with identical normalized variance. In such a symmetric condition, the outage behavior at all relays is statistically equivalent. The corresponding system outage probability can be expressed as

$$\begin{aligned} P_{\mathrm{out}} = & \sum_{\kappa=0}^{K} \binom{K}{\kappa} \overbrace{(1-p_{\mathrm{R}})^{\kappa} p_{\mathrm{R}}^{K-\kappa}}^{W_\kappa} \\ & \times \left(1 - \left(1 - \Pr\left\{ R > I_{\mathrm{A}} \big| |\mathcal{D}_{\mathrm{R}}| = \kappa \right\} \right)^2 \right) . \end{aligned} \tag{6}$$

Therein, p_{R} represents the outage probability at one relay with respect to the relay message and the kernel W_κ denotes the probability that a specific combination of κ relays decode the relay message correctly with $\binom{K}{\kappa}$ possibilities in total, $\kappa = 0, \cdots, K$. The calculation in (6) sums up the outage probability in the BC phase when κ relays are error-free with respect to the relay message over $0 \leq \kappa \leq K$. Note that p_{R} is derived in [7] based on the capacity region of the MA channel [10]. In this paper, specific APP-based decoding schemes are considered, where p_{R} is achieved by link-level simulations. Thus, we apply a semi-analytical method for outage analysis.

IV. Modified Adaptive BC Transmission

A. Modified Adaptive Relaying

As noted in Section II, SCD and G-JCNC estimate not only the relay message $\mathbf{c}_{\mathrm{R}}$ but also the individual source messages $\mathbf{c}_{\mathrm{A}}$ and $\mathbf{c}_{\mathrm{B}}$ [3]. Thus, it might happen that some relays only decode one source message correctly while the network coded message is erroneous. This case is ignored in the traditional adaptive transmission scheme in Section III leading to an outage. Here, we extend the adaptive scheme incorporating this case as well. To this end, the relays that only decode $\mathbf{c}_{\mathrm{A}}$ correctly are collected in $\mathcal{D}_{\mathrm{R}}^{\mathrm{A}}$. Note that the relays belonging to $\mathcal{D}_{\mathrm{R}}^{\mathrm{A}}$ must not be in $\mathcal{D}_{\mathrm{R}}$. The set $\mathcal{D}_{\mathrm{R}}^{\mathrm{B}}$ is defined similarly. The modified adaptive BC transmission scheme is described as follows.

- If $\mathcal{D}_\mathrm{R} \neq \emptyset$, the relays $\mathrm{R}_k \in \mathcal{D}_\mathrm{R}$ transmit the relay message using D-OSTBC as in the traditional scheme.
- If $\mathcal{D}_\mathrm{R} = \emptyset$, $\mathcal{D}_\mathrm{R}^\mathrm{A} \neq \emptyset$ and $\mathcal{D}_\mathrm{R}^\mathrm{B} \neq \emptyset$, the relays $\mathrm{R}_i \in \mathcal{D}_\mathrm{R}^\mathrm{A}$ and $\mathrm{R}_j \in \mathcal{D}_\mathrm{R}^\mathrm{B}$ transmit $\mathbf{s}_{\mathrm{R},i}^\mathrm{A}$ and $\mathbf{s}_{\mathrm{R},j}^\mathrm{B}$ using their respective D-OSTBCs to the sources simultaneously in the BC phase. Here, $\mathbf{s}_{\mathrm{R},i}^\mathrm{A}$ and $\mathbf{s}_{\mathrm{R},j}^\mathrm{B}$ denote the correctly decoded individual source messages from A and B after D-OSTBC encoding, respectively. Therefore, the l-th receive signal at source m is formulated as

$$y_{m,l} = \sum_{\mathrm{R}_i \in \mathcal{D}_\mathrm{R}^\mathrm{A}} h'_{m,i,l} s_{\mathrm{R},i,l}^\mathrm{A} + \sum_{\mathrm{R}_j \in \mathcal{D}_\mathrm{R}^\mathrm{B}} h'_{m,j,l} s_{\mathrm{R},j,l}^\mathrm{B} + n_{m,l} \, . \quad (7)$$

  Upon receiving in the BC phase, each source m subtracts the self-interference term with respect to $\mathbf{s}_{\mathrm{R},i}^m$ in (7) and performs D-OSTBC detection to estimate the message from the counterpart.
- Otherwise, the system is in outage.

