

Space-Time Block Coded Amplify-and-Forward Cooperative Relay Without Channel State Information At Relay Station

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Abstract—In this paper, we propose a space-time block coded (STBC) amplify-and-forward cooperative (STBC-Co-AF) relay which requires no knowledge of CSI at relay station (RS). In STBC-Co-AF relay, the source node transmits 2-block signal to both RS and the destination node in the first time slot and then, RS transmits amplified STBC-coded signal to the destination node in the second time slot. The destination node performs a series of frequency-domain equalization (FDE), diversity combining, and STBC decoding by viewing the concatenation of the channels between the source node-RS link and between the RS-destination node link as an equivalent channel. We evaluate, by computer simulation, the average bit error rate (BER) performance when using STBC-Co-AF relay and show that the STBC-Co-AF relay can achieve the BER performance superior to Co-AF relay.

Keywords—component; Space-time block coding, amplify-and-forward cooperative relay

I. INTRODUCTION

The bit error rate (BER) performance of broadband single-carrier (SC) transmissions significantly degrades due to the propagation path loss, shadowing loss and inter-symbol interference (ISI) caused by frequency-selective fading [1]. The minimum mean square error (MMSE) based frequency-domain equalization (FDE) is an effective method to overcome the frequency-selective fading [2-4]. An additional use of antenna diversity further improves transmission performance. SC transmission with space-time block coded (STBC) diversity can obtain full spatial diversity gain and frequency diversity gain, and accordingly, can achieve a good BER performance [5-7]. However, FDE and STBC diversity cannot cope with the negative impact of the propagation path loss and the shadowing loss.

Cooperative relay is a promising technique to solve this problem [8-10]. Cooperative relay can overcome the impact of the propagation path loss and the shadowing loss, and can expand the communication range while reducing the transmit power. There are two types of relay protocol: amplify-and-forward (AF) relay and decode-and-forward (DF) relay [9]. The relay station (RS) structure of cooperative AF relay is relatively simple; however, the BER performance is sometimes degraded by the noise which is transferred from RS. On the other hand, the cooperative DF relay can achieve the BER performance superior to cooperative AF relay; however, its RS structure is complicated compared to cooperative AF relay.

Ref. [8,10] proposed STBC-DF relay, which is a combination of DF relay and STBC diversity, and showed that STBC-DF relay

can overcome the propagation path loss, the shadowing loss, and the frequency-selective fading; it achieves a good BER performance while reducing the transmit power. However, STBC-DF relay requires the channel state information (CSI) at RS for demodulation, decoding, and re-modulation.

In this paper, we propose a new STBC amplify-and-forward cooperative (STBC-Co-AF) relay. RS applies modified STBC encoding which is the transposed version of conventional STBC encoding [5] without demodulation and decoding of the received signal. Therefore, no CSI is required at RS. We evaluate, by computer simulation, the average BER performance when using STBC-Co-AF relay and show that the STBC-Co-AF relay can achieve the BER performance superior to Co-AF relay.

The rest of this paper is organized as follows. Section 2 presents the system model and signal representation in the proposed STBC-Co-AF relay. The computer simulation results and discussed in Sect. 3, and finally, Sect. 4 offers some concluding remarks.

II. SC-STBC-CO-AF RELAY

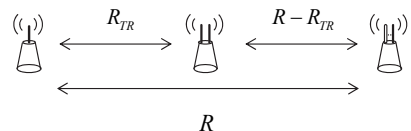


Fig. 1. SC-STBC-Co-AF relay model.

In STBC-Co-AF relay, the source node transmits 2-block signal to RS and the destination node in the first time slot. At RS, STBC encoding is directly applied to the received signal without decoding the received signal. Then, RS amplifies the STBC encoded transmit signal and transmits to the destination node in the second time slot. At the destination node, a series of FDE, diversity combining, and STBC decoding is performed by viewing the concatenation of the channels between the source node-RS link and between the RS-destination node link as an equivalent channel.

