Opportunistic Relaying in Time Division Broadcast Protocol with Incremental Relaying

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Abstract. *In this paper, we investigate the performance of time division broadcast protocol (TDBC) with incremental relaying (IR) when there are multiple available relays. Opportunistic relaying (OR), i.e., the "best" relay is select for transmission to minimize the system's outage probability, is proposed. Two OR schemes are presented. The first scheme, termed TDBC-OIR-I, selects the "best" relay from the set of relays that can decode both flows of signal from the two sources successfully. The second one, termed TDBC-OIR-II, selects two "best" relays from two respective sets of relays that can decode successfully each flow of signal. The performance, in terms of outage probability, expected rate (ER), and diversity-multiplexing tradeoff (DMT), of the two schemes are analyzed and compared with two TDBC schemes that have no IR but OR (termed TDBC-OR-I and TDBC-OR-II accordingly) and two other benchmark OR schemes that have no direct link transmission between the two sources.*

Keywords

Opportunistic relaying, incremental relaying, two-way channel, time division broadcast protocol.

1. Introduction

Two-way relaying improves the spectral efficiency of conventional half-duplex cooperative communications due to two concurrent flows of signal transmission from the two sources [1]. It executes information exchange between the two sources with the aid of the relay. There are two well-known protocols for decode-and-forward (DF) two-way relaying channel, i.e., physical-layer network coding (PNC) and time division broadcast protocol (TDBC) [2], [3]. To fulfill the information exchange, PNC needs two time slots while TDBC entails three time slots. Recently, there were research interests in studying two-way relaying with direct link transmission [2-6], since in many physical environments the direct link does exist between the two sources. The direct link transmission provides one more diversity order than the scenario where there is no direct link transmission [2], but suffers from spectral efficiency loss in the TDBC protocol because of its three-time-slot transmission. To overcome this disadvantage, we proposed to combine incremental relaying (IR) with TDBC to form a new scheme, i.e., TDBC-IR [7], since IR was well known for enhancing spectral efficiency [8], [9]. It has been shown that TDBC-IR possesses improved spectral efficiency performance compared with TDBC and even PNC (except at asymptotic high signal-to-noise ratio (SNR) regime where their spectral efficiency performance meets [7]), though it consumes three time slots in transmission. This is because TDBC-IR utilizes the acknowledgement (ACK) feedback information to reduce the unnecessary retransmission times if the direct link transmission is successful. The limitation of [7] is that it considers only one relay scenario while in practical systems there may be multiple available relays, such as the cellular system and wireless sensor networks.

In this paper we focus on the multiple-relay two-way relaying channel with IR. Particularly, we investigate opportunistic relaying (OR), i.e., the "best" relay is selected based on minimizing the system's outage probability. It has been revealed in one-way cooperative communications that opportunistic relaying could achieve the same diversity order as the all-relay-participation scheme but has improved multiplexing gain over the latter[1], since OR consumed two orthogonal channels (time slots, frequency bands, or CDMA codes) while the latter entailed multiple orthogonal channels for transmission [10]. For two-way relaying, OR had been widely adopted as well (see [12]-[21] and references therein). Max-min based relay selection criterion was adopted in [12]-[15] for amplify-and-forward (AF) two-way relaying channel. This criterion selects the relay corresponding to the maximum of the worse SNRs of the two sources. [16] chose the relay to maximize the sum ergodic rate of the two sources with AF retransmission. [17] optimized the achievable ergodic sum-rate by choosing the best relay for DF two-way relaying channel. The Max-min criterion was further utilized in [18] to minimize the frame error rate of DF two-way relaying channel. AF two-way

[1] It is noted that there was a distributed space-time-coded protocol [11] which also consumed two orthogonal channels for all relays' participation. However, it requires rigid synchronization among all relays which is hard to realize in practice and makes it beyond the scope of the paper.

relaying channel with direct link transmission employed still the max-min criterion to select the best relay to maximize the capacity in [19]. In [20], [21], the max-min criterion was used to select the relays to minimize the bit error rate of the three-time-slot two-way relaying channel with no direct transmission.

This paper studies the DF retransmission scheme and adopts the max-min criterion to select the best relay, aiming at minimizing the system's outage probability. Firstly, we propose two OR schemes for TDBC-IR, i.e., TDBC-OIR-I and TDBC-OIR-II (note that the acronym OIR means opportunistic relaying with incremental relaying). In the TDBC-OIR-I protocol, the best relay is selected in the set of relays that can decode successfully both flows of signal from the two sources according to the max-min criterion. In the TDBC-OIR-II protocol, the relays are selected from two sets of relays that can decode successfully each flow of signal. The selection process is identical to that of [20] and [21] in essence. It is noted that there may be one or two best relays in TDBC-OIR-II (which will be shown in section 2). Secondly, the performance of two proposed protocols is investigated in terms of outage probability, expected rate (ER), and diversity-multiplexing tradeoff (DMT). The expected rate is defined as the average spectral efficiency that can be supported without outage by a system [22]. The DMT provides a more comprehensive view on the performance of a system since it takes into account both the diversity gain and multiplexing gain simultaneously [23]. Since we study IR with the aim to improve spectral efficiency and the two metrics reflect the spectral efficiency performance directly (for ER) and indirectly (for DMT), they are adopted here. Finally, the performance of the two protocols are compared with two TDBC protocols with OR but no IR (termed TDBC-OR-I and TDBC-OR-II in accordance with the two proposed protocols) and two other benchmark protocols with no direct link transmission (denoted by PNC-OR-I and PNC-OR-II respectively, which will be shown in section 2). It found from the analysis that 1) TDBC-OIR-II has better outage and expected rate performance than TDBC-OIR-I while they have the same DMT performance; 2) TDBC-OIR-I (or TDBC-OIR-II) has the same outage performance as that of TDBC-OR-I (or TDBC-OR-II) but its expected rate and DMT performance are better than the latter; and 3) TDBC-OIR-I and TDBC-OIR-II possess improved outage, expected rate, and DMT performance over PNC-OR-I and PNC-OR-II.

The rest of the paper is structured in the following way. Section 2 introduces the system model and describes the protocols in detail. Performance analysis is presented in section 3. Simulation results and discussions are presented in section 4. Finally, section 5 concludes the paper.

Notation: $P_r(\cdot)$ denotes the probability of a random event and $P_r(\cdot|\cdot)$ represents the corresponding conditional probability. $f_X(\cdot)$ and $F_X(\cdot)$ are the probability density function (PDF) and cumulative distribution function (CDF) of random variable (RV) X, respectively while $f_{X|X\in D}(\cdot)$ and $F_{X|X\in D}(\cdot)$ are the corresponding conditional PDF and CDF conditioned on D. $\log(\cdot)$ is the logarithm function with base 2 except specified elsewhere. $o(\cdot)$ is the high order infinitesimal. Exponential equality $g(x) \doteq \rho^{\alpha}$ is defined as $\alpha = \lim_{\rho\to+\infty} \frac{\log g(x)}{\log \rho}$. $\max(\cdot|\cdot)$ and $\min(\cdot|\cdot)$ are the maximum and minimum operation of two operators, respectively. $x \sim CN(a, b)$ denotes RV x follows a complex Gaussian distribution with mean a and variance b. $\oplus$ is the XOR operator.(:) is the binomial coefficient.