B. Outage Analysis

Recall that in the traditional adaptive scheme, the system is in outage if $\mathcal{D}_\mathrm{R} = \emptyset$ happens, i.e., no relay is able to decode the relay message correctly. In contrast, the modified adaptive scheme exploits the decoding results of the individual source messages at the relays for SCD and G-JCNC. Thus, relays decoding $\mathbf{c}_\mathrm{R}$ erroneously but one individual source message $\mathbf{c}_m$ correctly can assist the e2e transmission improving the overall system performance. Using total probability the e2e outage probability for the modified adaptive BC transmission scheme can be expressed as

$$\begin{aligned} P_\text{out} = & \sum_{\mathcal{D}_\mathrm{R}/\emptyset} \Pr\{\mathcal{D}_\mathrm{R}\} \left(1 - \prod_{m=\{\mathrm{A},\mathrm{B}\}} \Big(1 - \Pr\{R > I_m | \mathcal{D}_\mathrm{R}\} \Big) \right) \\ & + \sum_{(\mathcal{D}_\mathrm{R}^\mathrm{A}, \mathcal{D}_\mathrm{R}^\mathrm{B}) | \mathcal{D}_\mathrm{R} = \emptyset} \Pr\{(\mathcal{D}_\mathrm{R}^\mathrm{A}, \mathcal{D}_\mathrm{R}^\mathrm{B})\} \\ & \times \left(1 - \prod_{m=\{\mathrm{A},\mathrm{B}\}} \Big(1 - \Pr\{R > I_m^* | (\mathcal{D}_\mathrm{R}^\mathrm{A}, \mathcal{D}_\mathrm{R}^\mathrm{B})\} \Big) \right) , \end{aligned} \quad (8)$$

where the mutual information I_m^* is defined as

$$I_m^* = \log_2 \left(1 + \frac{\text{SNR}}{|\mathcal{D}_\mathrm{R}^\mathrm{A}| + |\mathcal{D}_\mathrm{R}^\mathrm{B}|} \sum_{\mathrm{R}_k \in \mathcal{D}_\mathrm{R}^m} |h'_{m,k}|^2 \right) . \quad (9)$$

Note that the normalization factor $|\mathcal{D}_\mathrm{R}^\mathrm{A}| + |\mathcal{D}_\mathrm{R}^\mathrm{B}|$ in (9) guarantees that the transmit power at the relay cluster is normalized among the active relays in this case.

C. Outage Analysis in Symmetric Networks

Similar to the previous section, the special case of symmetric link characteristics is considered for the modified adaptive scheme. The outage behavior remains unchanged when at least one relay decodes the relay message correctly, which has been derived in (6) when $1 \leq \kappa \leq K$. Thus, the first term in (8) can be rewritten in the same form as (6) except that κ starts with 1. The second term in (8) can be reformulated as

$$\begin{aligned} P^* = & \sum_{q=0}^{K} \sum_{r=0}^{q} \binom{K}{r} \binom{K-r}{q-r} W_{r,q-r}^* \\ & \times \left(1 - \Big(1 - \Pr\big\{ R > I_\mathrm{A}^* \big| (|\mathcal{D}_\mathrm{R}^\mathrm{A}| = r, |\mathcal{D}_\mathrm{R}^\mathrm{B}| = q - r) \big\} \Big)^2 \right) \end{aligned} \quad (10)$$

with the kernel $W_{r,q-r}^*$ denoting the probability of one possible combination of q relays that yield the decoding results fulfilling $|\mathcal{D}_\mathrm{R}^\mathrm{A}| = r$, $|\mathcal{D}_\mathrm{R}^\mathrm{B}| = q - r$ and $|\mathcal{D}_\mathrm{R}| = 0$. Here $q = |\mathcal{D}_\mathrm{R}^\mathrm{A}| + |\mathcal{D}_\mathrm{R}^\mathrm{B}|$ represents the total number of relays with one correctly estimated source message. Now, a MA outage occurs if either $r = 0$ or $q - r = 0$ since only one source message is recovered correctly within the relay cluster leading to an e2e outage. In contrast, both sources are transmitted in the BC phase when $2 \leq q \leq K$ and $1 \leq r \leq q - 1$.

