Frontiers of Information Technology & Electronic Engineering
www.zju.edu.cn/jzus; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Efficient detection methods for amplify-and-forward relay-aided device-to-device systems with full-rate space-time block code*

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Received Jan. 8, 2017; Revision accepted Feb. 28, 2017; Crosschecked May 8, 2017

Abstract: Relay-aided device-to-device (D2D) communication is a promising technology for the next-generation cellular network. We study the transmission schemes for an amplify-and-forward relay-aided D2D system which has multiple antennas. To circumvent the prohibitive complexity problem of traditional maximum likelihood (ML) detection for full-rate space-time block code (FSTBC) transmission, two low-complexity detection methods are proposed, i.e., the detection methods with the ML-combining (MLC) algorithm and the joint conditional ML (JCML) detector. Particularly, the method with the JCML detector reduces detection delay at the cost of more storage and performs well with parallel implementation. Simulation results indicate that the proposed detection methods achieve a symbol error probability similar to that of the traditional ML detector for FSTBC transmission but with less complexity, and the performance of FSTBC transmission is significantly better than that of spatial multiplexing transmission. Diversity analysis for the proposed detection methods is also demonstrated by simulations.

Key words: Device-to-device; Relay; Detection; Full-rate space-time block code
http://dx.doi.org/10.1631/FITEE.1700018 **CLC number:** TN92

1 Introduction

To meet the needs of high data transmission rates for drastically increased wireless devices, device-to-device (D2D) communication is considered as the competent technology in fifth-generation (5G) cellular networks (Tehrani *et al.*, 2014). D2D communication enables direct transmission between two users without the help from the base station, thereby releasing the network load to local areas and improving the network latency performance. The merits of D2D communication also include helping in sharing of resources between devices, reducing the cost of communication among devices, and setting up emergency communication in a short time. Thus, it has a wide range of applications in future communications.

Relay-aided D2D communication is a complement to D2D communication. When the quality of direct link between devices is not good enough, relays can be adopted to improve the transmission reliability and correspondingly extend the network coverage. To this end, numerous studies on relay-aided D2D communication have been published, predominantly addressing relay selection (Kim and Dong, 2014; Gao *et al.*, 2016; Pan and Wang, 2016), resource allocation (Zhang G *et al.*, 2015; Ali *et al.*, 2016; Hoang *et al.*, 2017), and transmission security (Jayasinghe *et al.*, 2015). There is limited

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work focusing on the design of transmission schemes for relay-aided D2D systems. Chen (2016) considered only the signal transmission and detection for single-input single-output relay-aided D2D systems. However, numerous wireless devices have been configured with two or more antennas recently. Therefore, transmission schemes for the multiple-input multiple-output (MIMO) relay-aided D2D systems are required.

In this study, we investigate various transmission schemes for a $2 \times M \times N$ amplify-and-forward (AF) relay-aided D2D system, where 2, M, and N are the numbers of antennas at transmitting, relaying, and receiving devices, respectively. To maintain the transmission efficiency and achieve better communication quality, a full-rate space-time block code (FSTBC) transmission scheme (Sezginer and Sari, 2007) is leveraged to the relay-aided D2D system. However, the traditional maximum likelihood (ML) detection for the FSTBC transmission requires an exhaustive search over four symbols, thus involving high complexity for high-order constellations. To solve this problem, two efficient detection methods are proposed, i.e., the detection methods with the ML-combining (MLC) algorithm (Zhang K *et al.*, 2015) and the proposed joint conditional ML (JCML) detector. In the detection method with the MLC algorithm, the $2 \times M \times N$ relay-aided D2D system can be first transformed into an equivalent 2×2 D2D system, and then a low-complexity detector proposed by Sezginer and Sari (2007) can be adopted for symbol recovery. The detection method using the proposed JCML detector can preprocess signals from the source and relay separately at the destination. Therefore, it is friendly with both parallel implementation and reduction of detection delay. The proposed detection methods have the same complexity order as that of joint ML detection for spatial multiplexing (SM) transmission, which is just a square root of that for traditional ML detection used in the transmission with FSTBC. We prove by simulations that the FSTBC transmission with the proposed methods achieves a symbol error probability (SEP) almost identical to that with the traditional ML detector and twice the diversity gain relative to the SM transmission. Additionally, the diversity orders of the proposed detection methods are studied through analysis and simulation.