2. System Model

In this section, we first describe the two proposed protocols, i.e., TDBC-OIR-I and TDBC-OIR-II, and then the two benchmark protocols, i.e., PNC-OR-I and PNC-OR-II. For convenience of description, we assume throughout the paper that (1) the channels between any two users are reciprocal; (2) the two sources transmit with the same data rates, i.e., the symbols are of the same modulation type; and (3) the transmit power of all the users, including the two sources and all the relays, are the same[2].

2.1 TDBC-OIR-I and TDBC-OIR-II

The system consists of two sources (denoted by S_1 and S_2 respectively) and N relays (denoted by $R_1, R_2,\ldots, R_N$), see Fig. 1. The two sources want to exchange information to each other with the help of the relays. There is a direct link between the two sources.

For TDBC-OIR-I (see Fig.1 (a)), S_1 broadcasts the information-bearing symbol x_1 to S_2 and the relays in the first time slot. The received signal at S_2, denoted by $y_{S_2}^1$, is thus $y_{S_2}^1 = h_{S_1S_2}x_1 + n_{S_2}^1$, where $n_{S_2}^1$ is the complex additive white Gaussian noise (AWGN) at S_2 and $h_{S_1S_2}$ is the complex channel gain between S_1 and S_2. Throughout the paper, we adopt the following notation rules: (1) $y_{\Re}^i$ and $n_{\Re}^i$ denote the signal received by and the complex AWGN at user $\Re$ ($\Re\in\{S_1, S_2, R_1, R_2,\ldots,R_N\}$) at time slot i ($i\in\{1,2,3\}$), respectively; (2) h_{ab} denotes the complex channel gain from user a to b, with $a,b\in\{S_1, S_2, R_1, R_2,\ldots,R_N\}$ and $a \neq b$. Furthermore, $X_{ab} = |h_{ab}|^2$ is the square of the channel gain. The received signal at the jth ($j \in \psi$ and $\psi = \{1,2,\ldots,N\}$) relay is expressed as $y_{R_j}^1 = h_{S_1R_j}x_1 + n_{R_j}^1$. If S_2 decodes the symbol from S_1 successfully, it sends back an ACK to S_1. Otherwise, it sends back a non-acknowledgement (NACK). In the second time slot, S_2 broadcasts the information-bear

[2] The transmit power of the users may be different as well (see [2] or [7]), which makes the performance analysis (e.g. outage probability) more tedious but of less interest, since we focus more on the diversity gain and multiplexing gain (or spectral efficiency) of the protocols in the paper.

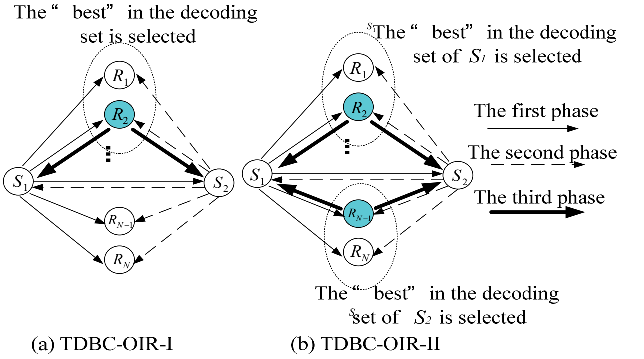

Fig. 1. The system models of TDBC-OIR-I and TDBC-OIR-II.

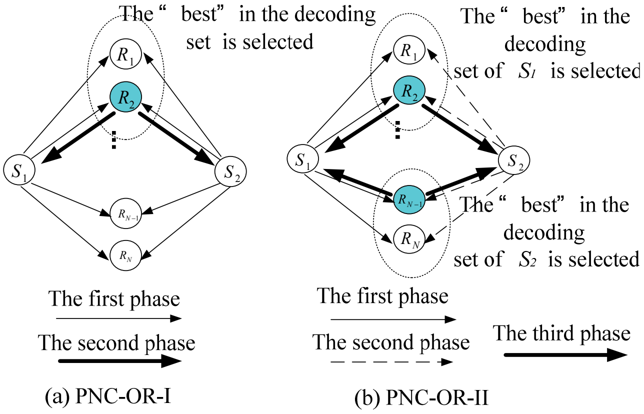

Fig. 2. The system models of PNC-OR-I and PNC-OR-II.

ing symbol x_2 to S_1 and the relays. The received signals at S_1 and the jth ($j \in \psi$) relay are written as $y_{S_1}^2 = h_{S_1 S_2} x_2 + n_{S_1}^2$ and $y_{R_j}^2 = h_{S_2 R_j} x_2 + n_{R_j}^2$, respectively. If S_1 decodes the symbol from S_2 successfully, it sends back an ACK, or else, it sends back a NACK. We assume that all the relays and the two sources receive the ACK or NACK feedback correctly and the feedback transmission consumes negligible time (or with no sacrificing of spectral efficiency) [10]. Then if the relays receives two ACKs (which means that the direct link transmission of the two sources is successful)[3], the system enters into the next round of new information transmission process. Otherwise, the system enters into the third time slot transmission. The relays that can decode successfully both flows of signal from the two sources constitute the decoding set, denoted by D_m (the subscript m denotes there are m relays in the set), which is given by $D_m = \left\{ i : i \in \psi, \left|h_{S_1 R_i}\right|^2 > G \text{ and } \left|h_{S_2 R_i}\right|^2 > G, \right\}$ with G being the threshold value the relay can decode the symbols successfully (the value of G is specified in section 3). In the third time slot, the best relay is selected, aiming at minimizing the system's outage probability, to transmit the received signals. The relay selection is based on the max-min criterion, i.e., the selected relay's index is $k = \arg\max_{i \in D_m} \min\left(X_{S_1 R_i}, X_{S_2 R_i}\right)$. The operation of the selected relay is that it first executes bit-level XOR operation (i.e., PNC) on the received information from the two sources, and then broadcasts the remapped symbol to both sources. The received signals at S_1 and S_2 are given by $y_{S_1}^3 = h_{S_1 R_k} x_3 + n_{S_1}^3$ and $y_{S_2}^3 = h_{S_2 R_k} x_3 + n_{S_2}^3$, respectively, where $x_3 = x_1 \oplus x_2$ [4]. Since the sources know their own transmitted symbols, they can execute backward propagating self-interference cancellation to recover their intended signals [1]. It is noted that if the decoding set is empty, the third time slot is idle.

For TDBC-OIR-II (see Fig. 1 (b)), the transmission process of the first and second time slots is the same as that of TDBC-OIR-I. If ACK is received by the relays, the system enters into the next round of transmission. Otherwise, the third time slot transmission is invoked. There are two decoding sets in the TDBC-OIR-II. The decoding set of S_1, denoted by D_{1,m_1} [5], includes relays that can decode successfully the symbol from S_1. It can be expressed as $D_{1,m_1} = \left\{ i : i \in \psi \text{ and } X_{S_1 R_i} > G \right\}$, where G is the threshold value. The decoding set of S_2 is defined similarly and expressed as $D_{2,m_2} = \left\{ j : j \in \psi \text{ and } X_{S_2 R_j} > G \right\}$. For relay selection, the relay in D_{1,m_1} with the largest channel gain to S_2 is selected as the best relay (denoted by R_k^1) for S_1. Similarly, the relay in D_{2,m_2} with the largest channel gain to S_1 is selected as the best relay (denoted by R_k^2) for S_2 [20, 21]. R_k^1 and R_k^2 may be two different relays or the same one. For the latter case, the operation process is identical to that of TDBC-OIR-I in the third time slot. For the former case, R_k^1 and R_k^2 retransmit the received symbols, respectively. Thus, the received signals at S_1 and S_2 are given by $y_{S_1}^3 = h_{S_1 R_k^1} x_1 + h_{S_1 R_k^2} x_2 + n_{S_1}^3$ and $y_{S_2}^3 = h_{S_2 R_k^2} x_2 + h_{S_2 R_k^1} x_1 + n_{S_2}^3$, respectively. Since the sources know their own transmitted symbols, the backward propagation self-interference can be cancelled and thus the received signals become $y_{S_1}^3 = h_{S_1 R_k^2} x_2 + n_{S_1}^3$ and $y_{S_2}^3 = h_{S_2 R_k^1} x_1 + n_{S_2}^3$. It is emphasized that the relay selection process can be executed in the same distributed way as that of [10] and is omitted here.

