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An adaptive randomized DSTC scheme for two-hop cooperative wireless networks

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ABSTRACT

An adaptive randomized distributed space-time coding (DSTC) scheme is proposed for two-hop cooperative MIMO networks. Linear minimum mean square error (MMSE) receiver filters and randomized matrices subject to a power constraint are considered with an amplify-and-forward (AF) cooperation strategy. In the proposed DSTC scheme, a randomized matrix obtained by a feedback channel is employed to transform the space-time coded matrix at the relay node. The effect of the limited feedback and feedback errors are considered. Linear MMSE expressions are devised to compute the parameters of the adaptive randomized matrix and the linear receive filters. A stochastic gradient algorithm is also developed with reduced computational complexity. The simulation results show that the proposed algorithms obtain significant performance gains as compared to existing DSTC schemes.

Keywords:- MIMO; DSTC; AF and MMSE

INTRODUCTION

Relaying has become a widely accepted means of cooperation in wireless networks. In this paper, we focus on networks composed of one source, one destination and one relay that operates under the half-duplex constraint *i.e.*, the relay can either receive or transmit, but not both at the same time. The relay thus listens to the source signal during a certain amount of time (the first slot) and is allowed to transmit towards the destination during the rest of the time (the second slot).

Diversity techniques is mainly used for overcome the fading problem in wireless communication, this problem is occurs due to No clear line of sight (LOS) between transmitter and receiver, the signal is reflected along multiple paths before finally being received. These introduce phase shifts, time delays, attenuations, and distortions that can destructively interfere with one another at the aperture of the receiving antenna. There are several wireless Diversity schemes that use two or more antennas to improve the quality and reliability of a wireless link. In this paper we are discussing about one of Cooperative diversity technique. In some practical scenarios (e.g., handheld terminals, sensor nodes, etc.), it may be difficult to support multiple antennas due to the terminal size, power consumption, and hardware limitations. To that, cooperative diversity is emerging as an alternative method to obtain the transmit diversity by allowing single-antenna terminals to share their antennas to form a virtual antenna array. So far, a wide range of relaying protocols have been proposed so far. Most of these protocols belong to one of the following families of relaying schemes: Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF). The amplify-and-forward strategy allows the relay station to amplify the received signal from the source node and to forward it to the destination station.

In cooperative wireless communication, we are concerned with a wireless network, of the cellular or ad hoc variety, where the wireless agents, which we call users, may increase their effective quality of service (measured at the physical layer by bit error rates, block error rates, or outage probability) via cooperation.

In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user (Fig. 1). Cooperation leads to interesting trade-offs in code rates and transmit power. In the case of power, one may argue on one hand that more power is needed because each user, when in cooperative mode, is transmitting for both users. On the other hand, the baseline transmits power for both users will be reduced because of diversity. In the face of this trade-off, one hopes for a net reduction of transmit power, given everything else being constant.

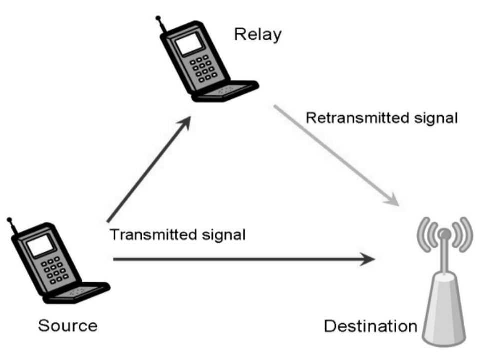

Fig 1**.** cooperative communication.

1.1 BENEFITS OF COOPERATIVE TECHNOLOGY MIMO VIEW)

The benefits of MIMO technology that help achieve such significant performance gains are array gain, spatial diversity gain, spatial multiplexing gain and interference reduction. These gains are described in brief below.

Array gain

Array gain is the increase in receive SNR that results from a coherent combining effect of the wireless signals at a receiver. The coherent combining may be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Array gain improves resistance to noise, thereby improving the coverage and the range of a wireless network.

Spatial diversity gain

As mentioned earlier, the signal level at a receiver in a wireless system fluctuates or fades. Spatial diversity gain mitigates fading and is realized by providing the receiver with multiple (ideally independent) copies of the transmitted signal in space, frequency or time. With an increasing number of independent copies (the number of copies is often referred to as the diversity order), the probability that at least one of the copies is not experiencing a deep fade increases, thereby improving the quality and reliability of reception. A MIMO channel with M_T transmit antennas and M_R receive antennas potentially offers M_T M_R independently fading links, and hence a spatial diversity order of M_T M_R

Spatial multiplexing gain

MIMO systems offer a linear increase in data rate through spatial multiplexing, i.e., transmitting multiple, independent data streams within the bandwidth of operation. Under suitable channel conditions, such as rich scattering in the environment, the receiver can separate the data streams. Furthermore, each data stream experiences at least the same channel quality that would be experienced by a single-input single-output system, effectively enhancing the capacity by a multiplicative factor equal to the number of streams. In general, the number of data streams that can be reliably supported by a MIMO channel equals the minimum of the number of transmit antennas and the number of receive antennas, i.e., min [M_T M_R]. The spatial multiplexing gain increases the capacity of a wireless network.

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Interference reduction and avoidance

Interference in wireless networks results from multiple users sharing time and frequency resources. Interference may be mitigated in MIMO systems by exploiting the spatial dimension to increase the separation between users. For instance, in the presence of interference, array gain increases the tolerance to noise as well as the interference power, hence improving the signal-to-noise-plus-interference ratio (SINR). Additionally, the spatial dimension may be leveraged for the purposes of interference avoidance, i.e., directing signal energy towards the intended user and minimizing interference to other users. Interference reduction and avoidance improve the coverage and range of a wireless network. In general, it may not be possible to exploit simultaneously all the benefits described above due to conflicting demands on the spatial degrees of freedom. However, using some combination of the benefits across a wireless network will result in improved capacity, coverage and reliability.

However, with rich scattering and $L \geq PM$, we can expect that the spatial signatures of the users are well separated to allow reliable detection. Using a multi-user ZF receiver will allow perfect separation of all the data streams at the base-station, yielding a multi-user multiplexing gain of PM. The use of more complex receivers for multi-user detection and the associated performance trade-offs. A similar thought experiment can be applied for the downlink, where the base-station exploits the spatial dimension to beam information intended for a particular user towards that user and steers nulls in the directions of the other users, thus completely eliminating interference.

2.MODULES

2.1 PROPOSED OPPORTUNISTIC DISTRIBUTED SPACE-TIME CODING (O-DSTC) SCHEMES

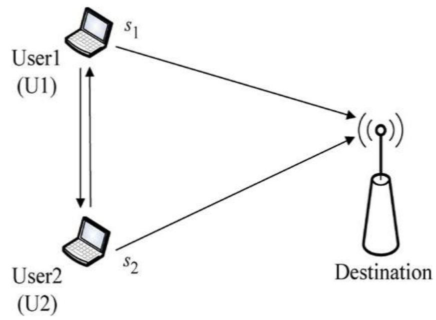

Fig 2. A decode-and-forward cooperation system with two cooperative users transmitting data to a common destination.