SC-STBC-Co-AF relay model is depicted in Fig.1. The distance between the source node and the destination node is denoted by R . The distance between the source node and RS is denoted by R_{TR} (the distance between RS and the destination node is given by $R - R_{TR}$). We assume that the source node and the destination node has single antenna, and RS has two antennas, respectively.

Fig.2 shows source node/RS/destination node structures at the data stage. In the first time slot, source node transmits uncoded 2-block signal to RS and the destination node. In the second time slot, RS transmits the STBC encoded signal to the destination node (the STBC operation will be described in the next subsection). At the destination node, the receive FDE, diversity combing and STBC decoding are jointly performed by viewing the concatenation of the channels between the source node-RS link and between the RS-destination node link as an equivalent channel.

In STBC-Co-AF relay, conjugate operation and block exchanging are only required at RS. Therefore, STBC-Co-AF relay can obtain spatial diversity gain without knowledge of CSI at RS.

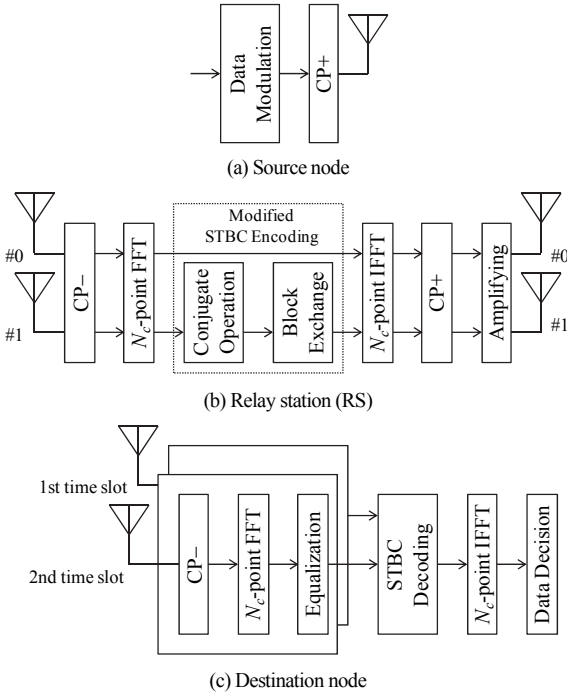


Fig. 2. Source node/Relay station/Destination node structures

A. Signal representation

Below, the symbol-spaced discrete time signal representation is used. At the source node, $2 \times N_c$ data modulated symbols are divided into the sequence of 2-block of N_c symbol each. After inserting cyclic prefix (CP) to the beginning of the transmit signal block, the source node broadcasts the transmit signal to RS and the destination node.

At the destination node, after CP removal, the received signal is transformed into the frequency-domain signal by N_c -point fast Fourier transform (FFT). The m th ($m=0,1$) frequency-domain received signal, $\{R_{B,m}^{1st}(k); k=0, \dots, N_c-1\}$ can be expressed as

$$\begin{aligned} R_{B,m}^{1st}(k) &= \sqrt{2P_t \cdot R^{-\alpha}} H_{TB}(k) S_m(k) + N_{B,m}^{1st}(k) \\ &= \sqrt{2\bar{P}_t} H_{TB}(k) S_m(k) + N_{B,m}^{1st}(k) \end{aligned} \quad (1)$$

where P_t denotes the actual transmit power of source node and α is the path loss exponent. $\bar{P}_t = P_t \cdot R^{-\alpha}$ is the normalized transmit power of the source node. $H_{TB}(k)$ is the k th frequency channel transfer function of the link between the source node and the destination node. $S_m(k)$ is the k th frequency component of the m th frequency-domain transmit signal. $N_{B,m}^{1st}(k)$ is the m th zero mean complex-valued additive white Gaussian noise (AWGN) having variance $2N_0/T_s$ with N_0 and T_s being the single-sided power spectrum density of AWGN and the symbol duration, respectively.