[3] With the assumptions (1), (2), and (3), we know that the transmission of S_1 and S_2 is both successful (or failed). Therefore only one ACK (or NACK) indicating the success (or failure) of the direct link transmission is needed [7]. In the following description of TDBC-OIR-II, we only say one ACK (or NACK).

[4] Here, the XOR operation denotes the operation in the third time slot (with bit-level XOR and remapping), not XOR directly on two symbols.

[5] The subscript i means that it is the decoding set of S_i(i = 1,2) whereas the subscript m_j (j = 1,2) denotes that there are m_1 relays in the set. This notation rule is also applied for other protocols expected specified otherwise.

For the comparison purpose, we also introduce two protocols, i.e., TDBC-OR-I and TDBC-OR-II. The TDBC-OR-I (TDBC-OR-II) protocol works in the same way as TDBC-OIR-I (TDBC-OIR-II) except that there is no feedback here, i.e., it has no IR). Thus, it always enters into the third time slot's transmission. This is also the reason why TDBC-OR-I (TDBC-OR-II) has worse spectral efficiency performance than TDBC-OIR-I (TDBC-OIR-II).

2.2 PNC-OR-I and PNC-OR-II

For PNC-OR-I (see Fig. 2(a)), there is no direct link between the two sources. The transmission is finished in two time slots. In the first time slot, S_1 and S_2 transmit simultaneously to the relays. The relays that can decode successfully both sources' information are collected in the decoding set D_{12}^{PNC}. The best relay in the decoding set is selected according to the max-min criterion, i.e., the index of the selected relay is $k = \arg\max_{j \in D_{12}^{PNC}} \min\left(X_{S_1R_j}, X_{S_2R_j}\right)$, the same as TDBC-OIR-I. In the second time slot, the selected relay operates in the same way as the third time slot's transmission of TDBC-OIR-I. After receiving in the second time slot, S_1 and S_2 execute self-interference cancellation to recover their corresponding signals.

For PNC-OR-II (see Fig. 2 (b)), there is no direct link either. However it consumes three time slots for transmission. Its operation process is identical to that of TDBC-OR-II (except that there is direct link transmission in the latter) and thus is omitted here.

3. Performance Analysis

Before the analysis, we make the following assumptions: (1) all complex AWGN terms, at different users and time slots, are independent and identical distributed (i.i.d.) with distribution $CN(0,1)$; (2) all channel gains are also i.i.d. complex RVs with distribution $CN(0,1)$, i.e., Rayleigh fading, and independent of the noises; and 3) the channels are slow, flat-block fading, i.e., the channel gains keep the same in one block's transmission and change independently from one block to the next block. The PDF of the square of the channel gain $X_{ab} = |h_{ab}|^2$ is then given as $f_{X_{ab}}(x) = e^{-x}$ when $x \geq 0$ and $f_{X_{ab}}(x) = 0$ otherwise.

To make performance comparison of the abovementioned protocols under a unified framework, we assume that each block of transmission includes M bits information and each time slot has a length of t seconds (s) [7]. The two sources thus have $M/2$ bits information to transmit to each other in one block. Let the transmit power be ρ, then the transmit SNR is ρ since the noise's power is 1. The system's transmission bandwidth B is assumed to be 1 Hz. Define $c \triangleq M/(3tB) = M/(3t)$ bits/s/Hz as the baseline data rate. It is further assumed that the relays know the instantaneous channel state information (CSI) of their corresponding backward and forward channels, and the corresponding receivers have their backwards channels' CSI[6]. In the following, we first derive the outage probability, then the expected rate, and finally the DMT performance of the abovementioned protocols.

3.1 Outage Probability Performance Analysis

For TDBC-OIR-I (with direct link), the instantaneous channel capacity of the direct link transmission is $I_{S_1S_2} = \frac{1}{2}\log\left(1+\rho X_{S_1S_2}\right)$, where the factor 1/2 accounts for the two-time-slot transmission if the direct transmission is successful. Similarly, the instantaneous channel capacity of the links $S_1 \to R_i$ and $S_2 \to R_i$ $(i \in \psi)$ are denoted by $I_{S_1R_i} = \frac{1}{3}\log\left(1+\rho X_{S_1R_i}\right)$ and $I_{S_2R_i} = \frac{1}{3}\log\left(1+\rho X_{S_2R_i}\right)$, respectively. Therefore, the probability that the ith relay R_i can decode successfully both flows of signal from the sources are given by

$$\begin{aligned} P_r^{12} &= P_r\left(I_{S_1R_i} > \frac{C}{2} \text{ and } I_{S_2R_i} > \frac{C}{2}\right) \\ &= P_r\left(X_{S_1R_i} > G \text{ and } X_{S_2R_i} > G\right) = e^{-2G} \end{aligned} \tag{1}$$

where $G = \dfrac{2^{1.5C}-1}{\rho}$.

For any relay in the decoding set (denote its index as i, i.e., $i \in D_m$), the conditional CDF and PDF of $X_{S_1R_i}$ (or $X_{S_2R_i}$) are written as

$$\begin{aligned} F_{X|X>G}(z) &= P_r\left(X < z \mid X > G\right) \\ &= \frac{P_r\left(G < X < z\right)}{P_r\left(X > G\right)} = \begin{cases} 1-e^{-(z-G)}, & z > G \\ 0, & z \leq G \end{cases} \end{aligned} \tag{2}$$

and

$$f_{X|X>G}(z) = \begin{cases} e^{-(z-G)}, & z > G \\ 0, & z \leq G \end{cases}. \tag{3}$$

Let $X_{R_i} = \min\left(X_{S_1R_i}, X_{S_2R_i}\right)$, $i \in D_m$, then the conditional CDF and PDF of X_{R_i} are expressed as

$$\begin{aligned} F_{X_{R_i}|X_{R_i}>G}(z) &= P_r\left(X_{R_i} < z \mid X_{R_i} > G\right) \\ &= 1 - P_r\left(X_{R_i} > z \mid X_{R_i} > G\right) \\ &= 1 - P_r\left(X_{S_1R_i} > z \mid X_{S_1R_i} > G\right) P_r\left(X_{S_2R_i} > z \mid X_{S_2R_i} > G\right) \\ &= \begin{cases} 1-e^{-2(z-G)}, & z \geq G \\ 0, & z < G \end{cases} \end{aligned} \tag{4}$$

and

$$f_{X_{R_i}|X_{R_i}>G}(z) = \begin{cases} 2e^{-2(z-G)}, & z \geq G \\ 0, & z < G \end{cases}. \tag{5}$$

[6] Since the channels are reciprocal, the transmitters know the instantaneous CSI as well.