In order to deduce $W_{r,q-r}^*$, p_R^A and p_R^B denoting the outage probabilities at one relay regarding the individual messages are again achieved by simulations for SCD and G-JCNC. Taking the overall $2K$ individual decoding results into account, the expression of $W_{r,q-r}^*$ for different APP-based decoders is given by

$$W_{r,q-r}^* = \begin{cases} (1 - p_\mathrm{R}^\mathrm{A})^q (p_\mathrm{R}^\mathrm{A})^{2K-q} & \text{P-SCD} \\ (p_\mathrm{R}^\mathrm{B} - p_\mathrm{R}^\mathrm{A})^q (p_\mathrm{R}^\mathrm{A})^{K-q} & \text{S-SCD} \\ (p_\mathrm{R} - p_\mathrm{R}^\mathrm{A})^q (2p_\mathrm{R}^\mathrm{A} - p_\mathrm{R})^{K-q} & \text{G-JCNC} \, . \end{cases} \quad (11)$$

and illustrated as follows.

- For P-SCD, p_R^A and p_R^B are equal and independent from each other. Therefore, $W_{r,q-r}^*$ corresponds to q times correct decoding and $2K - q$ times erroneous decoding with respect to the individual messages.
- For S-SCD, let p_R^A denote the outage probability of decoding the message from the stronger link. p_R^B then represents the outage probability of common decoding with respect to the interference reduced signal. Note that the performance of successive decoding is dependent on the initial decoding. To this end, the probabilities that a relay only decodes one source message from the initial decoding correctly and fails to decode both sources messages yield $(p_\mathrm{R}^\mathrm{B} - p_\mathrm{R}^\mathrm{A})$ and p_R^A, respectively. This results in the representation of $W_{r,q-r}^*$ in (11).
- For G-JCNC, p_R^A and p_R^B are equal but strongly dependent with each other since both source messages are jointly considered and estimated in the decoder. By some simple probability manipulations, the probabilities that only one source message is correctly decoded and both source messages are erroneously decoded are derived as $p_\mathrm{R} - p_\mathrm{R}^\mathrm{A}$ and $2p_\mathrm{R}^\mathrm{A} - p_\mathrm{R}$, respectively. The corresponding $W_{r,q-r}^*$ can then be represented easily.

D. Signaling Overhead

In practical systems, all relays perform APP-based PLNC decoding individually. By applying the same CRC code at both sources, each relay is aware of its local decoding status about the relay message as well as the individual source messages for SCD and G-JCNC. Subsequently, every relay $R_k \in \mathcal{D}_R$ transmits its own layer of the applied D-OSTBC whereas the other relays switch into reception mode. Therefore, each relay that is not in $\mathcal{D}_R$ is able to overhear the signal transmitted by $R_k \in \mathcal{D}_R$ and recognizes that at least one relay has decoded the relay message correctly. On the other hand, if the relay does not recognize any transmission during a specified time slot denoted as idle time T_I, it knows that no relay was capable of correctly estimating $\mathbf{c}_R$. In this case, the relay forwards the individual message $\mathbf{s}_A$ or $\mathbf{s}_B$ using its own layer in the applied D-OSTBC if it is in the decoding set $\mathcal{D}_R^A$ or $\mathcal{D}_R^B$, respectively. Otherwise, the system is in outage. By such an implicit CRC exchange between the relays termed *CRC over the air*, no extra signaling overhead is required except for the idle time T_I. Denoting T_F the time duration to transmit one data frame, the overall time consumption to finish one e2e transmission yields $2T_F + T_I$ for the modified adaptive scheme.

V. Numerical Results

A. Outage Analysis for Symmetric Networks

For outage analysis a symmetric network is considered as in Subsection III-C and IV-C, where the distance between every pair of source and relay nodes is normalized to 1. The outage probabilities p_R, p_R^A and p_R^B at each relay are achieved by simulating the frame error rate (FER) for SCD and G-JCNC. Practically, this is done assuming multi-path fading channels with $N_H = 5$ taps and the application of OFDM with QPSK modulation and $N_C = 1024$ subcarriers. An LDPC code of rate $R_C = 0.5$ is employed for each OFDM symbol.

