Adaptive Three-Phase Differential Transmission Scheme for Two-Way Relay Networks

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Abstract —This work considers two-way relay network (TWRN), where two source nodes transmit information bits to each other with the help of a relay node. To avoid channel estimation at the receiver and perfect synchronization, we propose adaptive three-phase differential transmission schemes for the TWRN where the relay node re-encodes its sending signals according to its detection status in the first and second phase dynamically. Numerical results show that the proposed optimal adaptive differential transmission schemes outperform the conventional two-phase protocol significantly in the high signal-to-noise ratio region. To further decrease the computation complexity, a sub-optimal combination scheme is proposed and proved to be as effective as optimal combination scheme to enhance system robustness.

Index Terms—Two-way relay networks, three-phase, differential transmission, direct link

I. Introduction

Recently, the Two-Way Relay Network (TWRN) has attracted considerable research interests, where two source nodes exchange information with the help of a relay node. The TWRN is pervasive in real-world instances, such as two mobile users exchanging information through one common base station, or sensors connected by a center router [1], [2]. An effective relaying scheme is critical to system performance and capacity. However, some simple protocols, e.g., Amplify-and-Forward (AF)/Decode-and-Forward (DF), provide low frequency efficiency since they need four phases to finish the exchange of one message with each other. Considering the special structure of TWRN, the concept of network coding has been applied including Analog Network Coding (ANC) [3], Physical-layer Network Coding (PNC) [4], Digital Network Coding (DNC) [5] and their equivalences to increase system spectrum efficiency. In general, the complete transmission of two-way relay channel can be divided into two or three phases. In [4], a two-phase PNC protocol for TWRN was proposed which allowed the two source nodes to transmit information simultaneously in the first phase, and the relay node broadcasted the signals to the two source nodes in the second phase. However, the two-phase scheme required perfect synchronization which was difficult to be achieved in practical wireless environment due to the distributed nature of the source and the relay nodes [6]. Furthermore, the two-phase relaying transmission scheme cannot exploit the direct link between the two source nodes, even though it may exist physically. In addition, the outage and the diversity performance of two-phase relaying schemes are poorer than the traditional one-way relaying scheme. Therefore, many three-phase relaying schemes have been investigated which can utilize the direct link by allowing the two source nodes to transmit in different two phases and the relay node to transmit in the third phase [7]-[11].

However, most of these studies on TWRN have been made under the unrealistic assumption of perfect channel state information (CSI). Although the CSI is likely to be acquired through the use of pilot signals, the channel estimation process increases the computational complexity. Furthermore, in fact it would be very difficult to obtain accurate CSI in a rapidly changing mobile environment, especially in TWRN where two channel coefficients are required to be estimated each way. The simulation results in [12], [13] showed that imperfect CSI can deteriorate system performance severely in TWRNs. In these cases, differential modulation, which does not rely on instant CSI, becomes a preferred choice. The receiver in this case decodes the information by comparing the phase of the current symbol to that of the previous symbol. Several differential relaying schemes have been proposed in the literatures for TWRNs [14]-[17]. In [14], an ANC scheme with differential modulation using AF protocol for two-phase relay networks was proposed. In [15], the authors proposed differential transmission scheme for TWRNs with AF and DF protocols. In [16], a double differential transmission scheme was proposed to achieve successful two-way relay two-phase transmission over Nakagami-m fading channels. Furthermore, these schemes may cause irreducible error floor due to the detection errors which may occur at the relay node. Simulation results showed that these schemes suffer from more than 3dB performance loss as compared to their coherent counterparts. In our early work [17], we proposed a generalized differential modulation scheme for AF based

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two-phase TWRN, which is able to bridge the 3dB performance gap.