We define the outage event occurs if either the link from S_1 to S_2 or the link from S_2 to S_1 is in outage in the paper [2]. Therefore, the outage probability of TDBC-OIR-I is written as (k is the index of the selected best relay)

$$\begin{aligned}
&P_r^{TDBC\text{-}OIR\text{-}I}(C) \\
&= P_r(\text{Both the direct and selected relayed links are in outage}) \\
&\overset{(a)}{=} P_r(D_0)P_r\left(2t\cdot I_{S_1S_2} < \frac{M}{2}\right) + \sum_{m=1}^{N} P_r(D_m) \\
&\qquad \times P_r\left(2t\cdot I_{S_1S_2} < \frac{M}{2} \text{ and } 3t\cdot\min\left(I_{S_1R_kS_2}, I_{S_2R_kS_1}\right) < \frac{M}{2} \middle| D_m\right) \\
&\overset{(b)}{=} P_r(D_0)P_r\left(2t\cdot I_{S_1S_2} < \frac{M}{2}\right) \\
&= \left(1-e^{-2G}\right)^N\left(1-e^{-G}\right)
\end{aligned} \tag{6}$$

where

$I_{S_1R_iS_2} = \frac{1}{3}\log\left(1+\rho\left(X_{S_1S_2}+X_{S_2R_i}\right)\right)$ and

$I_{S_2R_iS_1} = \frac{1}{3}\log\left(1+\rho\left(X_{S_1S_2}+X_{S_1R_i}\right)\right)$ are the instantaneous capacity at S_2 and S_1 respectively after the third time slot's transmission in TDBC-OIR-I [2, 3]. Equality (a) is derived according to the total probability formula and equality (b) results from the fact that whenever there is a relay that can simultaneously decode the two flows of signal from the sources the third time slot's transmission will be successful, i.e., the outage event will never happen.

Based on this fact, we know that the outage event may be possible for TDBC-OIR-II (with direct link) only when there is no relay that can simultaneously decode successfully both flows of signal if the direct link transmission is failed. Thus, we can redefine the decoding sets for the two sources. For S_1, its decoding set, denoted by D_{1,m_1}, is defined as the relays that can decode successfully the symbol from S_1 but cannot decode the symbol from S_2. Thus we have $D_{1,m_1} = \left\{i : i\in\psi, X_{S_1R_i} > G, \text{ and } X_{S_2R_i} < G\right\}$ ($m_1 \le N$). The decoding set of S_2 is defined similarly and denoted by $D_{2,m_2} = \left\{j : j\in\psi, X_{S_1R_j} < G, \text{ and } X_{S_2R_j} > G\right\}$ ($m_2 \le N - m_1$). It is obvious that $D_{1,m_1} \cap D_{2,m_2} = \phi$, where ϕ is the empty set. Except the relays in the two decoding sets, there are $N - m_1 - m_2$ relays left that can not decode successfully either flow of signal. Collecting these relay as the set $D_{12,N-m_1-m_2}$, we have

$$D_{12,N-m_1-m_2} = \left\{i : i\in\psi, X_{S_1R_i} < G, \text{ and } X_{S_2R_i} < G\right\}.$$

Let R_k^1 and R_k^2 be the two selected best relays for S_1 and S_2, i.e., $R_k^1 = \arg\max_{i\in D_{1,m_1}}\left(X_{S_2R_i}\right)$, and $R_k^2 = \arg\max_{i\in D_{2,m_2}}\left(X_{S_1R_i}\right)$, the outage probability of TDBC-OIR-II is thus written as (according to the total probability formula)

$$\begin{aligned}
&P_r^{TDBC-OIR-II}(C) \\
&= P_r(\text{Both the direct and selected relayed links are in outage}) \\
&= P_r(\Pi_0)P_r\left(I_{S_1S_2} < \frac{3C}{4} \mid \Pi_0\right) + \\
&\sum_{m_1=1}^{N-1}\sum_{m_2=1}^{N-m_1} P_r\left(D_{1,m_1}\right)P_r\left(D_{2,m_2}\right)P_r\left(D_{12,N-m_1-m_2}\right) \\
&\times P_r\left(I_{S_1S_2} < \frac{3C}{4}, \min(I_{S_1R_k^1S_2}, I_{S_1R_k^2S_2}) < \frac{C}{2} \mid D_{1,m_1}, D_{2,m_2}, \text{and } D_{12,N-m_1-m_2}\right) \\
&= 2\left(1-e^{-G}\right)^{N+1}\left(1-\left(1-e^{-G}\right)^N\right) + \left(1-e^{-G}\right)^{2N+1} \\
&\quad + \sum_{m_1=1}^{N-1}\sum_{m_2=1}^{N-m_1}\binom{N}{m_1}\binom{N-m_1}{m_2}P_1^{\,m_1}\left(1-P_2\right)^{m_1} \\
&\quad \times P_2^{\,m_2}\left(1-P_1\right)^{m_2}\left(\left(1-P_1\right)\left(1-P_2\right)\right)^{N-m_1-m_2} A_{m_1,m_2}
\end{aligned} \tag{7}$$

where Π_0 is the event that "either D_{1,m_1} or D_{2,m_2} is empty", $I_{S_1R_k^1S_2} = \frac{1}{3}\log\left(1+\rho\left(X_{S_1S_2}+X_{R_k^1}\right)\right)$ and $I_{S_1R_k^2S_2} = \frac{1}{3}\log\left(1+\rho\left(X_{S_1S_2}+X_{R_k^2}\right)\right)$ are the instantaneous capacity at S_2 and S_1 respectively after the third time slot's transmission in TDBC-OIR-II, $P_1 = e^{-G}$ and $P_2 = e^{-G}$ are the probability that one relay can decode successfully the symbols from S_1 and S_2, respectively, and $A_{m_1,m_2} = P_r\left(\min(X_{R_k^1}, X_{R_k^2}) < G \mid D_{1,m_1}, D_{2,m_2}, \text{and } D_{12,N-m_1-m_2}\right)$.

From the analysis above, we learn that the calculation of A_{m_1,m_2} is the key step in deriving $P_r^{TDBC-OIR-II}(C)$. To derive A_{m_1,m_2}, we first have the following conditional CDFs and PDFs.

For $i \in D_{1,m_1}$, the conditional CDF of $X_{S_2R_i}$ is given as

$$\begin{aligned}
F_{X_{S_2R_i}|X_{S_2R_i}<G}(z) &= P_r\left(X_{S_2R_i} < z \mid X_{S_2R_i} < G\right) \\
&= \frac{P_r\left(X_{S_2R_i} < z \text{ and } X_{S_2R_i} < G\right)}{P_r\left(X_{S_2R_i} < G\right)} \\
&= \begin{cases} 0, & z < 0 \\ \dfrac{1\text{-}e^{\text{-}z}}{1\text{-}e^{\text{-}G}}, & 0 \le z \le G \\ 1, & z > G \end{cases}
\end{aligned} \tag{8}$$

and thus the conditional CDF of $X_{R_k^1} = \max_{i\in D_{1,m_1}}\left(X_{S_2R_i}\right)$ is

$$F_{X_{R_k^1}|X_{R_k^1}<G}(z) = \begin{cases} 0, & z < 0 \\ \left(\dfrac{1-e^{-z}}{1-e^{-G}}\right)^{m_1}, & 0 \le z \le G\,. \\ 1, & z > G \end{cases} \tag{9}$$