At RS, after CP removal, the received signal is transformed into the frequency-domain signal by N_c -point FFT. The m th frequency-domain received signal, $\{R_{Rn,m}(k); k=0, \dots, N_c-1, n=0,1\}$ at the n th RS antenna can be expressed as

$$\mathbf{R}_{R,m}(k) = \sqrt{2P_t \cdot R^{-\alpha}} \mathbf{H}_{TR}(k) \mathbf{S}(k) + \mathbf{N}_{R,m}(k), \quad (2)$$

where $\mathbf{R}_{R,m}(k) = [R_{R0,m}(k), R_{R1,m}(k)]^T$ is the m th frequency-domain received signal vector. $\mathbf{H}_{TR}(k) = [H_{TR0}(k), H_{TR1}(k)]^T$ is the 2×1 channel transfer function matrix between the source node and RS. $\mathbf{S}(k) = [S_0(k), S_1(k)]$ is the m th frequency-domain transmit signal vector at the source node. $\mathbf{N}_{R,m}(k) = [N_{R0,m}(k), N_{R1,m}(k)]^T$ is the m th zero mean complex-valued AWGN vector at RS having variance $2N_0/T_s$. (2) can be written as

$$\begin{aligned} \mathbf{R}_{R,m}(k) &= \sqrt{2(P_t R^{-\alpha})} (\mathbf{R}_{TR}/R)^{-\alpha} \mathbf{H}_{TR}(k) \mathbf{S}_m(k) + \mathbf{N}_{R,m}(k) \\ &= \sqrt{2\bar{P}_t} \bar{\mathbf{H}}_{TR}(k) \mathbf{S}_m(k) + \mathbf{N}_{R,m}(k) \end{aligned} \quad (3)$$

where $\bar{\mathbf{H}}_{TR}(k) = \mathbf{H}_{TR}(k) \sqrt{r_{TR}^{-\alpha}}$ is the 2×1 complex valued channel gain matrix, including the impact of the normalized propagation path loss, between the source node and RS with denoting $r_{TR} = R_{TR}/R$ as the normalized distance between the source node and RS.

Then, at RS, STBC encoding is directly applied to the received signal. The STBC encoded signal, $\{\mathbf{X}(k); k=0, \dots, N_c-1\}$ is given as

$$\mathbf{X}(k) = \begin{pmatrix} R_{R0,0}(k) & R_{R0,1}(k) \\ -R_{R1,1}^*(k) & R_{R1,0}^*(k) \end{pmatrix}, \quad (4)$$

It is seen from (4) that the STBC coded signal at 0th antennas is the same as the received signal and that at 1th antenna is performed the conjugate operation and exchanging 2-blocks to the received signal. From (2) and (3), (4) can be written as

$$\begin{aligned} \mathbf{X}(k) &= \sqrt{2\bar{P}_t} \begin{pmatrix} \bar{H}_{TR0}(k) & 0 \\ 0 & \bar{H}_{TR1}^*(k) \end{pmatrix} \begin{pmatrix} S_0(k) & S_1(k) \\ -S_1^*(k) & S_0^*(k) \end{pmatrix} \\ &\quad + \begin{pmatrix} N_{R0,0}(k) & N_{R0,1}(k) \\ -N_{R1,1}^*(k) & N_{R1,0}^*(k) \end{pmatrix} \end{aligned} \quad (5)$$

It is seen from (5) that the STBC coded signal at RS can be considered as the concatenation of the channels between the source node and RS and the modified STBC encoding matrix which is the transposed version of the conventional STBC encoding matrix [5]. The STBC coded frequency-domain signal is transformed back to the time-domain signal by N_c -Point inverse

FFT (IFFT). After CP insertion, RS amplifies and transmits the signal to the destination node.