2 System model

Notations: A lower boldface letter represents a vector and a capital boldface letter represents a matrix. Symbols $(\cdot)^*$, $(\cdot)^{\mathrm{T}}$, and $(\cdot)^{\mathrm{H}}$ denote the complex conjugate, the transpose, and the Hermitian transpose, respectively. $|\mathcal{X}|$ is used to represent the cardinality of set $\mathcal{X}$ and $\|\boldsymbol{x}\|$ the norm of vector $\boldsymbol{x}$. $\|\boldsymbol{X}\|_{\mathrm{F}}$, $\mathrm{tr}\,[\boldsymbol{X}]$, and $\mathrm{chol}\,[\boldsymbol{X}]$ are the Frobenius norm, the trace, and the Cholesky factor of matrix $\boldsymbol{X}$, respectively. $\mathcal{CN}(0, \sigma^2)$ represents the complex Gaussian distribution with zero mean and variance σ^2. $\boldsymbol{I}_N$ is the $N \times N$ identity matrix.

Consider a three-node AF relay-aided D2D system (Fig. 1), which contains a source (S), a relay node (R), and a destination (D). In this system, S and D are users in the cellular network configured with 2 and N_{d} antennas respectively, and R can be a user or an infrastructure that helps transmission which has N_{r} antennas. The channel quality of the S-D link is bad but cannot be neglected; therefore, a relay is adopted to improve the communication quality between two users. Assume that R and D can respectively obtain the channel matrix for the S-R link and the channel matrices for all links through training with the existing methods for channel estimation (Kong and Hua, 2011; Rong *et al.*, 2012), and all channels are assumed to experience flat-fading and remain approximately constant during channel estimation and transmission. At S, the transmission codeword matrix $\boldsymbol{X}$ can be generated in two forms, given by

$$\boldsymbol{X}_1 = \begin{bmatrix} s_1 & s_3 \\ s_2 & s_4 \end{bmatrix},$$

$$\boldsymbol{X}_2 = \begin{bmatrix} as_1 + bs_3 & -cs_2^* - ds_4^* \\ as_2 + bs_4 & cs_1^* + ds_3^* \end{bmatrix}, \tag{1}$$

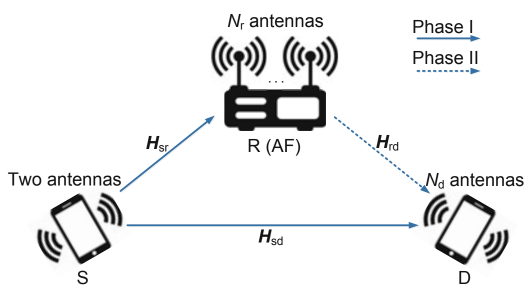

Fig. 1 A three-node amplify-and-forward relay-aided device-to-device system (S: source; R: relay node; D: destination)

where

$$\begin{cases} a = c = 1/\sqrt{2}, \\ b = \left[(1-\sqrt{7}) + \mathrm{i}\left(1+\sqrt{7}\right)\right]/(4\sqrt{2}), \\ d = -\mathrm{i}b, \end{cases}$$

and s_i ($i \in \{1,2,3,4\}$) denote the information symbols taken from constellation $\mathcal{X}$. Actually, $\boldsymbol{X}_1$ represents the SM transmission mode and $\boldsymbol{X}_2$ is a full-diversity FSTBC transmission proposed by Sezginer and Sari (2007). Although there are other FSTBC transmission schemes that can be applied in this system, such as the 2 × 2 golden code (Belfiore *et al.*, 2005) and the FSTBC transmission (Vakilian and Mehrpouyan, 2016), the selected one with the form in Eq. (1) achieves the best trade-off between detection complexity and error performance. Both $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ reach the full transmission rate, i.e., two symbols per slot.