Similarly, for $i \in D_{2,m_2}$, the conditional CDF of $X_{S_1R_i}$ is identical to that of $X_{S_2R_i}$ ($i \in D_{1,m_1}$). The conditional CDF of $X_{R_k^2} = \max_{i \in D_{2,m_2}} \left(X_{S_1R_i}\right)$ is then written as

$$F_{X_{R_k^2}|X_{R_k^2}<G}(z) = \begin{cases} 0, & z<0 \\ \left(\frac{1-e^{-z}}{1-e^{-G}}\right)^{m_2}, & 0 \le z \le G \\ 1, & z>G \end{cases} \quad (10)$$

Therefore, the CDF of $X = \min(X_{R_k^1}, X_{R_k^2})$ is

$$F_X(z) = \begin{cases} 0, & z<0 \\ 1-\left(1-\left(\frac{1-e^{-z}}{1-e^{-G}}\right)^{m_1}\right) \times \left(1-1-\left(\frac{1-e^{-z}}{1-e^{-G}}\right)^{m_2}\right), & 0 \le z \le G \\ 1, & z>G \end{cases} \quad (11)$$

and its PDF is

$$f_X(z) = \begin{cases} 0, & z<0 \text{ or } z>G \\ \left[\frac{m_1\left(1-e^{-z}\right)^{m_1-1}}{\left(1-e^{-G}\right)^{m_1}} + \frac{m_2\left(1-e^{-z}\right)^{m_2-1}}{\left(1-e^{-G}\right)^{m_2}} - \frac{\left(m_1+m_2\right)\left(1-e^{-z}\right)^{m_1+m_2-1}}{\left(1-e^{-G}\right)^{m_1+m_2}}\right] e^{-z}, & 0 \le z \le G \end{cases} . \quad (12)$$

With these (conditional) CDFs and (conditional) PDFs at hand, we thus calculated A_{m_1,m_2} as in (13). Substituting (13) into (7), we then obtain the outage probability of TDBC-OIR-II.

Remark: The outage probability of TDBC-OR-I (TDBC-OR-II) is identical to that of TDBC-OIR-I (TDBC-OIR-II). This is explained as follows. The outage event occurs in TDBC-OIR-I (TDBC-OIR-II) when the two events occur simultaneously, i.e., the direct link transmission is failed and the third time slot's transmission is unsuccessful either. Since the intersection of the two events is exactly the latter event. Thus the outage probability of TDBC-OIR-I (TDBC-OIR-II) is decided by the latter event, which is exactly the outage event of TDBC-OR-I (TDBC-OR-II) [7, 8].

For PNC-OR-I (without direct link), the relay R_i ($i \in \psi$) must meet three conditions to decode successfully both flows of signal in the first time slot, i.e., $2t \cdot \frac{1}{2}\log\left(1+\rho X_{S_1R_j}\right) > \frac{M}{2}$, $2t \cdot \frac{1}{2}\log\left(1+\rho X_{S_2R_j}\right) > \frac{M}{2}$ and $2t \cdot \frac{1}{2}\log\left(1+\rho\left(X_{S_1R_j}+X_{S_2R_j}\right)\right) > M$ [2]. Therefore, the decoding set D_{12}^{PNC} is written as $D_{12}^{PNC} = \left\{ j : j \in \psi, X_{S_1R_j} > G, X_{S_2R_j} > G, \text{ and } X_{S_1R_j} + X_{S_2R_j} > L \right\}$, where $L = \frac{2^{3C}-1}{\rho}$. Since the selected best relay (in the decoding set) is utilized to retransmit in the second time slot, outage event will never happen if the decoding set is not empty. Thus, the outage event of PNC-OR-I is exactly that the decoding set is empty. The outage probability of PNC-OR-I is then calculated as $P_r^{PNC-OR-I}(C) = \left(1-P_{12}^{PNC-OR-I}\right)^N$, where $P_{12}^{PNC-OR-I}$ is the probability that one relay can decode successfully both flows of signal in the first time slot and is expressed in (14).

$$\begin{aligned} A_{m_1,m_2} &= P_r\left(X_{S_1S_2}+X<G\right) \\ &= \int_0^G e^{-x}\left[1-\left(1-\left(1-\left(\frac{1-e^{-(G-x)}}{1-e^{-G}}\right)^{m_1}\right) \times \left(1-1-\left(\frac{1-e^{-(G-x)}}{1-e^{-G}}\right)^{m_2}\right)\right)\right]dx \\ &= \frac{1}{\left(1-e^{-G}\right)^{m_1}}\left[1-\left(m_1G+1\right)e^{-G}+\sum_{k_1=2}^{m_1}\binom{m_1}{k_1} \times (-1)^{k_1}\frac{e^{-k_1G}\left(e^{(k_1-1)G}-1\right)}{k_1-1}\right] \\ &+ \frac{1}{\left(1-e^{-G}\right)^{m_2}}\left[1-\left(m_2G+1\right)e^{-G}+\sum_{k_2=2}^{m_2}\binom{m_2}{k_2} \times (-1)^{k_2}\frac{e^{-k_2G}\left(e^{(k_2-1)G}-1\right)}{k_2-1}\right] \\ &- \frac{1}{\left(1-e^{-G}\right)^{m_1+m_2}}\left[1-\left(\left(m_1+m_2\right)G+1\right)e^{-G} + \sum_{k_3=2}^{m_1+m_2}\binom{m_1+m_2}{k_3} \times (-1)^{k_3}\frac{e^{-k_3G}\left(e^{(k_3-1)G}-1\right)}{k_3-1}\right] \end{aligned} \quad (13)$$

$$\begin{aligned} &P_{12}^{PNC-OR-I}(C) \\ &= P_r\left(X_{S_1R_j}>G, X_{S_2R_j}>G, \text{ and } X_{S_1R_j}+X_{S_2R_j}>L\right) \\ &= \int_G^{L-G} e^{-x}\int_{L-x}^{+\infty} e^{-y}dydx + \int_{L-G}^{+\infty} e^{-x}\int_G^{+\infty} e^{-y}dydx \\ &= e^{-L}\left(L-2G+1\right) \end{aligned} \quad (14)$$

With the same way as TDBC-OIR-II, we obtain the outage probability of PNC-OR-II (without direct link) according to the total probability formula as follows

$$
\begin{aligned}
&P_r^{PNC-OR-II}(C) \\
&\overset{(a)}{=} \sum_{m_1=0}^{N} \sum_{m_2=0}^{N-m_1} \binom{N}{m_1}\binom{N-m_1}{m_2} P_1^{\ m_1} \left(1-P_2\right)^{m_1} P_2^{\ m_2} \\
&\qquad \times \left(1-P_1\right)^{m_2} \left(\left(1-P_1\right)\left(1-P_2\right)\right)^{N-m_1-m_2} \\
&\times P_r\left(\text{the outage event occurs}|D_{1,m_1}, D_{2,m_2}, \text{and } D_{12,N-m_1-m_2}\right) \\
&\overset{(b)}{=} \sum_{m_1=0}^{N} \sum_{m_2=0}^{N-m_1} \binom{N}{m_1}\binom{N-m_1}{m_2} P_1^{\ m_1} \left(1-P_2\right)^{m_1} P_2^{\ m_2} \\
&\qquad \times \left(1-P_1\right)^{m_2} \left(\left(1-P_1\right)\left(1-P_2\right)\right)^{N-m_1-m_2} \\
&= \sum_{m_1=0}^{N} \sum_{m_2=0}^{N-m_1} \binom{N}{m_1}\binom{N-m_1}{m_2} P_1^{\ (m_1+m_2)} \left(1-P_1\right)^{2N-m_1-m_2}
\end{aligned} \tag{15}
$$

where $P_1 = P_2 = e^{-G}$ and equality (b) is obtained since the conditional probability term in equality (a) is always 1.