At the destination node, after CP removal, the received signal is transformed into the frequency-domain signal by N_c -Point FFT. The frequency-domain received signal, $\{R_{B,m}^{2nd}(k); k=0, \dots, N_c-1, m=0,1\}$ in the m th block is expressed as

$$\mathbf{R}_B^{2nd}(k) = \overline{\mathbf{H}}_{RB}(k)\mathbf{G}\mathbf{X}(k) + \mathbf{N}_B^{2nd}(k), \quad (6)$$

where $\mathbf{R}_B^{2nd}(k) = [R_{B,0}^{2nd}(k), R_{B,1}^{2nd}(k)]$ is the frequency-domain received signal vector. $\overline{\mathbf{H}}_{RB}(k) = \mathbf{H}_{RB}(k)\sqrt{r_{RB}^{-\alpha}}$ is the 1×2 complex valued channel gain matrix, including the impact of the normalized propagation path loss, with denoting $\mathbf{H}_{RB}(k) = [H_{RB0}(k), H_{RB1}(k)]$ and $r_{RB} = (R - R_{TR})/R$ as the 1×2 channel transfer function matrix between RS and the destination node and the normalized distance between RS and the destination node, respectively. \mathbf{G} is the amplification factor matrix. It is set so as to keep average transmit power constant and given as

$$\mathbf{G} = \begin{pmatrix} G_0 & 0 \\ 0 & G_1 \end{pmatrix}, \quad (7)$$

where G_n is the n th antenna amplification factor expressed as

$$G_n = \sqrt{\frac{2\overline{P}_r}{2\overline{P}_r \left\{ \frac{1}{N_c} \sum_{k=0}^{N_c} |\overline{H}_{TR}(k)|^2 + \left(\frac{2N_0}{T_s} \right)^{-1} \right\}}}, \quad (8)$$

where $\overline{P}_r = P_r R^{-\alpha}$ is the normalized transmit power of RS with denoting P_r is the actual transmit power of RS. $\mathbf{N}_B^{2nd}(k) = [N_{B,0}^{2nd}(k), N_{B,1}^{2nd}(k)]$ is the m th zero mean complex-valued AWGN vector at the BS in the second time slot and having variance $2N_0/T_s$. From (1), (5) and (6), the frequency-domain received signal matrix $\mathbf{R}_B(k) = [\mathbf{R}_B^{1st}(k)^T, \mathbf{R}_B^{2nd}(k)^T]^T$ is the frequency-domain received signal matrix can be expressed as

$$\mathbf{R}_B(k) = \sqrt{2\overline{P}_r} \begin{pmatrix} H_{TB}(k) & 0 \\ \overline{H}_{e0}(k) & \overline{H}_{e1}(k) \end{pmatrix} \begin{pmatrix} S_0(k) & S_1(k) \\ -S_1^*(k) & S_0^*(k) \end{pmatrix} + \mathbf{N}_B(k), \quad (9)$$

where $\overline{H}_{e0}(k)$ and $\overline{H}_{e1}(k)$ are equivalent channel that is the concatenation of the channels between the source node-RS link and between RS-the destination node. They are given as

$$\begin{aligned} \overline{H}_{e0}(k) &= G_0 \overline{H}_{TR0}(k) \overline{H}_{RB0}(k) \\ \overline{H}_{e1}(k) &= G_1 \overline{H}_{TR1}^*(k) \overline{H}_{RB1}(k) \end{aligned} \quad (10)$$

$\mathbf{N}_B(k)$ is the noise matrix, including the noise which is received and amplified by RS and expressed as

$$\begin{aligned} \mathbf{N}_B(k) &= \begin{pmatrix} 0 & 0 \\ G_0 \overline{H}_{RB0}(k) & G_1 \overline{H}_{RB1}(k) \end{pmatrix} \begin{pmatrix} N_{R0,0}(k) & N_{R0,1}(k) \\ -N_{R1,1}^*(k) & N_{R1,0}^*(k) \end{pmatrix} \\ &+ \begin{pmatrix} N_{B,0}^{1st}(k) & N_{B,1}^{1st}(k) \\ N_{B,0}^{2nd}(k) & N_{B,1}^{2nd}(k) \end{pmatrix} \end{aligned} \quad (11)$$