In this section, we first present the system model used throughout this paper. Next, we propose the O-DSTC schemes with full-duplex and half-duplex considerations, which are referred to as the full-duplex and half-duplex-based O-DSTC, respectively. For the comparison purpose, we also present the conventional S-DF.

As shown in Fig. 1, we consider a cooperative diversity system consisting of two cooperative users (as denoted by U1 and U2), which assist each other using a DF protocol in transmitting their information (i.e., and) to a common destination, where the subscripts 1 and 2 represent U1 and U2, respectively. Although only two cooperative users are considered in this paper, this is an essential scenario to be addressed, since a more generic scenario with multiple source users can be typically converted to the two-user cooperation by designing an additional grouping and partner selection protocol. In addition, each node as shown in Fig. 1 is assumed to have a single antenna, for which two duplex modes (i.e., full-duplex and half-duplex) are considered in the paper. It is pointed out that full-duplex and half-duplex refer to the antenna with and without the capability of transmitting and receiving a signal simultaneously over the same channel, respectively.

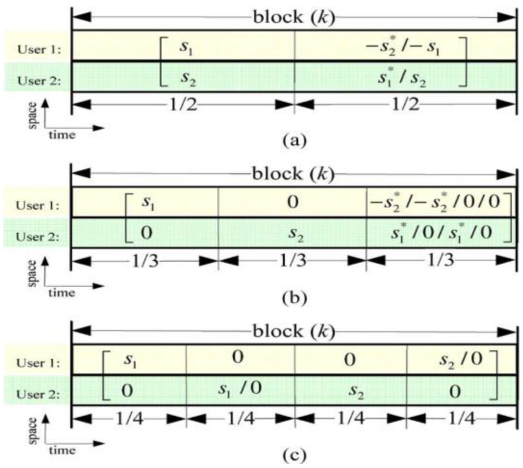

Fig. 2(a) illustrates that the proposed full-duplex-based O-DSTC scheme divides a total block into two time frames which are shared between U1 and U2. In the first time frame, both U1 and U2 exchange and transmit their own information and to the destination. At the same time, by considering the full-duplex regime, U1 and U2 can receive and decode each other's information over the channels between the two users, called inter-user channels. In the subsequent time frame, U1 and U2 transmit and in an opportunistic encoding manner depending on whether U1 and U2 decode each other's information successfully or not, One can observe from Fig. 2(a) that the full-duplex-based O-DSTC utilizes two time frames for transmitting two symbols (i.e., and), implying that full multiplexing gain (also known as full rate) is achieved. We will prove in following section that such an O-DSTC scheme also achieves the full diversity gain and, in contrast, the traditional fixed DSTC (F-DSTC) is unable to achieve full diversity due to the bottleneck effect caused by inter-user channels. Notice that, in the traditional F-DSTC scheme, either U1 or U2 failing to decoding its partner's information will result in interference at the destination in decoding both the two users' information.

In Fig. 2(b), we depict the half-duplex-based O-DSTC, where a total block is divided into three time frames. The difference between the full-duplex and half-duplex-based O-DSTC is that the former scheme utilizes one time frame to exchange the information between U1 and U2, however the half-duplex-based O-DSTC requires two frames to complete the exchange process. From Fig. 2(b), one can see that, in the first two time frames, U1 and U2, respectively, broadcast and to each other and the destination. During the third time frame, U1 and U2 encode and transmit and using an opportunistic encoding approach, for which a detailed explanation will be presented in Section II-C. As shown in Fig. 2(b), the half-duplex-based O-DSTC uses three time frames for the transmission of and , thus a maximum multiplexing gain of two-third is achieved. This is very attractive as compared with the conventional S-DF cooperation and previous DSTC researches where a maximum multiplexing gain of only one-half is obtained.

Fig. 2(c) shows the conventional S-DF cooperation scheme as proposed in [4], where U1 and U2 are assisting each other's data transmissions (i.e., and) using four time frames. Specifically, in the first time frame of block, U1 broadcasts its own information to the destination and U2 that attempts to decode its received signal. Then, in the second time frame, U2 forwards its decoded outcome in a selective manner depending on whether it succeeds in decoding or not. If U2 decodesU1's transmission successfully, it will forward to the destination. Otherwise, U2 just keeps silent in the second time frame. The process of transmitting during the remaining two time frames of block is essentially same as the procedure of transmitting in the first two frames. One can see from Fig. 2(c) that four time frames are used to complete the transmissions of and, implying that a maximum multiplexing gain of one-half only is achieved by the conventional S-DF cooperation.

2.2 FULL DUPLEX DISTRIBUTED SPACE-TIME CODING (H-DSTC) SCHEMES

As a baseline, let us consider the non-cooperative transmission with one block consisting of two time frames where two users take turns in

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accessing the time frames to transmit their own data with power at data rates and in bits per frame, respectively. One can see from Fig. 2(a) that, in the full-duplex- based O-DSTC, two independent symbols and are transmitted by using two time frames, which means that no extra channel resource is wasted by retransmission. Thus, when U1 and U2, respectively, transmit at data rates and in the full-duplex-based O-DSTC scheme, it is guaranteed to transmit the same amount information (during one block) as the non-cooperative scheme. However, the proposed full-duplex-based O-DSTC scheme requires both U1 and U2 always transmitting in two frames during one block, differing from non-cooperative scheme where U1 and U2 take turns in the time block to transmit their information. Hence, for a fair comparison with the non-cooperative transmission in terms of power consumption, we consider one-half power $E_S/2$ for each user during one time frame in the full-duplex-based O-DSTC scheme. Accordingly, the received signal at the destination in the first time frame of block **k is** expressed as

$$y_d^1 = \sqrt{\frac{E_s}{2}} h_{1d} s_1 + \sqrt{\frac{E_s}{2}} h_{2d} s_2 + n_d^1 \quad (1)$$