3.2 Expected Rate Performance Analysis

According to the definition [22, eq. (12)], the expected rates of TDBC-OIR-I, TDBC-OIR-II, TDBC-OR-I, TDBC-OR-II, PNC-OR-I, and PNC-OR-II are written as follows respectively.

$$
\begin{aligned}
R_{TDBC-OIR-I} &= \frac{3C}{2}\left(1-P_r^{direct}\right) \\
&\quad + C \cdot P_r^{direct}\left(1-P_r^{TDBC-OIR-I}(C)\right),
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
R_{TDBC-OIR-II} &= \frac{3C}{2}\left(1-P_r^{direct}\right) \\
&\quad + C \cdot P_r^{direct}\left(1-P_r^{TDBC-OIR-II}(C)\right),
\end{aligned} \tag{17}
$$

$$R_{TDBC-OR-I} = C \cdot \left(1-P_r^{TDBC-OR-I}(C)\right), \tag{18}$$

$$R_{TDBC-OR-II} = C \cdot \left(1-P_r^{TDBC-OR-II}(C)\right), \tag{19}$$

$$R_{PNC-OR-I} = \frac{3C}{2} \cdot \left(1-P_r^{PNC-OR-I}(C)\right), \tag{20}$$

$$R_{PNC-OR-II} = C \cdot \left(1-P_r^{PNC-OR-II}(C)\right), \tag{21}$$

where $P_r^{direct}(C)$ is the outage probability of the direct link transmission, $P_r^{TDBC-OR-I}(C)$ and $P_r^{TDBC-OR-II}(C)$ are the outage probability of TDBC-OR-I and TDBC-OR-II and are equal to $P_r^{TDBC-OIR-I}(C)$ and $P_r^{TDBC-OIR-II}(C)$ respectively. Substituting the corresponding outage probability expressions in subsection 3.1 into these expressions, we readily obtain the expected rates of the six protocols. The expected rate's physical meaning is the maximum data rate or spectral efficiency that can be supported without outage. Note that the expected rate is defined on the system's basis not on each source's.

3.3 DMT Performance Analysis

To derive the DMT of TDBC-OIR-I, let $\rho \to +\infty$, then the expected rate becomes $R_{TDBC-OIR-I}^{\inf} = \lim_{\rho\to+\infty} R_{TDBC-OIR-I} = \frac{3C}{2}$ since P_r^{direct} and $P_r^{TDBC-OIR-I}(C)$ tends to zero. Furthermore, let $R_{TDBC-OIR-I}^{\inf} = r\log\rho$, where r is the multiplexing gain, we have $G = (2^{1.5C} - 1)/\rho \doteq \rho^{r-1}$. According to the DMT definition [10, Definition 3], the DMT of TDBC-OIR-I is given as follows

$$
\begin{aligned}
d_{TDBC-OIR-I}(r) &= -\lim_{\rho\to+\infty} \frac{\log P_r^{TDBC-OIR-I}\left(C = \frac{2}{3} r\log\rho\right)}{\log\rho} \\
&= -\lim_{\rho\to+\infty} \frac{\log\left(1-e^{-2\rho^{r-1}}\right)^N \left(1-e^{-\rho^{r-1}}\right)}{\log\rho} \\
&= -\lim_{\rho\to+\infty} \frac{\log\left(\left(2^N \rho^{N(r-1)}\right) + o\left(\rho^{N(r-1)}\right)\right)\left(\rho^{r-1} + o\left(\rho^{r-1}\right)\right)}{\log\rho} \\
&= -\lim_{\rho\to+\infty} \frac{\log\left(\left(2^N \rho^{(N+1)(r-1)}\right) + o\left(\rho^{(N+1)(r-1)}\right)\right)}{\log\rho} \\
&= (N+1)(1-r)
\end{aligned} \tag{22}
$$

For TDBC-OIR-II, its DMT is given in the following theorem.

Theorem: The DMT of TDBC-OIR-II is expressed as $d_{TDBC-OIR-II}(r) = (N+1)(1-r)$ with $0 \le r \le 1$, the same as TDBC-OIR-I.

Proof: Let $\rho \to +\infty$, then the expected rate becomes $R_{TDBC-OIR-II}^{\inf} = \lim_{\rho\to+\infty} R_{TDBC-OIR-II} = \frac{3C}{2}$. Considering the outage probability expression (7) and let $R_{TDBC-OIR-II}^{\inf} = r\log\rho$, the first two terms can be expressed as $2(1 - e^{-G})^{N+1}(1 - (1 - e^{-G})^N) \doteq \rho^{-(N+1)(1-r)}$ and $(1 - e^{-G})^{2N+1} \doteq \rho^{-(2N+1)(1-r)}$. In the following we calculate the third term of (7). Denoting $X_{S_1S_2} = \rho^{-u}$, $X = \rho^{-v}$, and $B_{m_1,m_2} = \binom{N}{m_1}\binom{N-m_1}{m_2} P_1^{\ m_1}\left(1-P_2\right)^{m_1} P_2^{\ m_2}\left(1-P_1\right)^{m_2}\left(\left(1-P_1\right)\left(1-P_2\right)\right)^{N-m_1-m_2} A_{m_1,m_2}$, it is shown from [24, eq. (5)] that the PDF of u is given by

$$f_u(u) \doteq \begin{cases} \rho^{-u}, & u > 0 \\ 0, & u < 0 \end{cases} \tag{23}$$

The PDF of v can be derived through variable change based on (12), and is written as

$$f_v(v)=\left[\begin{array}{l}\dfrac{m_1\left(1-e^{-\rho^{-v}}\right)^{m_1-1}}{\left(1-e^{-G}\right)^{m_1}}+\dfrac{m_2\left(1-e^{-\rho^{-v}}\right)^{m_2-1}}{\left(1-e^{-G}\right)^{m_2}}\\-\dfrac{(m_1+m_2)\left(1-e^{-\rho^{-v}}\right)^{m_1+m_2-1}}{\left(1-e^{-G}\right)^{m_1+m_2}}\end{array}\right]e^{-\rho^{-v}}\rho^{-v}\ln\rho$$

$$\doteq\begin{cases}\rho^{-\min(m_1,m_2)(v+(r-1))}, & v>1-r\\ 0 & \text{others}\end{cases} \quad (24)$$

Then, we rewrite A_{m_1,m_2} according to [24, eq. (6)] in the following.

$$\begin{aligned}&A_{m_1,m_2}\\&=P_r\left(X_{S_1S_2}+X<G\mid D_{1,m_1},D_{2,m_2},\text{and } D_{12,N-m_1-m_2}\right)\\&\doteq\int_\Lambda\rho^{-\min(m_1,m_2)(v+(r-1))}\rho^{-u}dudv\\&=\int_\Lambda\rho^{-(\min(m_1,m_2)(v+(r-1))+u)}dudu\\&\doteq\rho^{-d_{m_1,m_2}(r)}\end{aligned} \quad ,(25)$$

where $\Lambda=\{(u,v):u>1-r \text{ and } v>1\text{-}r\}$ and $d_{m_1,m_2}(r)=\inf_{(u,v)\in\Lambda}\left(\min(m_1,m_2)(v+(r-1))+u\right)=1-r$.