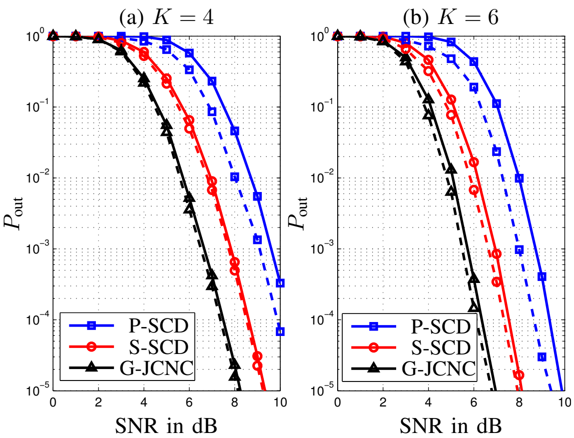

Fig. 2. Outage probability P_{out} versus SNR for both traditional (-) and modified (- -) adaptive schemes using P-SCD, S-SCD and G-JCNC at the relays. A symmetric network is considered with (a) $K = 4$ relays and (b) $K = 6$ relays. The rate of the BC phase is set to $R = 0.5$.

The e2e outage probabilities in (6) and (10) are drawn in Fig. 2 for the traditional and the modified adaptive transmission scheme, respectively. It is observed that the modified scheme leads to decreased outage probability especially for P-SCD. However, the improvement is nearly not observable for S-SCD and G-JCNC when $K = 4$. This is because p_R^A and p_R^B are highly correlated with each other, and thus it rarely occurs that one relay decodes only one source message correctly. The improvement becomes more significant when $K = 6$ since the event that both $\mathcal{D}_R^A$ and $\mathcal{D}_R^B$ are not empty occurs more frequently with increasing number of relays which provides larger diversity gain.

B. FER Performance

For link-level simulations similar parametrization is applied in the BC phase as in the MA phase described in the previous subsection. Here, we consider a linear topology of the relay nodes as shown in Fig. 3 where the K relays are equally distributed on a line $R_1 - R_K$ with d_R denoting the distance between R_1 and R_K. Therefore, the distance between neighboring relays amount to $d_R/(K-1)$. Furthermore, the angle of the two lines connecting the sources A − B and the relays $R_1 - R_K$ respectively is set to $\pi/4$ leading to the minimum and maximum distances $d_{min/max} = 1 \mp d_R + \frac{1}{2}d_R^2$ between a source and a relay. Note that $d_R = 0$ corresponds to the symmetric network in the previous subsection, where all relays are assumed to be located at the same position but still the involved channels are uncorrelated. The path-loss factor is set to $\alpha = 4$. In the sequel, $K = 4$ relays are assumed with rate matching for the adaptive scheme. Specifically, when 2 relays are active, Alamouti code [11] is applied. When 3 or 4 relays are active, the 3/4-rate D-OSTBC [12] is applied with the channel code rate adapted by puncturing to $R'_C = 2/3$. Therefore, the same data rate is achieved when different events occur.

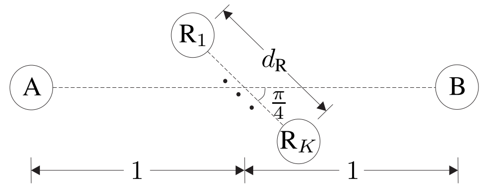

Fig. 3. A two-way relaying network with K linearly positioned relays. Equal distance is assumed between neighboring relays. The two lines connecting the sources and the relays respectively form an angle of $\pi/4$.

As can be observed in Fig. 4, the FER performance is only slightly improved by the modified adaptive scheme for S-SCD and G-JCNC in a symmetric network. However, the improvement is enhanced greatly when the relays are linearly positioned with $d_R = 0.4$, especially in the low SNR region. This is because the asymmetric topology leads to increased chances that the relays decode only one source message correctly. Specifically, the relays closer to source m compared to the other tend to only obtain correct estimation of $\mathbf{c}_m$. Correspondingly, it occurs with higher frequency that both $\mathcal{D}_R^A$ and $\mathcal{D}_R^B$ are not empty for the network topology depicted in Fig. 3, making the modified adaptive scheme more advantageous against the traditional one.