It is seen from (9) that the received signal matrix can be expressed the concatenation of the equivalent channel matrix and the

modified STBC encoding matrix. Then, the received FDE is performed to the received signal matrix. The equalized signal, $\{\hat{D}_{i,j}(k); k=0, \dots, N_c-1, i=0,1, j=0,1\}$ is expressed as

$$\begin{pmatrix} \hat{D}_{00}(k) & \hat{D}_{01}(k) \\ \hat{D}_{10}(k) & \hat{D}_{11}(k) \end{pmatrix} = \begin{pmatrix} W_2(k) & W_0(k) \\ 0 & W_1(k) \end{pmatrix} \mathbf{R}_B(k). \quad (12)$$

where $W_0(k)$, $W_1(k)$ and $W_2(k)$ is received FDE weight. STBC decoding is performed. The m th STBC decoded frequency-domain signal, $\{\hat{S}_m(k); k=0, \dots, N_c-1\}$ can be expressed as

$$\begin{pmatrix} \hat{S}_0(k) \\ \hat{S}_1(k) \end{pmatrix} = \begin{pmatrix} \hat{D}_{00}(k) + \hat{D}_{11}^*(k) \\ \hat{D}_{01}(k) - \hat{D}_{10}^*(k) \end{pmatrix}. \quad (13)$$

The decoded frequency-domain signal is transformed back to the time-domain signal by the N_c -point IFFT, and finally, the data demodulation is carried out.

B. Received FDE Weight

The received FDE weight is derived so as to minimize the mean square error (MSE) between the STBC decoded signal at the destination node and transmit signal at the source node. MSE, e , is given as

$$e = E \left[\left| \frac{1}{\sqrt{2P_t}} \hat{S}_m(k) - S_m(k) \right|^2 \right], \quad (14)$$

where $E[\cdot]$ is ensemble average. By solving $\partial e / \partial W_n(k) = 0$ $\{k=0, \dots, N_c-1\}$, the received MMSE-FDE weight can be obtained as

$$W_0(k) = \frac{\overline{H}_{e0}^*(k)}{(|\overline{H}_{e0}(k)|^2 + |\overline{H}_{e1}(k)|^2 + K(k)|H_{TB}(k)|^2) + K(k) \left(\frac{\overline{P}_r}{\sigma^2} \right)^{-1}}, \quad (15a)$$

$$W_1(k) = \frac{\overline{H}_{e1}^*(k)}{(|\overline{H}_{e0}(k)|^2 + |\overline{H}_{e1}(k)|^2 + K(k)|H_{TB}(k)|^2) + K(k) \left(\frac{\overline{P}_r}{\sigma^2} \right)^{-1}}, \quad (15b)$$

$$W_2(k) = \frac{K(k)H_{TB}^*(k)}{(|\overline{H}_{e0}(k)|^2 + |\overline{H}_{e1}(k)|^2 + K(k)|H_{TB}(k)|^2) + K(k) \left(\frac{\overline{P}_r}{\sigma^2} \right)^{-1}}, \quad (15c)$$

where $K(k)$ $\{k=0, \dots, N_c-1\}$ is given as

$$K(k) = |G_0 \overline{H}_{RB0}(k)|^2 + |G_1 \overline{H}_{RB1}(k)|^2 + 1. \quad (16)$$

III. COMPUTER SIMULATION

We evaluate, by computer simulation, the average BER performance when using STBC-Co-AF relay. The simulation conditions are summarized in Table I.

We consider QPSK data modulation. FFT block size N_c and CP length N_g are set to $N_c=128$ symbols and $N_g=16$ samples, respectively. The channel is assumed to be a frequency-selective block Rayleigh fading channel having symbol spaced $L=16$ path uniform power delay profile. Path loss exponent is assumed to be $\alpha=3.5$. In this paper, we consider a quasi-static fading channel (i.e., Doppler frequency $f_D \rightarrow 0$). It is assumed that the perfect CSI is available at the destination node.