Then we have

$$\begin{aligned}B_{m_1,m_2}&=e^{-G(m_1+m_2)}\left(1-e^{-G}\right)^{2N-m_1-m_2}A_{m_1,m_2}\\&=\left(1-G(m_1+m_2)+o(G(m_1+m_2))\right)\left(G+o(G)\right)^{2N-m_1-m_2}A_{m_1,m_2}\\&\doteq\rho^{-(2N-m_1-m_2)(1-r)}\rho^{-(1-r)}=\rho^{-(2N-m_1-m_2+1)(1-r)}\end{aligned}, \quad (26)$$

and

$$\sum_{m_1=1}^{N}\sum_{m_2=1}^{N-m_1}B_{m_1,m_2}\doteq\sum_{m_1=1}^{N}\sum_{m_2=1}^{N-m_1}\rho^{-(2N-m_1-m_2+1)(1-r)}\doteq\rho^{-(N+1)(1-r)}. \quad (27)$$

Therefore, the outage probability can be rewritten as

$$P_r^{TDBC-OIR-II}(C)\doteq\rho^{-(N+1)(1-r)}+\rho^{-(N+1)(1-r)}\doteq\rho^{-(N+1)(1-r)}. \quad (28)$$

The DMT of TDBC-OIR-II is thus $(N+1)(1-r)$. ■

To derive the DMTs of TDBC-OR-I and TDBC-OR-II, we utilize the same way as that of TDBC-OIR-I and TDBC-OIR-I. Their DMTs are provided in the following corollary, the proof of which is omitted due to its straightforwardness.

Corollary 1: The DMTs of the two protocols, i.e., TDBC-OR-I and TDBC-OR-II are same and expressed as $d_{TDBC-OR-I}(r)=d_{TDBC-OR-II}(r)=(N+1)(1-3r/2)$ with $0\le r\le 2/3$.

Following the same way, we obtain the DMTs of PNC-OR-I and PNC-OR-II in corollary 2.

Corollary 2: The DMTs of PNC-OR-I and PNC-OR-II are derived as $d_{PNC-OR-I}(r)=N(1-r)$ with $0\le r\le 1$ and $d_{PNC-OR-II}(r)=N(1-3r/2)$ with $0\le r\le 2/3$, respectively.

Proof: Let $\rho\to+\infty$, then the expected rates of the two protocols, i.e., PNC-OIR-I and PNC-OIR-II become $R_{PNC-OR-I}^{\inf}=\frac{3C}{2}$ and $R_{PNC-OR-II}^{\inf}=C$. We first derive the DMT of the former protocol then the latter.

Let $R_{PNC-OR-I}^{\inf}=r\log\rho$, where r is the multiplexing gain, then $G=(2^{1.5C}-1)/\rho\doteq\rho^{-(1-r)}$ and $L=(2^{3C}-1)/\rho\doteq\rho^{-(1-2r)}$. Therefore, we have

$$\begin{aligned}1-P_{12}^{PNC-OR-I}&=\left(1-e^{-\rho^{-(1-2r)}}\left(\rho^{-(1-2r)}-2\rho^{-(1-r)}+1\right)\right)\\&=1-e^{-\rho^{-(1-2r)}}+e^{-\rho^{-(1-2r)}}\left(2\rho^{-(1-r)}-\rho^{-(1-2r)}\right)\\&=\rho^{-(1-2r)}+o\left(\rho^{-(1-2r)}\right)+\left(1-\rho^{-(1-2r)}+o\left(\rho^{-(1-2r)}\right)\right)\cdot\\&\qquad\times\left(2\rho^{-(1-r)}-\rho^{-(1-2r)}+1\right)\\&=2\rho^{-(1-r)}+o\left(\rho^{-(1-r)}\right)\doteq\rho^{-(1-r)}\end{aligned} \quad (29)$$

The DMT of PNC-OR-I is thus written as

$$d_{PNC-OR-I}(r)=-\lim\frac{\log P_r^{PNC-I}(C)}{\log\rho}=N(1-r). \quad (30)$$

For PNC-OR-II, let $R_{PNC-OR-II}^{\inf}=r\log\rho$, where r is the multiplexing gain, then $G=(2^{1.5C}-1)/\rho\doteq\rho^{-\left(1-\frac{3}{2}\rho\right)}$. Therefore, we have $P_r^{PNC-II}(C)\doteq\sum_{m_1=0}^{N}\sum_{m_2=0}^{N-m_1}\rho^{-\left(1-\frac{3}{2}r\right)(2N-m_1-m_2)}\doteq\rho^{-N\left(1-\frac{3}{2}r\right)}$, the DMT of PNC-OR-II is readily obtained as $d_{PNC-OR-II}(r)=N(1-3r/2)$. ■

4. Simulation Results and Discussions

In this section, we provide simulation results to validate the analytical results in the above section. The baseline data rate is set to be C =1 bits/s/Hz. The transmit power is equal to the transmit SNR ρ since the AWGNs are assumed to be with unit power. All channel gains are independent complex Gaussian distributed RVs with distribution $CN(0,1)$. The number of relays is denoted by N.

Fig. 3 presents the DMTs of the six protocols, i.e., TDBC-OIR-I, TDBC-OIR-II, TDBC-OR-I, TDBC-OR-II, PNC-OR-I, and PNC-OR-II. It is shown that all the protocols achieve the full diversity order (i.e., the maximum achievable diversity gain, corresponding to $r=0$). For the former four protocols, the diversity order is N+1. The diversity order of the latter two protocols is N because of lack of direct link transmission (leading to one diversity order loss). As for multiplexing gain, TDBC-OIR-I (TDBC-OIR-II) has greater multiplexing gain than TDBC-

OR-I (TDBC-OR-II) for given diversity gain. This is because the former utilize feedback to reduce the number of time slots for transmission. Since multiplexing gain reflects the increase of spectral efficiency (or data rate) [23], the spectral efficiency performance of the former is better than the latter (see from Fig. 5 and Fig. 7). Though TDBC-OIR-I and TDBC-OIR-II may consume three time slots for transmission, its maximum achievable multiplexing gain is the same as PNC-OR-I (with two time slots for transmission). The PNC-OR-II protocol has the worst DMT performance (its maximum achievable diversity and multiplexing gains are N and 2/3 respectively) since it has no direct link transmission and consumes three time slots for transmission.

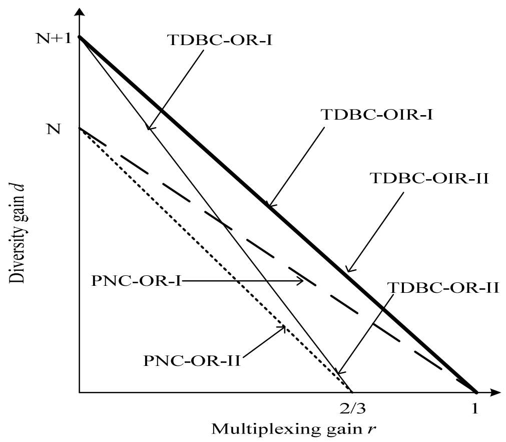

Fig. 3. The DMTs of TDBC-OIR-I, TDBC-OIR-II, TDBC-OR-I, TDBC-OR-II, PNC-OR-I, and PNC-OR-II.