Where the superscript 1 represents the first time frame of block $\boldsymbol{k}$, h_{1d} and h_{2d} are fading coefficients of the channel from U1 to destination and that from U2 to destination, respectively, and n_d^1 represents AWGN with zero mean and variance N_0. Note that the fading coefficients are modeled as constant during one block (including two frames for full-duplex-based O-DSTC) and vary independently in next time block. Meanwhile, the full-duplex enables U1 and U2 to receive and decode each other's information over the inter-user channels at the same time. Hence, the received signals at U1 and U2 are, respectively, given by

$$y_1 = \sqrt{\frac{E_s}{2}} h_{21} s_2 + n_1 \quad (2)$$

Where h_{21} represents the channel from U2 to U1 and n_1 is AWGN with zero mean and variance N_0, and

$$y_2 = \sqrt{\frac{E_s}{2}} h_{12} s_1 + n_2$$

Where h_{12} represents the channel from U1 to U2 and n_2 is AWGN with zero mean and variance N_0. Then, U1 and U2 decode each other's information using their received signals as given by (2) and (3), respectively. For the full-duplex-based O-DSTC scheme, we consider that U1 and U2 will acknowledge each other and the destination if they succeed in decoding or not using feedback channels. It is assumed that both U1 and U2 always decode the acknowledgement information successfully, considering the fact that an acknowledgment consists of only one-bit information. In the second time frame of block , U1 and U2 encode and transmit s_1 and s_2 in an opportunistic manner depending on their decoded outcomes in the first frame. To be specific, if both U1 and U2 decode each other's information successfully, the Alamouti space-time coding [13] will be utilized, i.e.,-S^*_2 and S^*_1 are transmitted by U1 and U2, respectively. Otherwise, U1 and U2, respectively, transmit $-S_1$ and S_2 to the destination, instead of the Alamouti coding. This is due to the fact that, when either U1 or U2 fails to decode, the use of Alamouti space-time code will introduce interference at the destination in decoding S_1 and S_2. Meanwhile, the destination cannot rely on its received signal in the first frame to decode S_1 and S_2, since two unknowns (S_1 and S_2) are in one equation, as shown in (1). In order to recover S_1 and S_2 at the destination in this case, U1 and U2 are allowed to transmit $-S_1$ and S_2 , respectively, to the destination in the second time frame, which guarantees the full multiplexing gain achieved and has the advantage of simple implementation for decoding S_1 and S_2 at the destination. The mutual information from U2 to U1 as denoted by can be calculated from (2) as

$$I_{21} = \log_2\left(1 + \frac{|h_{21}|^2 \gamma}{2}\right)$$

$$I_{12} = \log_2\left(1+\frac{|h_{12}|^2\gamma}{2}\right)$$

In an information-theoretic sense, when the channel capacity falls below a predefined data rate, it is regarded as an outage event and the receiver is doomed to fail to decode the original data no matter what decoding algorithm is used. Hence, considering data rates R_1 and R_2 (for U1 and U2, respectively), the event that both U1 and U2 succeed in decoding can be described as $I_{12}>R_1$ and $I_{21}>R_2$, which is denoted by for notation convenience. Similarly, we use to represent the other case that either U1 or U2 or both fail to decode, i.e., $I_{12}<R_1$ and/or $I_{21}<R_2$. In the case of , the Alamouti space-time coding will be utilized, and $-S^*_1$ and S^*_2 are transmitted by U1 and U2 in the second time frame of block ***k***. Thus, the received signal at the destination is written as

$$y_d^2(\theta=1) = -\sqrt{\frac{E_s}{2}}h_{1d}s_2^* + \sqrt{\frac{E_s}{2}}h_{2d}s_1^* + n_d^2$$

Where the superscript 2 represents the second time frame and n_d^2 is the AWGN received at destination. Combining (1) and (6), we can obtain from Alamouti decoding algorithm as

$$\begin{bmatrix} h_{1d}^* & h_{2d} \\ h_{2d}^* & -h_{1d} \end{bmatrix}\begin{bmatrix} y_d^1 \\ y_d^2(\theta=1)^* \end{bmatrix} = \sqrt{\frac{E_s}{2}}\begin{bmatrix} |h_{1d}|^2+|h_{2d}|^2 & 0 \\ 0 & |h_{1d}|^2+|h_{2d}|^2 \end{bmatrix}\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} h_{1d}^* n_d^1 + h_{2d}(n_d^2)^* \\ h_{2d}^* n_d^1 + h_{1d}(n_d^2)^* \end{bmatrix} \quad (7)$$

The mutual information from U1 and U2 to the destination is calculated from (7)

$$I_{1d}(\theta=1) = I_{2d}(\theta=1) = \log_2\left(1+\frac{|h_{1d}|^2+|h_{2d}|^2}{2}\gamma\right) \quad (8)$$

U1 or U2 or both fail to decode each other's information, U1 and U2, respectively, transmit $-s_1$ and s_2 to the destination. The received signal at the destination in the second time frame is given by

$$y_d^2(\theta=2) = -\sqrt{\frac{E_s}{2}}h_{1d}s_1 + \sqrt{\frac{E_s}{2}}h_{2d}s_2 + n_d^2 \quad (5)$$

By solving (1) and (9), the destination can easily decode s_1 and s_2 as follows

$$\begin{bmatrix} h_{1d}^* & 0 \\ 0 & h_{2d}^* \end{bmatrix}\begin{bmatrix} y_d^1 - y_d^2(\theta=2) \\ y_d^1 + y_d^2(\theta=1) \end{bmatrix} = \begin{bmatrix} \sqrt{2E_s}|h_{1d}|^2 s_1 \\ \sqrt{2E_s}|h_{2d}|^2 s_2 \end{bmatrix} + \begin{bmatrix} h_{1d}^*(n_d^1 - n_d^2) \\ h_{2d}^*(n_d^1 + n_d^2)^* \end{bmatrix}$$

From which s_1 and s_2 are estimated as $\arg\min_{s\in s_2}\left|h_{1d}^*\left[y_d^1 + y_d^2(\theta=2) - h_{1d}\sqrt{2E_s s}\right]\right|^2$ and $\arg\min_{s\in s_2}\left|h_{2d}^*\left[y_d^1 + y_d^2(\theta=2) - h_{2d}\sqrt{2E_s s}\right]\right|^2$ by using the maximum likelihood (ML) detection.

$$I_{1d}(\theta=2) = \log_2\left(1+|h_{1d}|^2\gamma\right)$$

and

$$I_{2d}(\theta=2) = \log_2\left(1+|h_{2d}|^2\gamma\right) \quad (6)$$

In addition, it is pointed out that, by considering that both U1 and U2 notify the destination whether or not they succeed in decoding each other's information through feedback channels, the destination is able to determine which detection algorithm should be selected between (7) and (10) and used for decoding s_1 and s_2.

2.3 HALF DUPLEX DISTRIBUTED SPACE-TIME CODING (H-DSTC) SCHEMES

This subsection discusses the half-duplex-based O-DSTC scheme. One can see from Fig. 2(b) that in the half-duplex- based O-DSTC scheme, three time frames within one block are required to transmit two symbols s_1 and s_2. In order to send the same amount information as the non-cooperative scheme during one block, the half-duplex-based O-DSTC scheme shall transmit at 1.5 times data rate of the non-cooperative transmission. Thus, we consider U1

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and U2 with data rates $\frac{3R_1}{2}$ and $\frac{3R_2}{2}$ in bits per frame, respectively, for the half-duplex-based O-DSTC. In addition, as shown in Fig. 2(b), the half-duplex-based O-DSTC scheme divides one block into three time frames and requires both U1 and U2 to transmit in either one or two frames per block. Assuming the worst case of the two users transmitting in two frames per block, we consider the power of $\frac{3E_s}{4}$ for each user during one time frame in the half-duplex-based O-DSTC scheme for a fair comparison with the non-cooperative scheme in terms of power consumption.