In order to exploit the direct link, some three-phase differential modulation schemes are proposed [18], [19]. Compared with two-phase relaying scheme, no perfect synchronization is required in the three-phase relay protocol as the two source nodes transmit in different two phases. Furthermore, the system performance can be improved by exploiting the direct link. In our early work [19], several relaying three-phase differential transmission schemes for the TWRN with direct link were proposed and simulation results showed that the proposed schemes outperform the existing schemes significantly in the high SNR region. However, it's assumed that in the first and second times slots, the relay node always can detect correctly which cannot be achieved in real-life scenarios. This problem inspired the proposed adaptive three-phase differential modulation schemes of this paper.

In this paper, we propose an adaptive three-phase differential modulation strategy for TWRN where the relay node re-encodes its sending signals according to its detection status in the first and second phase dynamically. Furthermore, both optimal and suboptimal combination schemes are proposed. It's shown that with the two proposed combination schemes, the BER performance can be significantly improved in high SNR region.

The remainder of the paper is organized as follows. The system model is presented in Section II. In Section III, we introduce the proposed adaptive differential modulation and combination methods. The simulation results are analyzed in Section IV. Finally conclusions are drawn in Section V.

II. System Model

Consider a two-way relay network with two source nodes *A* and *B*, which are communicating with the help of the relay node *R*. Assuming that all the nodes are equipped with single antenna and employing half-duplex mode, i.e., each node cannot transmit and receive at the same time. As shown in Fig. 1, the node *A* and *B* exchange data in three phases. In the first phase, the node *A* sends data to the relay *R* and *B*. In the second phase, the node *B* transmits data to the relay *R* and *A*. In the third phase, the relay node *R* broadcasts signal to node *A* and *B*.

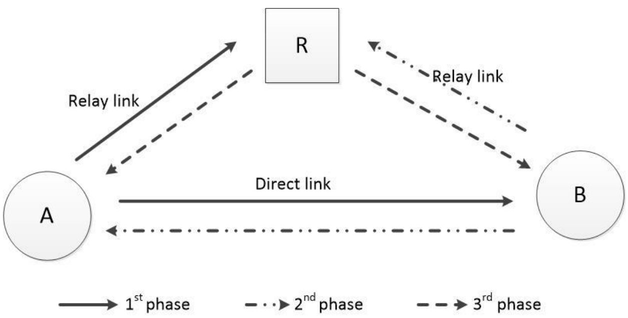

Fig. 1. Three-phase transmission scheme for two-way relay network.

Suppose *A* and *B* transmit $s_u(k)\in\Phi, u=A,B$ to each other, where Φ is the signal constellation of the M-ary phase shift keying (M-PSK) unit-power information symbol, i.e., $\Phi=\{e^{j\theta}\mid\theta=\frac{2\pi}{M}l, l=0,1,\ldots M-1\}$. We adopt classical differential encoder, the transmit signals of node *A*, *B* are modulated as $x_u(k)=x_u(k-1)s_u(k), u=A,B$. While $x_u(0)$, $u=A,B$ are the initial reference symbols which are known at node *A* and *B*. No instant CSI is needed at any node.

In the first phase, the node *A* transmits signal $x_A(k)$ to node *B* and *R*. So the received signals at node *B* and *R* can be expressed respectively as

$$y_{B,1}(k)=h_{AB}x_A(k)+z_{B,1}(k) \tag{1}$$

$$y_{R,1}(k)=h_{AR}x_A(k)+z_{R,1}(k) \tag{2}$$

where h_{AB} and h_{AR} are the channel coefficients from node *A* to *B* and *R* respectively. $Z_{B,1}(k)$ and $Z_{R,1}(k)$ denote the additive white Gaussian noise (AWGN) with zero mean and a variance of N_0 of node *B* and *R* in the first phase.