In this paper, we discussed the performance comparison among STBC-Co-AF relay, STBC-AF relay, which is the proposed scheme that does not use the received signal in the first time slot at the destination node, and conventional relay protocols, i.e. STBC-Co-DF relay, STBC-DF relay, Co-AF relay, AF relay, Co-DF relay, DF relay and direct transmission. The number of antennas in each relay protocol is shown in Table II. For fair comparison, we assume that the normalized total transmit power P_{total} is constant and equally allocated to the source node and RS, i.e. $\bar{P}_t = \bar{P}_r = P_{total}/2$.

TABLE I. COMPUTER SIMULATION CONDITIONS

Data Modulation	QPSK
FFT block size	$N_c=128$
CP length	$N_g=16$
Channel estimation	Ideal
Fading type	Block Rayleigh fading
Power delay profile	Uniform
Delay time	Symbol spaced
No. of paths	$L=16$
Path loss exponent	$\alpha=3.5$
No. of RS	1
Normalized source node-destination node distance	$R=1$
Normalized source node-RS distance	$R_{TR}=0.5, 0.1\sim 0.9$

TABLE II. THE NUMBER OF ANTENNAS

System	The number of antennas		
	Source node	RS	Destination node
STBC-(Co-AF, AF, Co-DF, DF)	1	2	1
Co-AF, AF, Co-DF, DF	1	1	1
Direct	1		1

A. Comparison with Other Systems

Fig.3 shows the average BER performances when using STBC-Co-AF relay as a function of total transmit power to noise power ratio P_{total}/σ^2 . Normalized source node-RS distance, r_{TR} is set to $r_{TR}=0.5$. For the comparison, the performances when using STBC-AF relay, STBC-Co-DF relay, STBC-DF relay, Co-AF relay, AF relay, Co-DF relay, DF relay and direct transmission are

also plotted in Fig.3. It is seen from Fig.3 that STBC-AF relay can achieve a better BER performance than AF relay. For example, when the allowable BER is $BER=10^{-4}$, STBC-AF relay can reduce the transmit P_{total}/σ^2 required about 6dB than AF relay. This is because spatial diversity gain can be obtained by STBC encoding at RS. Furthermore, STBC-Co-AF relay can achieve the better BER performance than STBC-AF relay. This is because higher spatial diversity gain can be obtained by combining the signals transmitted from source node in the first time slot and RS in the second time slot. It is also seen from Fig. 3 that STBC-Co-AF relay outperform Co-AF relay and Co-DF relay. For example, when the allowable BER is $BER=10^{-4}$, STBC-Co-AF relay can reduce the transmit P_{total}/σ^2 required by 2dB (1.2dB) compared to Co-AF (Co-DF). It is also seen from Fig.3 that STBC-Co-AF relay underperform STBC-Co-DF relay due to addition of the noise which is received and amplified at RS. However, STBC-Co-AF relay can obtain large spatial diversity gain and hence, STBC-Co-AF relay can suppress the increase of the transmit P_{total}/σ^2 required for $BER=10^{-4}$ by about 3.5 dB from STBC-Co-DF relay while keeping the RS structure simple.