In the first time frame of block *k*, U1 broadcasts its signal with power $\frac{3E_s}{4}$ and rate $\frac{3R_1}{4}$ to U2 and destination. Thus, the received signals at the destination and U2 are expressed as

$$y_d^1 = \sqrt{\frac{3E_s}{4}} h_{1d} s_1 + n_d^1$$

and

$$y_2 = \sqrt{\frac{3E_s}{4}} h_{12} s_1 + n_2$$

Similarly, in the second time frame, U2 transmits to U1 and destination with power $\frac{3E_s}{4}$ and rate $\frac{3R_2}{4}$. Hence, the received signals at the destination and U1 are given by

$$y_d^2 = \sqrt{\frac{3E_s}{4}} h_{2d} s_2 + n_d^2$$

and

$$y_1 = \sqrt{\frac{3E_s}{4}} h_{21} s_2 + n_1$$

Then, U1 and U2 attempt to decode their received signals based on (14) and (16), respectively. In the third time frame of block, the transmit symbols sent by U1 and U2 depend on their local decoded outcome without any acknowledgment (feedback) between each other. Specifically, if U1 succeeds in decoding U2's information, it will transmit; otherwise, it just keeps quiet to avoid interference. Similarly, if U2 succeeds in decoding, it will transmit to the destination; otherwise, no signal is transmitted. Hence, there are four possible outcomes at the destination which requires respective decoding algorithms. As shown in Fig. 3,we can implement four decoding branches in parallel at the destination and, in general, only one branch output will pass the forward error detection (e.g., CRC checking). This means that the destination can decode and locally without any feedback information from U1 and U2 about whether the two users decode each other's information successfully or not. This advantage comes at the cost of implementation complexity due to the parallel decoding architecture. It is pointed out that, if feedback channels are available for U1 and U2 to notify the destination whether they succeed in decoding or not, the multiple parallel decoding branches as illustrated in Fig. 3 can be reduced to a single branch structure.

(13)

With the coherent detection, the mutual information from U2 to U1 and that fromU1 to U2 are calculated from (14) and (16) as (14)

$$I_{1d} = \log_2\left(1 + \frac{3|h_{1d}|^2 \gamma}{4}\right)$$

and

$$I_{21} = \log_2\left(1 + \frac{3|h_{21}|^2 \gamma}{4}\right)$$

(15)

As discussed above, there are four possible outcomes with regard to whether U1 and U2 succeed in decoding each other. For simplicity, let ω=1, 2, 3, and 4, respectively, denote U1 and U2 decode successfully, U1 succeeds and U2 fails, U1 fails and U2 succeeds, and both fail. Hence, in an information-theoretic sense, events ω = 1, 2, 3, and 4 are described as

(16)

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$$\omega = 1 : I_{12} > \frac{3R_1}{2} \quad and \quad I_{21} > \frac{3R_2}{2}$$

$$\omega = 2 : I_{12} > \frac{3R_1}{2} \quad and \quad I_{21} > \frac{3R_2}{2}$$

$$\omega = 3 : I_{12} > \frac{3R_1}{2} \quad and \quad I_{21} > \frac{3R_2}{2}$$

$$\omega = 4 : I_{12} > \frac{3R_1}{2} \quad and \quad I_{21} > \frac{3R_2}{2}$$

In the case of $\omega = 1$, $-S_2^*$ and S_1^* are transmitted by U1 and U2 in the third time frame of block Thus, the received signal at the destination in this case is written as

$$y_d^3(\omega=1) = -\sqrt{\frac{3E_s}{4}} h_{1d} s_2^* + \sqrt{\frac{3E_s}{4}} h_{2d} s_1^* + n_d^3 a$$

Where is AWGN with zero mean and variance N_0. By using (13), (15) and (20), S_1 and S_2 are demodulated at the destination as follows

$$\begin{bmatrix} h_{1d}^* & h_{2d} \\ h_{2d}^* & -h_{1d} \end{bmatrix} \begin{bmatrix} y_d^1 + y_d^2 \\ y_d^3(\omega=1)^* \end{bmatrix} = \sqrt{\frac{3E_s}{4}} \begin{bmatrix} |h_{1d}|^2 + |h_{2d}|^2 & 0 \\ 0 & |h_{1d}|^2 + |h_{2d}|^2 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} h_{1d}^* n'_d + h_{2d} (n_d^3)^* \\ h_{2d}^* n'_d - h_{1d} (n_d^3)^* \end{bmatrix}$$

where $n'_d = n_d^1 + n_d^2$. Note that the motivation of using $y_d^1 + y_d^2$ jointly with is to employ the Alamouti decoding algorithm to decode the desired signals S_1 and S_2. One can see that the first matrix in (21) is the exact Alamouti decoding matrix which is also used in (7) for the full-duplex-based O-DSTC scheme. It is pointed out that the decoding strategy adopted in (21) has low computational complexity and preserves the full diversity, as will be shown later in (66). Hence, given $\omega = 1$, the mutual information from U1 and U2 to the destination calculated from (21) as

$$I_{1d}(\omega = 1) = \log_2 \left[1 + \frac{3\left(|h_{1d}|^2 + |h_{2d}|^2\right)^2}{4\left(2|h_{1d}|^2 + |h_{2d}|^2\right)}\gamma\right] \geq \log_2 \left(1 + \frac{3\left(|h_{1d}|^2 + |h_{2d}|^2\right)}{8}\gamma\right)$$

$$I_{2d}(\omega = 1) = \log_2 \left[1 + \frac{3\left(|h_{1d}|^2 + |h_{2d}|^2\right)^2}{4\left(|h_{1d}|^2 + 2|h_{2d}|^2\right)}\gamma\right] \geq \log_2 \left(1 + \frac{3\left(|h_{1d}|^2 + |h_{2d}|^2\right)}{8}\gamma\right).$$

Given $\omega = 2$ occurred, i.e., U1 succeeds in decoding S_2 from (16) and U2 fails to decode S_1 from (14), U1 transmits $-S_2^*$ and U2 keeps quiet during the third time frame of block. Therefore, in the case of $\omega = 2$, the received signal at the destination is given by

$$y_d^3(\omega=2) = -\sqrt{\frac{3E_s}{4}} h_{1d} s_2^* + n_d^3 \tag{19}$$

Using (13), (15) and (24), the destination will decode and S_1 as S_2 follows

$$\begin{bmatrix} h_{1d}^* & 0 & 0 \\ 0 & h_{2d}^* & h_{1d} \end{bmatrix} \begin{bmatrix} y_d^1 \\ y_d^2 \\ y_d^3(\omega=2)^* \end{bmatrix} = \sqrt{\frac{3E_s}{4}} \begin{bmatrix} |h_{1d}|^2 s_1 \\ \left(|h_{1d}|^2 + |h_{2d}|^2\right) s_2 \end{bmatrix} + \begin{bmatrix} h_{1d}^* n_d^1 \\ h_{2d}^* n_d^2 + h_{1d} (n_d^3)^* \end{bmatrix}. \tag{20}$$