In the second phase, the node *B* transmits signal $x_B(k)$ to node *A* and *R*. The received signals at node *A* and *R* can be presented respectively as

$$y_{A,2}(k)=h_{BA}x_B(k)+z_{A,2}(k) \tag{3}$$

$$y_{R,2}(k)=h_{BR}x_B(k)+z_{R,2}(k) \tag{4}$$

where h_{BA} and h_{BR} are the channel coefficients from *B* to *A* and *R* respectively. $Z_{A,2}(k)$ and $Z_{R,2}(k)$ denote the AWGN with zero mean and a variance of N_0 of node *A* and *R* in the second phase.

In the first and second phases, the relay node *R* decodes the received signals from node *A* and *B* respectively using the standard differential detection operation, i.e.,

$$\hat{s}_A(k)=\arg\min_{S_A(k)}\left\|y_{R,1}(k)-y_{R,1}(k-1)s_A(k)\right\|^2, k=1,\ldots,K \tag{5}$$

$$\hat{s}_B(k)=\arg\min_{S_B(k)}\left\|y_{R,2}(k)-y_{R,2}(k-1)s_B(k)\right\|^2, k=1,\ldots,K \tag{6}$$

and estimate the node *A* and *B*'s transmit information bits separately.

Then, the relay *R* performs re-encoding to generate the transmit signal as

$$x_R(k)=f(y_{R,1}(k),y_{R,2}(k)) \tag{7}$$

where $f(x,y)$ is the re-encoding function, which is depending on the detection status of $S_A(k)$ and $S_B(k)$, the relay node will perform adaptive re-encoding to obtain the transmit signal $x_R(k)$ in the third phase. The detailed adaptive differential encoding process will be specified in Section III.

Let $x_R(k)$ be the re-encoded signal at relay *R*. In the third phase, the relay node *R* broadcasts $x_R(k)$ to the node *A* and *B*. The received signals at node *A*, *B* can be written as

$$y_{u,3}(k) = h_{R,u} x_R(k) + z_{u,3}(k), \quad u = A,B \tag{8}$$

where $h_{R,u}$, $u=A,B$ are the channel coefficients from node R to A and B respectively. $z_{u,3}(k), u = A,B$ denote the AWGN with zero mean and a variance of N_0 of node A and B in the third phase.

Node A and B detect information bits using the two received signals from the relay link and direct link adaptively which will be specified in Section III as well.

III. Adaptive Differential Modulation and Detection Method

In this section, we propose an adaptive three-phase differential modulation and combination scheme based on TWRN that relay R combines unit-power information symbol $S_R(k)$ and operates differential encoder according to the relay node detection status in the first and second phases. The relay node R may estimate information from node A and B correctly or not, so there are four possible situations including detection correctly for both two source node, correctly only for node A or B and incorrectly for both two source nodes.

A. Detect Correctly for both Node A and B

Differential Transmission Scheme: If relay R detects the information bits for both node A and B successfully, i.e., $\hat{s}_u(k) = s_u(k)$, $u = A,B$, R combines the two unit-power information symbols as:

$$s_R(k) = \hat{s}_A(k) \times \hat{s}_B(k) \tag{9}$$

Then relay R operates the differential MPSK encoding process as:

$$x_R(k) = x_R(k-1) \times s_R(k) \tag{10}$$

Detection Method: As the relay R detects information bits correctly, the noises in the first phase and second phase are removed by the relay R. So in the third phase, node A and B decode just following the standard differential detection operations.

In this case, node A and B can detect information bits as:

$$u_A(k) = y^*_{A,2}(k-1) y_{A,2}(k) + y^*_{A,3}(k-1) s^*_A(k) y_{A,3}(k) \tag{11}$$

$$u_B(k) = y^*_{B,1}(k-1) y_{B,1}(k) + y^*_{B,3}(k-1) s^*_B(k) y_{B,3}(k) \tag{12}$$

B. Dectect Correctly Only for Node A

Differential Transmission Scheme: If relay R succeeds in detecting the information bits only for node A, i.e., $\forall k, \hat{s}_A(k) \neq s_A(k), \exists k_1, \hat{s}_B(k_1) \neq s_B(k_1)$, R combines unit-power information symbol following hybrid differential network coding as follows.