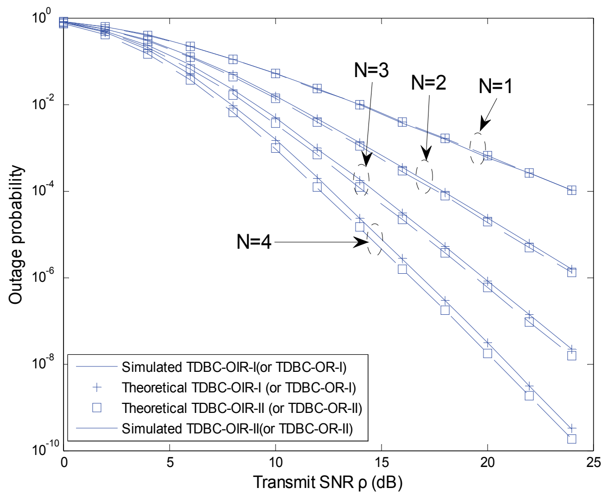

Fig. 4. Outage performance comparison between TDBC-OIR-I and TDBC-OIR-II for various numbers of relays.

Fig. 4 gives the outage performance of TDBC-OR-I, TDBC-OR-II, TDBC-OIR-I, and TDBC-OIR-II for various numbers of relays. It is revealed that the simulated results coincide with the theoretical results exactly for all the protocols and TDBC-OIR-II has slightly better outage performance than TDBC-OIR-I except for N=1. This is because when there is no relay that can decode successfully both flows of signal, there may be two relays that can decode successfully each flow of signal for TDBC-OIR-II. When N=1(i.e., the single relay case in [7]), the two protocols' performance are the same since there does not exist such case when two best relays are selected. As the number of relays increases, the outage performance gets better because of increased diversity order. It is furthermore revealed that TDBC-OIR-I (TDBC-OIR-II) has the same outage performance as TDBC-OR-I (TDBC-OR-II), which has also be shown in section 3.

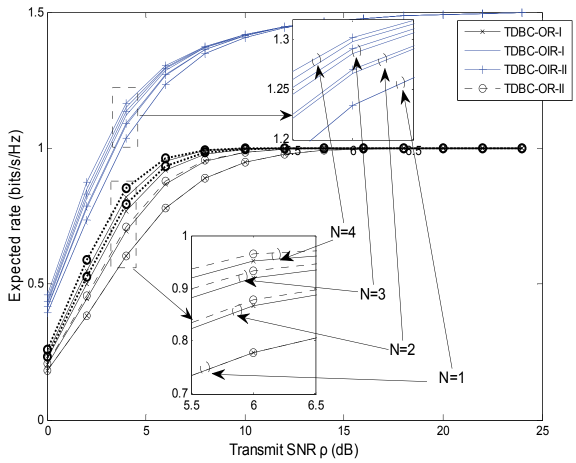

Fig. 5. ER performance comparison between TDBC-OIR-I and TDBC-OIR-II for various numbers of relays.

Fig. 5 shows the expected rate performance of TDBC-OR-I, TDBC-OR-II, TDBC-OIR-I, and TDBC-OIR-II. It is revealed that TDBC-OIR-I (TDBC-OIR-II) has improved expected rate (or spectral efficiency) performance over TDBC-OR-I (TDBC-OR-II) since the time slots for transmission are reduced when the direct link transmission is successful. TDBC-OIR-II (TDBC-OR-II) has better ER performance than TDBC-OIR-I (TDBC-OR-I) because of its better outage performance (see Fig. 4). The expected rates for TDBC-OIR-I (TDBC-OIR-II) and TDBC-OR-I (TDBC-OR-II) are 1.5 bits/s/Hz and 1 bits/s/Hz at asymptotic high SNR regime, which is also shown by (16)-(19).

The outage performance comparison of TDBC-OIR-I, TDBC-OIR-II, PNC-OR-I, and PNC-OR-II is presented in Fig. 6 when there are two relays, i.e., N=2. From the figure, we learn that (1) the simulated results coincide with the theoretical results exactly; (2) the outage performance of PNC-OR-II is better than PNC-OR-I with the same reason as in Fig. 4, i.e., there may be two best relays for transmission when there is no relay that can successfully decode both flows of signal; and (3) both PNC-OR-I and PNC-OR-II have worse outage performance than TDBC-OIR-I or TDBC-OIR-II resulting from the lack of direct link transmission (i.e., with one diversity order loss).

The ER performance of the six protocols when N=2 is provided in Fig. 7. From the figure, it is revealed that (1) TDBC-OIR-I (or TDBC-OIR-II) has better expected rate performance than PNC-OR-I at low to medium SNR regime, though it may consume three time slots. This is because it has much better outage performance than PNC-OR-I; (2) TDBC-OR-I (or TDBC-OR-II) has improved ER performance over PNC-OR-II at low to medium SNR regime because of its better outage performance; and (3) the ER performance of PNC-OR-I is better than PNC-OR-II at medium to high SNR regime since it consumes less time slots for transmission and time slot plays the dominant role in ER performance. At low SNR regime, the situation reverses because at this regime the outage probability is the dominant role in ER performance.

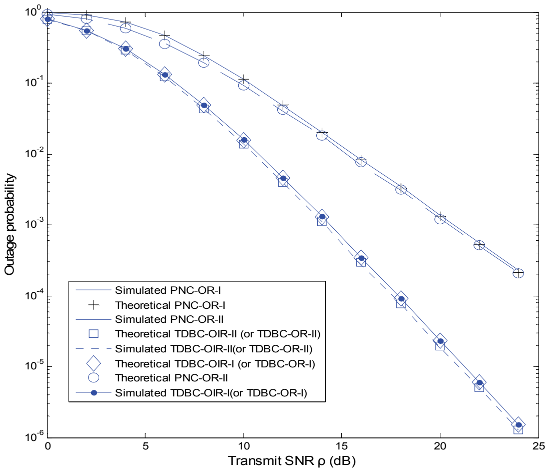

Fig. 6. Outage performance comparison of TDBC-OIR-I, TDBC-OIR-II, PNC-OR-I, and PNC-OR-II with *N*=2.

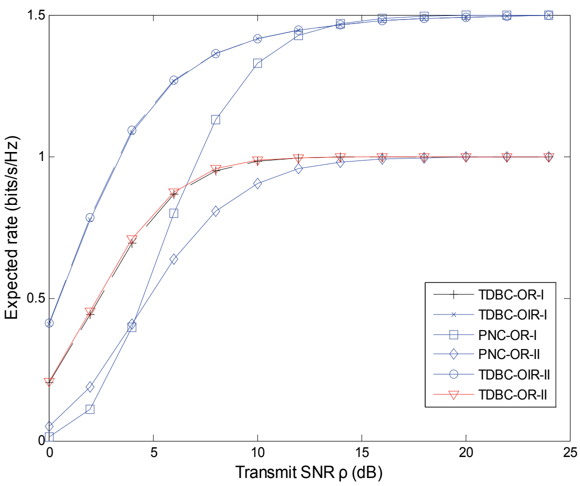

Fig. 7. ER performance comparison of TDBC-OIR-I, TDBC-OIR-II, TDBC-OR-I, TDBC-OR-II, PNC-OR-I, and PNC-OR-II when N=2.

5. Conclusions

In this paper, we propose two relay selection schemes for time division broadcast protocol with direct link transmission and incremental relaying in two-way relaying channel when there are multiple available relays, i.e., TDBC-OIR-I and TDBC-OIR-II. The two schemes utilize feedback to improve the spectral efficiency of the relay selection schemes of TDBC without feedback. As for performance comparison, we also introduce two benchmark protocols without direct link transmission, i.e., PNC-OR-I and PNC-OR-II. The performance of the abovementioned protocols are analyzed and compared in terms of outage probability, expected rate, and diversity-multiplexing tradeoff. It is revealed that the proposed schemes have improved spectral efficiency performance over all the other protocols, even PNC-OR-I that consumes two time slots for transmission.

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