Hence, given $\omega = 2$, the mutual information from U1 to the destination and that from U2 to the destination are given by

$$I_{1d}(\omega = 2) = \log_2 \left(1 + \frac{3|h_{1d}|^2 \gamma}{4}\right)$$

$$I_{2d}(\omega = 2) = \log_2 \left[1 + \frac{3\left(|h_{1d}|^2 + |h_{2d}|^2\right)}{8}\gamma\right]. \tag{21}$$

Note that case $\omega = 2$ occurs when the channel from U1 to U2 is in outage. Thus, the destination will fail to decode S_1 only when both the channels from U1 to U2 and that from U1 to destination are in outage. This implies that a diversity gain of two is still achieved by the U1's transmissions given $\omega = 2$, which will be proven in Section IV. In the case of $\omega = 2$, i.e., U1 fails to decode S_2 from (16) and U2 succeeds in decoding S_1 from (14), U1 keeps quiet and U2 transmits S^*_1 in the third time frame of block . Hence, given $\omega = 2$, the received signal at the destination can be given by

$$y_d^3(\omega = 3) = \sqrt{\frac{3E_s}{4}} h_{2d} s_1^* + n_d^3. \tag{22}$$

(23)

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Combining (13), (15), and (28), the destination can decode S_1 and S_2 as given by

$$\begin{bmatrix} h_{1d}^* & h_{2d} & 0 \\ 0 & 0 & h_{2d}^* \end{bmatrix} \begin{bmatrix} y_d^1 \\ y_d^3(\omega=2)^* \\ y_d^2 \end{bmatrix} = \sqrt{\frac{3E_s}{4}} \begin{bmatrix} \left(|h_{1d}|^2+|h_{2d}|^2\right) s_1 \\ |h_{2d}|^2 s_2 \end{bmatrix} + \begin{bmatrix} h_{1d}^* n_d^1 + h_{2d}\left(n_d^3\right)^* \\ h_{2d}^* n_d^2 \end{bmatrix}$$

from which the mutual information from U1 and U2 to the destination can be calculated as

$$I_{1d}(\omega=3) = \log_2\left[1+\frac{3\left(|h_{1d}|^2+|h_{2d}|^2\right)}{8}\gamma\right]$$

$$I_{2d}(\omega=3) = \log_2\left(1+\frac{3|h_{2d}|^2\gamma}{4}\right).$$

The last case $\omega = 4$ indicates that both U1 and U2 fail to decode each other's information. In this case, the destination can only rely on (13) and (15) to decode S_1 and S_2, respectively. Thus, the corresponding mutual information from U1 and U2 to destination are given by

$$I_{1d}(\omega=4) = \log_2\left(1+\frac{3|h_{1d}|^2\gamma}{4}\right)$$

$$I_{2d}(\omega=4) = \log_2\left(1+\frac{3|h_{2d}|^2\gamma}{4}\right).$$

2.4 OUTAGE PROBABILITY ANALYSIS OVER RAYLEIGH FADING CHANNELS

In this section, we examine the outage probability for full-duplex O-DSTC schemes as well as the conventional S-DF and F-DSTC. We only focus on the performance analysis of the transmission of s_1 from U1 to destination throughout this paper, and similar performance results can be obtained for the transmission of s_2 from U2 to destination. Let us first consider the traditional non-cooperative scenario in a Rayleigh fading environment, where the outage probability of U1's transmissions with power E_S and rate R_1 is given by

$$Pout_{non} = \Pr\left\{\log_2\left(1+|h_{1d}|^2\gamma\right) < R_1\right\} = 1-\exp\left(-\frac{2^{R_1}-1}{\sigma_{1d}^2\gamma}\right)$$

<u>Outage Analysis of Full-Duplex Based O-DSTC Scheme:</u> the full-duplex-based O-DSTC scheme utilizes an opportunistic encoding approach depending on whether U1 and U2 succeed in decoding each other's information. Following (8) and (11), an outage probability of the U1's transmission can be expressed as

$$Pout_{fill-ODSTC} = \Pr(\theta=1)\Pr(outage\,|\,\theta=1)+\Pr(\theta=2)\Pr(outage\,|\,\theta=2)$$

$$= \Pr(I_{12}>R_1, I_{21}>R_2)\Pr(I_{1d}(\theta=1)<R_1) + \left[1-\Pr(I_{12}>R_1, I_{21}>R_2)\right]\Pr(I_{1d}(\theta=2)<R_1) \quad (29)$$

Where I_{21}, $I_{12,}$ $I_{1d}(\theta=1)$, and $I_{1d}(\theta=2)$ are, respectively, given by (4),(5),(8) and (11). The following closed form solutions to term $\Pr(I_{12}>R_1, I_{21}>R_2)$ is given by (30) (31)

$$\Pr(I_{12}>R_1, I_{21}>R_2) = \exp\left[-\frac{2\left(2^{R_1}-1\right)}{\gamma\sigma_{12}^2}\right]\exp\left[-\frac{2\left(2^{R_2}-1\right)}{\gamma\sigma_{12}^2}\right]$$

Using (8), we can calculate $\Pr(I_{1d}(\theta=1)<R_1)$ as

$$\Pr(I_{1d}(\theta=1)<R_1) = \Pr\left[|h_{1d}|^2+|h_{2d}|^2 < \frac{2\left(2^{R_1}-1\right)}{\gamma}\right] \quad (32)$$

$$= \begin{cases} 1-\left[1+\frac{2\left(2^{R_1}-1\right)}{\sigma_{1d}^2\gamma}\right] X \exp\left[-\frac{2\left(2^{R_1}-1\right)}{\sigma_{1d}^2\gamma}\right], & \sigma_{1d}^2=\sigma_{2d}^2 \\ 1-\frac{\sigma_{1d}^2}{\sigma_{1d}^2-\sigma_{2d}^2}\exp\left[-\frac{2\left(2^{R_1}-1\right)}{\sigma_{1d}^2\gamma}\right] \\ \quad -\frac{\sigma_{2d}^2}{\sigma_{2d}^2-\sigma_{1d}^2}\exp\left[-\frac{2\left(2^{R_1}-1\right)}{\sigma_{1d}^2\gamma}\right], & otherwise \end{cases} \quad (33)$$

Similarly, substituting (11) into term $\Pr(I_{1d}(\theta=2)<R_1)$, we easily obtain

$$\Pr\left[I_{1d}(\theta=2)<R_1\right] = \left[1-\exp\left(-\frac{2\left(2^{R_1}-1\right)}{\sigma_{1d}^2\gamma}\right)\right]$$

Now, we complete the closed-form outage probability analysis for the full-duplex-based O-DSTC scheme.