Firstly, R operates $\hat{s}_A(k)$ follows differential decoding as

$$x_{R,1}(k) = x_{R,1}(k-1) \hat{s}_A(k) \tag{13}$$

Then R multiplies $x_{R,1}(k)$ by $y_{R,2}(k)$ and one amplification coefficient a_{AR} directly as the transmit signal of node R in the third phase.

$$x_R(k) = a_{AR} x_{R,1}(k) y_{R,2}(k) \tag{14}$$

a_{AR} is chosen to satisfy the transmit power constraint at the relay, which is given by

$$a_{AR} = \sqrt{\frac{P_R}{G_{BR} P_B + N_0}} \tag{15}$$

Here, P_B and P_R are the average transmission powers of node B and R, G_{BR} is the average channel gain from node B to R and N_0 is the variance of AWGN in node R.

Detection Method: As relay R cannot detect the information bits from node B and amplifies the received signal from B directly, the noise is amplified as well as the useful signal.

Substituting (13) and (4) into (8), the received signal in source A in the third phase can be expressed as

$$\begin{aligned} y_{A,3}(k) &= h_{RA} x_R(k) + z_{A,3}(k) \\ &= a_{AR} h_{RA} x_{R,1}(k) y_{R,2}(k) + z_{A,3}(k) \\ &= a_{AR} h_{RA} x_{R,1}(k)(h_{BR} x_2(k) + z_{R,2}(k)) + z_{A,3}(k) \\ &= a_{AR} h_{RA} h_{BR} x_{R,1}(k) x_2(k) + a_{AR} h_{RA} x_{R,1}(k) z_{R,2}(k) + z_{A,3}(k) \end{aligned} \tag{16}$$

where $a_{AR} h_{RA} x_{R,1}(k) z_{R,2}(k)$ and $z_{A,3}(k)$ are the noise terms whose variance is given by $\delta^2 = (1+a_{AR}{}^2 |h_{RA}|^2) N_0$. Since the instant CSI is unknown in source nodes, we use the average channel gain G_{AR} to substitute $|h_{RA}|^2$. Then A needs to combine the signal from direct link in the second phase and relay link in the third phase based on noise variance as

$$\begin{aligned} u_A(k) &= y^*_{A,2}(k-1) y_{A,2}(k) \\ &+ \frac{1}{1+a^2_{AR} G_{AR}} y^*_{A,3}(k-1) s^*_A(k) y_{A,3}(k) \end{aligned} \tag{17}$$

$$\begin{aligned} u_B(k) &= y^*_{B,1}(k-1) y_{B,1}(k) \\ &+ \frac{1}{1+a^2_{AR} G_{AR}} y^*_{B,3}(k-1) s^*_B(k) y_{B,3}(k) \end{aligned} \tag{18}$$

C. Dectect Correctly Only for Node B

Differential Transmission Scheme: If relay R succeeds in detecting the information bits for node B, i.e., $\forall k, \hat{s}_B(k) \neq s_B(k), \exists k_2, \hat{s}_A(k_2) \neq s_A(k_2)$, R combines unit-power information symbol following hybrid differential network coding as follows.

Firstly, R operates $\hat{s}_B(k)$ follows differential decoding as

$$x_{R,2}(k) = x_{R,2}(k-1) \hat{s}_B(k) \tag{19}$$

Then R multiplies $y_{R,1}(k)$ by $x_{R,2}(k)$ and one amplification coefficient a_{BR} directly as the transmit signal of node R in the third phase.

$$x_R(k) = a_{BR} y_{R,1}(k) x_{R,2}(k) \tag{20}$$

a_{BR} is chosen to satisfy the transmit power constraint at the relay, which is given by

$$a_{BR} = \sqrt{\frac{P_R}{G_{AR}P_A + N_0}} \tag{21}$$

Here, P_A and P_R are the average transmission powers of node A and R, G_{AR} is the average channel gain from node A to R and N_0 is the variance of AWGN in R.