The transmission includes two phases. In Phase I, S broadcasts signals to R and D in two time slots. Then the signal received at D is reserved to be jointly detected with the signal from R. In Phase II, R forwards the scaled signal received from S to D in two time slots, while S remains silent. Note that due to the two-phase transmission, the average transmission rate for the whole system is one symbol per slot. The received signals at R and D in Phase I are respectively formulated as follows:

$$\boldsymbol{Y}_{\mathrm{r}} = \boldsymbol{H}_{\mathrm{sr}}\boldsymbol{X} + \boldsymbol{N}_{\mathrm{r}}, \tag{2}$$

$$\boldsymbol{Y}_{\mathrm{d},1} = \boldsymbol{H}_{\mathrm{sd}}\boldsymbol{X} + \boldsymbol{N}_{\mathrm{d},1}, \tag{3}$$

where $\boldsymbol{H}_{\mathrm{sr}} \in \mathbb{C}^{N_{\mathrm{r}}\times 2}$ and $\boldsymbol{H}_{\mathrm{sd}} \in \mathbb{C}^{N_{\mathrm{d}}\times 2}$ denote the channel matrices for the S-R and S-D links respectively, and $\boldsymbol{N}_{\mathrm{r}} \in \mathbb{C}^{N_{\mathrm{r}}\times 2}$ and $\boldsymbol{N}_{\mathrm{d},1} \in \mathbb{C}^{N_{\mathrm{d}}\times 2}$ are the additive noise matrices at R and D, respectively, whose elements are independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian (CSCG) random variables following distributions $\mathcal{CN}(0,\sigma_{\mathrm{r}}^2)$ and $\mathcal{CN}(0,\sigma_{\mathrm{d}}^2)$, respectively. In Phase II, the received signal at D is formulated by

$$\boldsymbol{Y}_{\mathrm{d},2} = \boldsymbol{H}_{\mathrm{rd}}\alpha\boldsymbol{Y}_{\mathrm{r}} + \boldsymbol{N}_{\mathrm{d},2}, \tag{4}$$

where $\boldsymbol{H}_{\mathrm{rd}} \in \mathbb{C}^{N_{\mathrm{d}}\times N_{\mathrm{r}}}$ denotes the channel matrix for the R-D link, $\boldsymbol{N}_{\mathrm{d},2} \in \mathbb{C}^{N_{\mathrm{d}}\times 2}$ denotes the additive noise matrix at D for Phase II with i.i.d. CSCG elements following the distribution $\mathcal{CN}(0,\sigma_{\mathrm{d}}^2)$, and α is the adaptive scaling factor to normalize the transmit power per antenna at R, whose value is yielded by the following equation:

$$\alpha = \sqrt{\frac{1}{\|\boldsymbol{H}_{\mathrm{sr}}\|_{\mathrm{F}}^2/N_{\mathrm{r}} + \sigma_{\mathrm{r}}^2}}. \tag{5}$$

The received signal at D in Phase II can be further rewritten as follows by substituting Eq. (2) into Eq. (4):

$$\boldsymbol{Y}_{\mathrm{d},2} = \boldsymbol{H}_{\mathrm{srd}}\boldsymbol{X} + \boldsymbol{N}_{\mathrm{srd}}, \tag{6}$$

where

$$\begin{cases} \boldsymbol{H}_{\mathrm{srd}} = \alpha\boldsymbol{H}_{\mathrm{rd}}\boldsymbol{H}_{\mathrm{sr}}, \\ \boldsymbol{N}_{\mathrm{srd}} = \alpha\boldsymbol{H}_{\mathrm{rd}}\boldsymbol{N}_{\mathrm{r}} + \boldsymbol{N}_{\mathrm{d},2}, \end{cases} \tag{7}$$

represent the equivalent channel and additive noise matrices for the S-R-D link, respectively.

After the two-phase transmission, $\boldsymbol{Y}_{\mathrm{d},1}$ and $\boldsymbol{Y}_{\mathrm{d},2}$ are jointly used to recover the symbols transmitted from S. In the SM transmission, the MLC algorithm can be adopted with the ML detection for point-to-point MIMO systems to achieve the best error performance, and the complexity order of the corresponding detection is $\mathcal{O}(|\mathcal{X}|^2)$. While for the transmission with FSTBC in Eq. (1), new detection methods are needed, which are detailed in the next section.

3 Detection methods for relay-aided device-to-device systems with full-rate space-time block code transmission

In this section, we propose two detection methods for the AF relay-aided D2D system with FSTBC transmission described in Section 2. Both of these methods have lower complexity compared to the traditional ML detector for the transmission with FSTBC.