***Outage Analysis of Full-Duplex Based F-DSTC Scheme**:* Distributed Alamouti space-time coding to achieve the cooperative diversity, no matter whether U1 and U2 decode each other's information (34) successfully or not. To be specific, in the first time frame of block , both U1 and U2 transmit their own information s_1 and s_2 to the destination with power $E_S/2$. Considering the full-duplex regime, U1 and U2 can receive and decode each other's information, where the decoded outcomes at U1 andU2 are denoted by $\hat{s}_2$ and $\hat{s}_1$, respectively. Then, in the subsequent time frame, U1 and U2 transmit their decoded outcomes according to the Alamouti space-time coding, i.e., $-\hat{S}_2^*$ and $-\hat{S}_1^*$ are forwarded to the destination.

$$\begin{bmatrix} y_d^1 \\ y_d^2 \end{bmatrix} = \sqrt{\frac{E_s}{2}} \begin{bmatrix} h_{1d}s_1 + h_{2d}s_2 \\ -h_{1d}\hat{s}_2^* + h_{2d}\hat{s}_1^* \end{bmatrix} + \begin{bmatrix} n_d^1 \\ n_d^2 \end{bmatrix} \quad (39)$$

which can be further rewritten as

$$\begin{aligned} \begin{bmatrix} y_d^1 \\ (y_d^2)^* \end{bmatrix} &= \sqrt{\frac{E_s}{2}} \begin{bmatrix} h_{1d}s_1 + h_{2d}s_2 \\ -h_{1d}^*(s_2 + \hat{s}_2 - s_2) + h_{2d}^*(s_1 + \hat{s}_1 - s_1) \end{bmatrix} \\ &\quad + \begin{bmatrix} n_d^1 \\ (n_d^2)^* \end{bmatrix} \\ &= \sqrt{\frac{E_s}{2}} \begin{bmatrix} h_{1d} & h_{2d} \\ h_{2d}^* & -h_{1d}^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \\ &\quad + \begin{bmatrix} n_d^1 \\ h_{2d}^*(\hat{s}_1 - s_1) - h_{1d}^*(\hat{s}_2 - s_2) + (n_d^2)^* \end{bmatrix}. \end{aligned} \quad (40)$$

By applying the Alamouti decoding to (40),

$$\begin{bmatrix} h_{1d}^* & h_{2d} \\ h_{2d}^* & -h_{1d} \end{bmatrix} \begin{bmatrix} y_d^1 \\ (y_d^2)^* \end{bmatrix} = \sqrt{\frac{E_s}{2}} \begin{bmatrix} |h_{1d}|^2 + |h_{2d}|^2 & 0 \\ 0 & |h_{1d}|^2 + |h_{2d}|^2 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$
$$+ \begin{bmatrix} |h_{2d}|^2(\hat{s}_1 - s_1) - h_{1d}^* h_{2d}(\hat{s}_2 - s_2) + h_{1d}^* n_d^1 + h_{2d}\left(n_d^2\right)^* \\ -h_{1d}h_{2d}^*(\hat{s}_1 - s_1) + |h_{2d}|^2(\hat{s}_2 - s_2) + h_{2d}^* n_d^1 - h_{1d}\left(n_d^2\right)^* \end{bmatrix}.$$

The destination attempts to decode s_1 and s_2 as shown in (18) at the bottom of the page. One can observe from the second term in the right-hand side (RHS) of (18) that either U1 or U2 or both failing to decode will lead to $\hat{s}_1 \neq s_1$ and/or $\hat{s}_2 \neq s_2$, which results in interference at the destination in decoding both s_1 and s_2, and severely degrades the transmission performance. This also implies that the inter-user channels between U1 and U2 are the bottleneck of the traditional F-DSTC scheme.

Numerical Results: We present the outage probability comparison of the proposed full-duplex-based O-DSTC scheme with the traditional non-cooperative and the full-duplex-based F-DSTC schemes. In Fig. 4, we show the outage probability performance versus transmit SNR of the non-cooperative, the full-duplex-based F-DSTC and O-DSTC schemes with $R_1 = R_2 = 1$ bits/s/Hz. As shown in Fig. 4, the proposed O-DSTC scheme strictly outperforms both the non-cooperative and the F-DSTC schemes in terms of the outage probability across the whole SNR region. One can also see from Fig. 4 that, in the low SNR region, the outage probability of the F-DSTC scheme is even worse than that of the non-cooperative transmission. On the other hand, in high SNR region, as the transmit SNR increases, the outage probability of the F-DSTC scheme decreases at the same speed as the non-cooperative transmission. However, the outage probability decrease of the proposed O-DSTC scheme is at higher speed than both the F-DSTC and non-cooperative schemes. This implies that the proposed O-DSTC achieves higher diversity order (also known as diversity gain).

<u>Outage Analysis of Half-Duplex Based O-DSTC:</u> In this subsection, we study the outage probability performance of the proposed half-duplex-based O-DSTC scheme. An outage probability of the U1's transmission with the half-duplex-based O-DSTC scheme is calculated as

$$\begin{aligned} \mathrm{Pout}_{\mathrm{half-ODSTC}} = &\Pr(\omega = 1)\Pr\left[I_{1d}(\omega = 1) < \frac{3R_1}{2}\right] \\ &+ \Pr(\omega = 2)\Pr\left[I_{1d}(\omega = 2) < \frac{3R_1}{2}\right] \\ &+ \Pr(\omega = 3)\Pr\left[I_{1d}(\omega = 3) < \frac{3R_1}{2}\right] \\ &+ \Pr(\omega = 4)\Pr\left[I_{1d}(\omega = 4) < \frac{3R_1}{2}\right]. \end{aligned} \quad (41)$$

In the following, we examine closed-form solutions to these terms as given in the RHS of the above equation.

$\Pr(\omega = 1)$, $\Pr(\omega = 2)$, $\Pr(\omega = 3)$, and $\Pr(\omega = 4)$ as

$$\Pr(\omega = 1) = \exp\left[-\frac{4(2^{3R_1/2} - 1)}{3\gamma\sigma_{12}^2}\right]\exp\left[-\frac{4(2^{3R_2/2} - 1)}{3\gamma\sigma_{21}^2}\right]$$
$$\Pr(\omega = 2) = \left[1 - \exp\left(-\frac{4(2^{3R_1/2} - 1)}{3\gamma\sigma_{12}^2}\right)\right] \times \exp\left[-\frac{4(2^{3R_2/2} - 1)}{3\gamma\sigma_{21}^2}\right]$$
$$\Pr(\omega = 3) = \exp\left[-\frac{4(2^{3R_1/2} - 1)}{3\gamma\sigma_{12}^2}\right]$$