Detection Method: As relay R cannot detect the information bits from node A and amplifies the received signal from A directly, the noise is amplified as well as the useful signal. Similar to section B, A needs to combine the signal from direct link in the second phase and relay link in the third phase based on noise variance as

$$\begin{aligned} u_A(k) &= y_{A,2}^*(k-1)y_{A,2}(k) \\ &\quad + \frac{1}{1+a_{BR}^2 G_{AR}} y_{A,3}^*(k-1)s_A^*(k)y_{A,3}(k) \end{aligned} \tag{22}$$

$$\begin{aligned} u_B(k) &= y_{B,1}^*(k-1)y_{B,1}(k) \\ &\quad + \frac{1}{1+a_{BR}^2 G_{AR}} y_{B,3}^*(k-1)s_B^*(k)y_{B,3}(k) \end{aligned} \tag{23}$$

D. Detect Incorrectly for Both Node A and B

Differential Transmission Scheme: If relay R cannot detect the information bits both for node A and B, i.e., $\exists k_1, \hat{s}_A(k_1) \neq s_A(k_1)$ and $\exists k_2, \hat{s}_B(k_2) \neq s_B(k_2)$. R just amplifies the product of $y_{R,1}(k)$ and $y_{R,2}(k)$ as

$$x_R(k) = a_R y_{R,1}(k) y_{R,2}(k) \tag{24}$$

where a_R is chosen to satisfy the transmit power constraint at the relay, which is given by

$$a_R = \sqrt{\frac{P_R}{G_{AR}G_{BR}P_AP_B + (G_{AR}P_A + G_{BR}P_B)N_0}} \tag{25}$$

P_A, P_B are the average transmission powers of node A and B respectively, G_{AR} , G_{BR} are the average channel gains from node A to R and from node B to R. N_0 is the variance of AWGN in node R.

Detection Method: Since relay R cannot detect the information bits both for node A and B, R just amplifies the received signal from A and B directly, the noises are amplified as well as the useful signal. A needs to combine the signal from the second phase and third phase based on noise variance as

$$\begin{aligned} u_A(k) &= y_{A,2}^*(k-1)y_{A,2}(k) + \\ &\quad \frac{1}{a_R^2(G_{AR}P_A + G_{BR}P_B)} y_{A,3}^*(k-1)s_A^*(k)y_{A,3}(k) \end{aligned} \tag{26}$$

$$\begin{aligned} u_B(k) &= y_{B,1}^*(k-1)y_{B,1}(k) + \\ &\quad \frac{1}{a_R^2(G_{AR}P_A + G_{BR}P_B)} y_{B,3}^*(k-1)s_B^*(k)y_{B,3}(k) \end{aligned} \tag{27}$$

E. Suboptimal Detection Method

As shown in the previous subsections, the source nodes combine the signals from the direct link and the relay link based on the knowledge of the noise variance, the detection status at the relay node as well as the average channel gains. That means the source nodes need feedback links to obtain the detection status in relay node which will increase the system complexity. In this subsection, we propose a low complexity suboptimal scheme for each source to combine the received signals from the direct link and relay link.

Specifically, each source node directly superimposes the two received signals as Eq. (11) and (12) regardless of the detection status at the relay node. Therefore in this suboptimal scheme, no channel information and relay detection status are required at the source nodes so that no feedback link is needed between relay node and source nodes. It can greatly reduce the implementation complexity and time delay compared with the optimal combination scheme presented in the above sections. However, since in the suboptimal scheme the source node combine the received signals regardless the detection status at the relay node, the system performance with the suboptimal scheme will be degraded to some degree. It's a trade-off between system complexity and performance.