B. The Position of RS

Fig.4 shows the average BER performance as a function of the normalized distance between the source node and RS, r_{TR} . The total transmit power to noise power ratio P_{total}/σ^2 is set to $P_{total}/\sigma^2 = 10$ (dB). For the comparison, STBC-Co-AF relay, Co-AF relay and AF relay are also plotted in Fig.4. It is seen from Fig.4 that STBC-Co-AF relay can achieve a better BER performance than Co-AF relay and AF relay in all positions. It is seen from Fig. 4 that the best BER performance is obtained at $r_{TR}=0.5$ when using STBC-Co-AF relay while the best BER performance is obtained at $r_{TR}=0.6$ when using another schemes. The reason for this is explain as follows. In AF relay, the noise received at RS is amplified and forwarded to the destination node. Therefore, the BER performance when using AF relay is affected by the both noises received at RS and the destination node and as consequence, the best BER performance is achieved when RS locates the position that the both noise effect becomes equal. In Co-AF and AF relay with equal power allocation, the impact of the noise received at the destination node is larger than that of the noise received at RS when $r_{TR}=0.5$, and therefore, the position where the best BER performance is obtained is slightly larger than $r_{TR}=0.5$. On the other hand, in STBC-Co-AF relay, the impact of the noise at the destination node can be reduced by the spatial diversity gain by STBC coding. Therefore, with equal power allocation, the impacts of the noise at RS and the destination node can be almost the same and the best BER performance can be obtained at $r_{TR}=0.5$.

IV. CONCLUSION

In this paper, we proposed STBC-Co-AF relay which requires no CSI at RS. RS of the proposed STBC-Co-AF relay directly applies modified STBC encoding to the received signal waveform

without demodulation and decoding of the received signal. Therefore, no CSI is required at RS, resulting in a simplified RS structure. We compared STBC-Co-AF relay with STBC-AF, AF, Co-AF, DF, and Co-DF relay about the BER performance. We showed, by the computer simulation that STBC-Co-AF relay can provide better BER performance than AF, Co-AF, DF and Co-DF relay. In this paper, we assumed that perfect CSI is available at destination node. The impact of CSI error is left as our future work.

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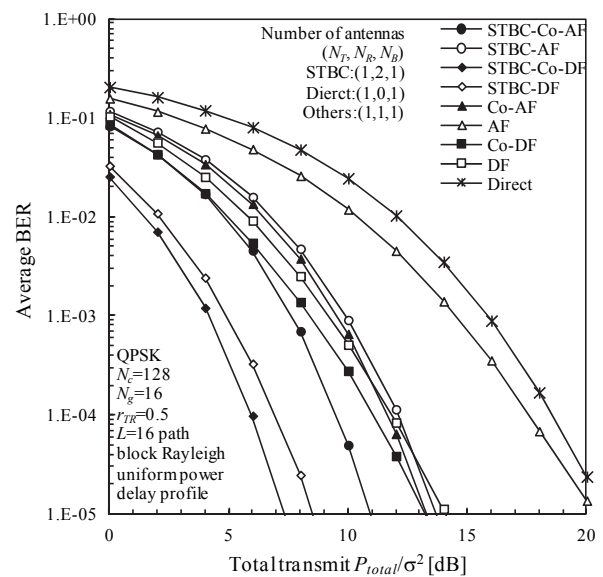


Fig. 3. The Average BER performance

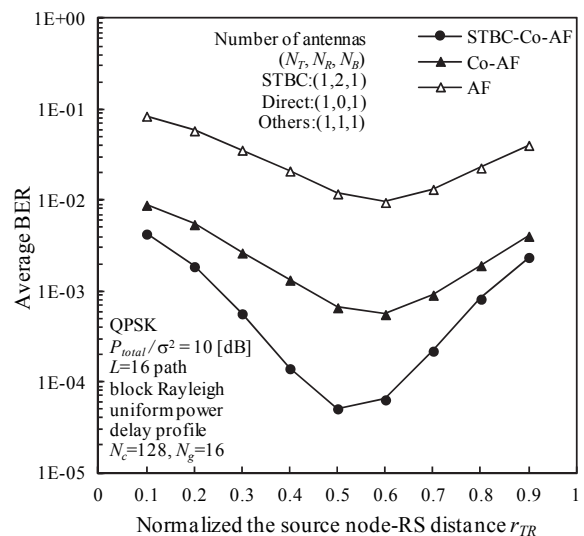


Fig. 4. Source node-RS distance