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$$\times\left[1-\exp\left(-\frac{4(2^{3R_2/2}-1)}{3\gamma\sigma_{21}^2}\right)\right]$$

$$\Pr(\omega=4)=\left[1-\exp\left(-\frac{4(2^{3R_1/2}-1)}{3\gamma\sigma_{12}^2}\right)\right]\times\left[1-\exp\left(-\frac{4(2^{3R_2/2}-1)}{3\gamma\sigma_{21}^2}\right)\right].$$

$$\Pr\left[I_{1d}(\omega=1)<\frac{3R_1}{2}\right]=\Pr\left[I_{1d}(\omega=3)<\frac{3R_1}{2}\right]=\begin{cases}1-\left[1+\frac{8(2^{3R_1/2}-1)}{3\sigma_{1d}^2\gamma}\right]\times\exp\left(-\frac{8(2^{3R_1/2}-1)}{3\sigma_{1d}^2\gamma}\right), & \sigma_{1d}^2=\sigma_{2d}^2\\ 1-\frac{\sigma_{1d}^2}{\sigma_{1d}^2-\sigma_{2d}^2}\exp\left(-\frac{8(2^{3R_1/2}-1)}{3\sigma_{1d}^2\gamma}\right)-\frac{\sigma_{2d}^2}{\sigma_{2d}^2-\sigma_{1d}^2}\exp\left(-\frac{8(2^{3R_1/2}-1)}{3\sigma_{2d}^2\gamma}\right), & \text{otherwise.}\end{cases}$$

$$\Pr\left[I_{1d}(\omega=2)<\frac{3R_1}{2}\right]=\Pr\left[I_{1d}(\omega=4)<\frac{3R_1}{2}\right]=1-\exp\left[-\frac{4(2^{3R_1/2}-1)}{3\gamma\sigma_{1d}^2}\right]$$

This completes a closed-form outage probability analysis for the proposed half-duplex-based O-DSTC scheme. In what follows, we present an outage analysis of the traditional F-DSTC scheme with the half-duplex relaying, referred to as the half-duplex based F-DSTC.

DIVERSITY-MULTIPLEXING TRADEOFF ANALYSIS

In this section, we conduct the DMT analysis for the proposed full-duplex and half-duplex-based O-DSTC schemes. The diversity gain of a wireless transmission system can be defined as

$$d=-\lim_{\gamma\to\infty}\frac{\log[Pout(\gamma)]}{\log(\gamma)}$$

Where $Pout(\gamma)$ represents an outage probability of the wireless transmission system and γ is the transmit SNR. Meanwhile, given multiplexing gains r_1 and r_2, the date rates of U1 and U2 (i.e., R_1 and R_2) are given by

$$R_1=r_1\log_2(1+\gamma)$$

and

$$R_2=r_2\log_2(1+\gamma)$$

FULL-DUPLEX-BASED O-DSTC SCHEME

Considering $\gamma\to\infty$ and following (35), we calculate an outage probability limit of the full-duplex-based O-DSTC scheme as

$$\lim_{\gamma\to\infty}Pout_{full-ODSTC}$$

$$=\lim_{\lambda\to\infty}\Pr(I_{12}>R_1,I_{21}>R_2)\lim_{\gamma\to\infty}\Pr[I_{1d}(\theta=1)<R_1]$$

$$+\left[1-\lim_{\gamma\to\infty}\Pr(I_{21}>R_1,I_{21}>R_2)\right]$$

$$x\lim_{\gamma\to\infty}\Pr[I_{1d}(\theta=2)<R_1]. \qquad (43)$$

The DMT of the full-duplex-based O-DSTC scheme is obtained as

$$d_{\text{full}-\text{ODSTC}}+r_1+\max(r_1,r_2)=2,\quad 0\le(r_1,r_2)\le 1$$

Which shows that a maximum diversity gain of two is obtained as $(r_1,r_2)\to 0$. One can observe from (64) that the diversity gain of U1 not only depends on its (44) own multiplexing gain r_1, but also relates to its partner's multiplexing gain r_2. This reason is that, either U1 or U2 increases the multiplexing gain (i.e., higher data rate), it decreases the probability of occurrence of case $\theta=1$ and increases the occurrence probability of the other case $\theta=2$. Moreover, under cases $\theta=1$ and 2, different diversity gains are achieved by U1 as implied from (8) and (11), which finally leads to the fact that the diversity gain of U1 depends on both r_1 and r_2. From (50), given a U1's multiplexing gain r_1, the diversity gain of the U1's transmissions can be maximized when r_2 <. r_1 Also, one can imagine that given r_2 , the diversity gain of theU2's transmissions is given by $2-r_2-\max(r_1,r_2)$, which is maximized with $r_1<r_2$. Therefore, by jointly (46) considering U1 and U2, an optimal DMT of the proposed full-duplex-based O-DSTC scheme is achieved when $r_1=r_2$.

HALF-DUPLEX-BASED O-DSTC SCHEME

We investigate the DMT performance of the (47) half-duplex- based O-DSTC scheme. Letting $\gamma\to\infty$ and following, we can obtain (48)

$$d_{half-ODSTC}+3r_1=2,\qquad 0\le r_1\le 2/3$$

This shows that a maximum diversity gain of two is obtained as the multiplexing gain approaches zero. One can also observe from (50) that the diversity gain achieved by U1 only depends on its own multiplexing

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gain and has nothing to do with its partner's multiplexing gain. This is because that the U2's multiplexing gain only affects U1 in decoding U2's information. However, no matter whether U1 succeeds in decoding U2's information or not, the diversity gain of U1 keeps unchanged

$$d_{half-FDSTC} + \tfrac{3}{2}\max(r_1, r_2) = 1$$

Where $0 \le r_1 \le 2/3$ and $0 \le r_2 \le 2/3$. As shown in (52), a maximum diversity gain of only one is achieved. Moreover, mutual dependence between U1 and U2 exists in terms of DMT performance, which arises from the fact that either U1 or U2 failing to decode would result in interference at the destination in decoding both users' information. As shown in (51).

3.SIMULATION RESULTS

We present the outage probability comparison of the proposed full-duplex-based O-DSTC scheme with the traditional non-cooperative and the full-duplex-based F-DSTC schemes. In Fig. 11, we show the outage probability performance versus transmit SNR of the non-cooperative, the full-duplex-based F-DSTC and O-DSTC schemes with $R_1 = R_2 = 1$ bit/s/Hz.