C. Throughput Performance

The normalized throughput of the investigated schemes is shown in Fig. 5 assuming no idle time for the modified adaptive transmission. The figure shows similar performance

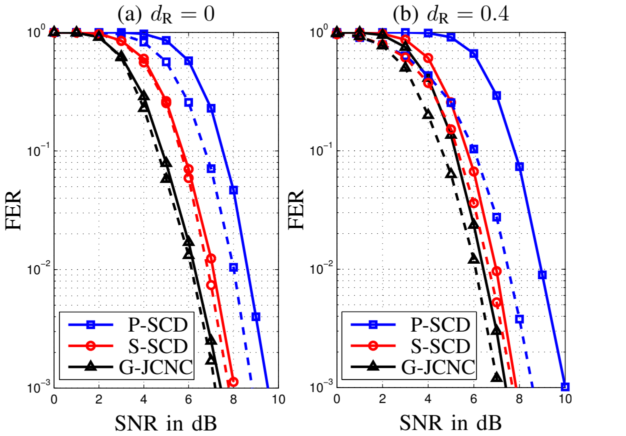

Fig. 4. FER performance versus SNR for both traditional (-) and modified (- -) adaptive schemes using P-SCD, S-SCD and G-JCNC at the relays, (a) is for $d_\mathrm{R} = 0$ and (b) is for $d_\mathrm{R} = 0.4$.

characteristics for the schemes as observed in Fig. 4. Note that tremendous gains are achieved especially in the low SNR region when $d_\mathrm{R} = 0.4$. In Fig. 6 the dependency of the throughput on the ratio $T_\mathrm{I}/T_\mathrm{F}$ is shown for SNR $= 4$dB. Obviously, longer idle time T_I leads to decreased throughput for the modified adaptive scheme. Moreover, the performance of the modified scheme decreases more rapidly in Fig. 6(b) as the probability of requiring an idle time increases for the asymmetric topology. However, the throughput gain compared to the traditional adaptive scheme is even more dramatic due to significantly improved FER performance.

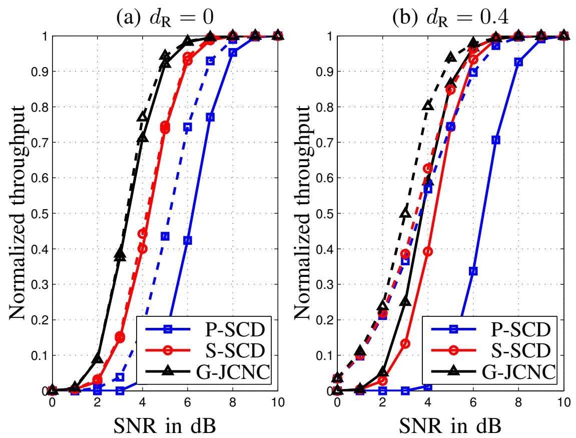

Fig. 5. Normalized throughput versus SNR for both traditional (-) and modified (- -) adaptive schemes using P-SCD, S-SCD and G-JCNC at the relays with $T_\mathrm{I} = 0$, (a) is for $d_\mathrm{R} = 0$ and (b) is for $d_\mathrm{R} = 0.4$.

VI. Concluding Remarks

In this paper we considered PLNC in distributed two-way relaying networks. We proposed a modified adaptive scheme where also relays that estimated only one source message correctly participate in the broadcast transmission. Furthermore, we have examined the outage probability of the presented scheme by a semi-analytical method and verified the results by link-level simulation indicating severe performance improvements especially for asymmetric networks.

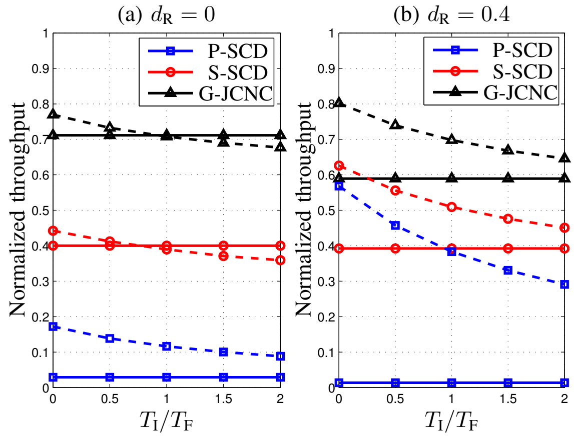

Fig. 6. Normalized throughput versus $T_\mathrm{I}/T_\mathrm{F}$ for both traditional (-) and modified (- -) adaptive schemes using P-SCD, S-SCD and G-JCNC at the relays with SNR $= 4$dB, (a) is for $d_\mathrm{R} = 0$ and (b) is for $d_\mathrm{R} = 0.4$.

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