IV. Performance Analysis

We investigate the performances of the proposed adaptive differential transmission with optimal and suboptimal combination schemes in this section. The channels are assumed to be independent Rayleigh fading, and modeled as $E\left[|h_{ij}|^2\right] = d_{ij}^{-3}$, $i, j \in A,B,R$, where d_{ij} denotes the distance between the two nodes. We assume that the channel coefficients keep unchanged during the three-phase transmission. Differential 8PSK modulation is used, and there are 512 symbols in each transmit frame. The signal-to-noise-ratio (SNR) in the figure is defined as $SNR=P_t/N_0$, where P_t is the total transmit power of the two source nodes and the relay node. During simulations, we assume equal power allocation among the three nodes with $P_A=P_B=P_C=P_t/3$. In every experiment, a total of 10^5 packets are transmitted from one source node to the other via relay node.

In the following figures, the proposed adaptive differential transmissions with optimal and suboptimal detection methods are denoted as “Proposed, opt.” and “Proposed, subopt”. Three schemes are adopted for comparison which are two phase scheme in [14], three-phase differential multiply-and-forward (DMF) in [19] and direct differential transmission. They are denoted as “Two-phase scheme”, “Three-phase DMF” and “Direct trans”.

The first experiment tests the Bit Error Rate (BER) performances of the proposed optimal and suboptimal combination schemes. The relay node R is placed in the middle of the two source node with $d_{AR}=d_{BR}=0.5$, and $d_{AB}=1$. The channel coefficients keep unchanged during the three-phase transmission. We set the range of SNR value from *1* to *40dB*. The proposed optimal and

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suboptimal combination schemes are compared with the direct differential transmission, the three-phase Differential Multiply-and-Forward (DMF) in [19] and the two-phase differential relaying scheme in [14]. Note that for comparison fairly, DQPSK modulation is used for the direct transmission scheme so that the transmission rates are the same for the proposed three-phase differential relaying schemes. Furthermore, the transmit power of the two source nodes is *Pt*/2 for the direct transmission.

Fig. 2 plots the BER performances of these five schemes. From the figure, we find that the BER performances of these five schemes are almost the same in the low SNR region. While in the high SNR region (SNR>20dB), the three-phase differential transmission schemes outperform the two-phase relaying and the direct transmission. This is due to the fact that the direct link is exploited so that the additional diversity can be obtained in the three-phase differential transmission schemes. In addition, as shown in Fig. 2 we note that the proposed two schemes even outperform the three-phase DMF scheme about 5dB when the BER is 10^{-4}. This is due to the fact that relay node re-encode the signals adaptively according to its detection status to obtain better performance. Furthermore, we note that the suboptimal combination scheme almost have the same system performance as the optimal scheme both in the low and high SNR regions.

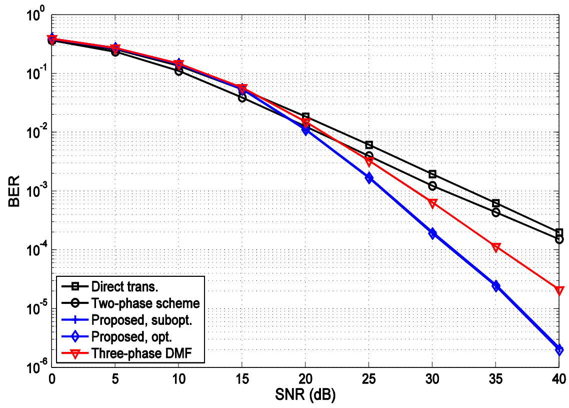

Fig. 2. BER performance of the proposed three-phase differential transmission schemes, quasi-static fading channels.

The second experiment investigates the performance of these schemes under time-varying channels. It's supposed that the relay node *R* is located in the middle of the two source nodes with d_{AR}=d_{BR}=0.5, and d_{AB}=1. The SNR is fixed to be 30dB. The channel coefficients are generated according to the Clarke's model [20]. The normalized Doppler frequency is defined as $D_m = f_d T_s$, where f_d is the Doppler frequency shift and T_s denotes the symbol duration. The range of normalized Doppler frequency is from 10^{-6} to 10^{-1}.