Fig. 11. Outage probability versus transmit SNR of the non-cooperative, the half-duplex-based O-DSTC schemes with $R_1=R_2=1$ bit/s/Hz and $\sigma_{1d}^2 = \sigma_{2d}^2 = 1$

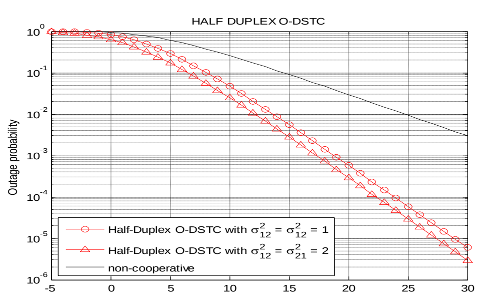
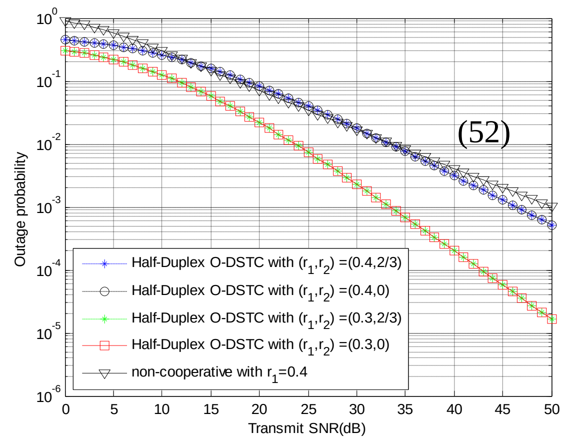


Fig.3 Outage probability of O-DSTC and non-cooperative network

Fig 4 Outage probability versus transmit SNR of the non-cooperative and the half-duplex-based O-DSTC schemes for different multiplexing gains of U1 and U2 (and) with $\sigma_{12}^2 = \sigma_{1d}^2 = \sigma_{21}^2 = \sigma_{2d}^2 = 1$



Fg.5. Outage probability of O-DSTC for different multiplexing gain

The outage probability of the O-DSTC scheme decreases at the same speed as the non-cooperative in high SNR region, which shows that no diversity gain is achieved by U1's transmissions given the U2's multiplexing gain $r_2 = 1$. As decreases from $r_2 = 1$ to 0.4, the speed of the outage probability decrease in high SNR region improves.

We present the outage probability comparison of the proposed full-duplex-based O-DSTC scheme with the traditional non-cooperative and the full-duplex-based F-DSTC schemes. In Fig. 4, we show the outage probability performance versus transmit SNR of the non-cooperative, the full-duplex-based F-DSTC and O-DSTC schemes with $R_1 = R_2 = 1$ bit/s/Hz.

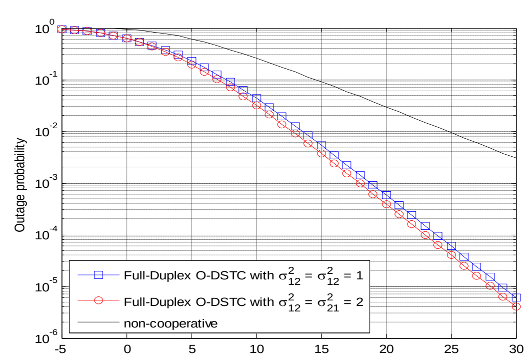


Fig.6

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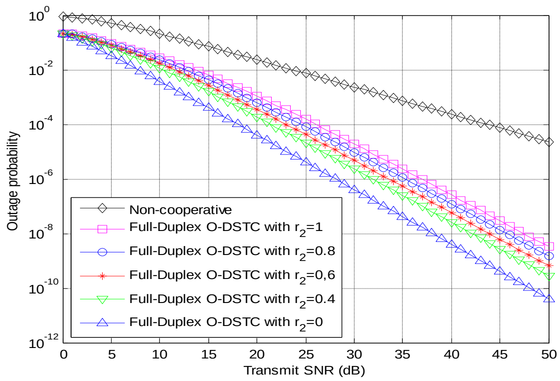

Fig.7

The outage probability of the O-DSTC scheme decreases at the same speed as the non-cooperative in high SNR region, which shows that no diversity gain is achieved by U1's transmissions given the U2's multiplexing gain $r_2 = 1$. As decreases from $r_2 = 1$ to 0.4, the speed of the outage probability decrease in high SNR region improves. Outage probability versus transmit SNR of the non-cooperative, the half-duplex-based F-DSTC and O-DSTC schemes with R_1=R_2=1 bit/s/Hz and $\sigma_{1d}^2 = \sigma_{2d}^2 = 1$

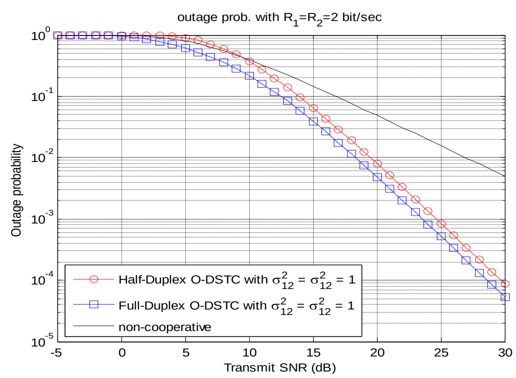

Fig.8.

Outage probability versus transmit SNR of the non-cooperative, the half-duplex-based F-DSTC and O-DSTC schemes with R_1=R_2=2 bit/s/Hz and $\sigma_{1d}^2 = \sigma_{2d}^2 = 1$

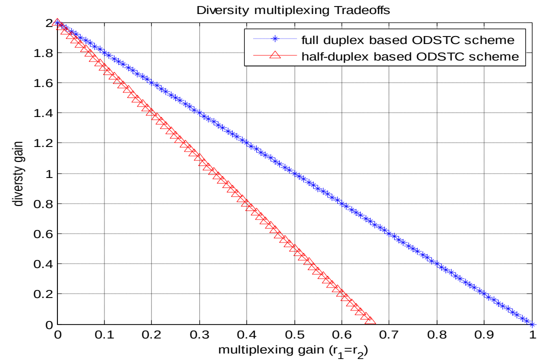

Fig.9.

Above figure shows a DMT comparison among the half-duplex-based O-DSTC, and the full-duplex-based O-DSTC schemes with $r_1 = r_2$. Notice that the DMT curve of the non-cooperative scheme is identical to that of the full-duplex- based F-DSTC scheme. It was shown that, no matter which duplex mode (i.e., full-duplex and half-duplex) is considered, the proposed O-DSTC scheme strictly outperforms the conventional S-DF and F-DSTC schemes.

CONCLUSION

In this paper, we explored O-DSTC for DF cooperation systems. We proposed the full-duplex and half-duplex-based O-DSTC schemes and evaluated their outage probability performance over Rayleigh fading channels. For the comparison purpose, we conducted an outage analysis for the non-cooperative, the conventional S-DF cooperation, and the full-duplex and half-duplex-based fixed DSTC (F-DSTC) schemes. Numerical results showed that the proposed O-DSTC scheme outperforms the conventional S-DF and F-DSTC schemes in terms of the outage probability considering both the full-duplex and half-duplex modes. In addition, we examined the DMT of the full-duplex and half-duplex-based O-DSTC and F-DSTC schemes as well as the conventional S-DF cooperation. It was shown that, no matter which duplex mode (i.e., full-duplex and half-duplex) is considered, the proposed O-DSTC scheme strictly outperforms the conventional S-DF and F-DSTC schemes. We also illustrated that, in the full-duplex-based O-DSTC scheme, mutual dependence exits between two cooperative users in terms of DMT. However, for the half-duplex- based O-DSTC scheme, the DMT performance of the two users are independent of each other, i.e., the diversity gain of a user only relates to its own multiplexing gain.

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