Fig. 3 shows the BER performance of these five schemes under different Doppler frequency shifts. From the figure, we find that the proposed adaptive three-phase differential transmission schemes can obtain better BER performance than the direct, two-phase and three-phase DMF transmission scheme. Furthermore, we note that the suboptimal combination scheme is as robust as the optimal scheme under time-varying channels.

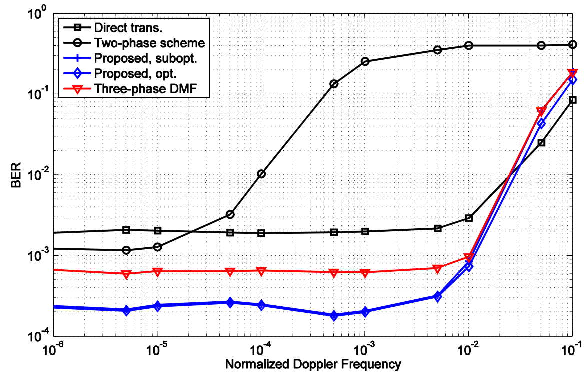

Fig. 3. BER performance of the proposed three-phase differential transmission schemes under different Doppler frequency shifts.

The third simulation illustrates the effect of relay location to system performance. We move the relay node with the line of the two source nodes and calculate the system BER with different relay locations. We set the distance of two source nodes d_{AB}=1, the distance of node d_{AR} changing from 0.1 to 0.9 and the SNR value is fixed to be 30dB.

Fig. 4 compares the BER performance of five different schemes under different relay locations. From the figure, we find that system performance of the two-phase scheme is even worse than direct transmission scheme when relay is close to one source node and far away from another source node due to the signal sent from direct link is not exploited. Generally, three-phase transmission schemes outperform two-phase transmission scheme and direct transmission wherever the relay locates. The proposed three-phase schemes outperform three-phase DMF all the time. However, the proposed sub-optimal scheme is more sensitive to the change of relay locations than the optimal combination scheme. When relay *R* is close to one source node and far away from another source node, the system performance of sub-optimal combination scheme deteriorates sharply while the optimal combination scheme keeps stable relatively.

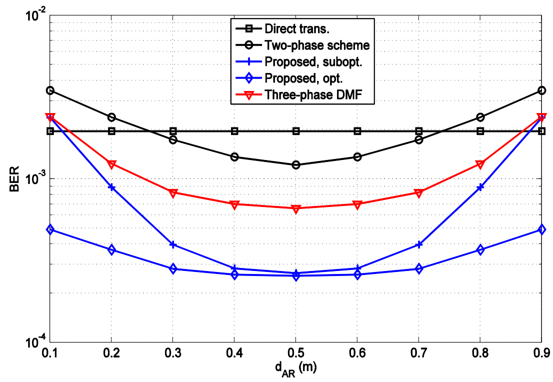

Fig. 4. BER performance of the proposed three-phase differential transmission schemes under different relay locations.

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V. CONCLUSIONS

This paper considered the adaptive three-phase differential transmission strategy and optimal/suboptimal combination schemes for TWRN. No instant CSI is needed for signal detection at the source nodes and the relay node. Comparison of their BER performances with the existing schemes indicates that the proposed adaptive three-phase differential transmission and combination methods outperforms the existing schemes significantly by exploiting the direct link and differential modulation adaptively. In addition, suboptimal scheme can reduce the system implementation complexity and time delay since feedback is not required to obtain the detection status at the relay node. The simulation results show that the proposed sub-optimal combination scheme got a good tradeoff between implementation complexity and system performance. The system performance of suboptimal scheme is almost as good as that of optimal scheme under different SNR and Doppler frequency shifts. The extension to TWRN with multiple relay nodes would be an interesting direction for future work.

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