For AF relay-aided D2D systems with the adopted FSTBC transmission given in Eq. (1), traditional ML detection requires a search over symbols s_1, s_2, s_3, and s_4 based on the following criterion:

$$\begin{aligned}\min_{s_1,s_2,s_3,s_4\in\mathcal{X}} (&\|\boldsymbol{Y}_{\mathrm{d},1} - \boldsymbol{H}_{\mathrm{sd}}\boldsymbol{X}_2\|^2/\sigma_{\mathrm{d}}^2 \\ &+ \|\boldsymbol{W}(\boldsymbol{Y}_{\mathrm{d},2} - \boldsymbol{H}_{\mathrm{srd}}\boldsymbol{X}_2)\|^2),\end{aligned} \tag{8}$$

where

$$\boldsymbol{W} = \mathrm{chol}\left[\left(\alpha^2\boldsymbol{H}_{\mathrm{rd}}\boldsymbol{H}_{\mathrm{rd}}^{\mathrm{H}}\sigma_{\mathrm{r}}^2 + \boldsymbol{I}_{N_{\mathrm{d}}}\sigma_{\mathrm{d}}^2\right)^{-1}\right] \tag{9}$$

denotes the whitening matrix. This exhaustive search needs the computation of $|\mathcal{X}|^4$ metrics and $|\mathcal{X}|^4-1$ comparisons, resulting in a prohibitive complexity for high-order constellations, such as 16-quadrature amplitude modulation (16QAM).

3.1 Detection method with maximum likelihood combining algorithm

One way to reduce the detection complexity is first using the MLC algorithm to convert the $2\times N_{\rm r}\times N_{\rm d}$ relay-aided D2D system into an equivalent 2×2 D2D system, whose equivalent channel matrix and combined signal matrix are given as follows:

$$\begin{cases} \boldsymbol{H}_{\rm E}={\rm chol}\left[\boldsymbol{H}_{\rm sd}^{\rm H}\boldsymbol{H}_{\rm sd}/\sigma_{\rm d}^2+\boldsymbol{H}_{\rm srd}^{\rm H}\boldsymbol{W}^{\rm H}\boldsymbol{W}\boldsymbol{H}_{\rm srd}\right], \\ \boldsymbol{Y}_{\rm C}=\left(\boldsymbol{H}_{\rm E}^{\rm H}\right)^{-1}\left(\boldsymbol{H}_{\rm sd}^{\rm H}\boldsymbol{Y}_{\rm d,1}/\sigma_{\rm d}^2+\boldsymbol{H}_{\rm srd}^{\rm H}\boldsymbol{W}^{\rm H}\boldsymbol{W}\boldsymbol{Y}_{\rm d,2}\right). \end{cases} \tag{10}$$

Then the detector designed by Sezginer and Sari (2007) is used to recover s_1, s_2, s_3, and s_4. In this detector, the ML estimates of s_1 and s_2 can be obtained independently with a given pair (s_3, s_4). The related transformations are formulated by

$$\begin{cases} r_1=\sqrt{2}\left[\left(\boldsymbol{h}_1^{\rm E}\right)^{\rm H} \ \ \left(\boldsymbol{h}_2^{\rm E}\right)^{\rm T}\right]\left[\boldsymbol{z}_1^{\rm T} \ \ \boldsymbol{z}_2^{\rm H}\right]^{\rm T} \\ \quad =\|\boldsymbol{H}_{\rm E}\|_{\rm F}^2\, s_1+n_1, \\ r_2=\sqrt{2}\left[\left(\boldsymbol{h}_2^{\rm E}\right)^{\rm H} \ \ -\left(\boldsymbol{h}_1^{\rm E}\right)^{\rm T}\right]\left[\boldsymbol{z}_1^{\rm T} \ \ \boldsymbol{z}_2^{\rm H}\right]^{\rm T} \\ \quad =\|\boldsymbol{H}_{\rm E}\|_{\rm F}^2\, s_2+n_2, \end{cases} \tag{11}$$

where

$$\begin{cases} \boldsymbol{z}_1=\boldsymbol{y}_1^{\rm C}-b\boldsymbol{H}_{\rm E}[s_3 \ \ s_4]^{\rm T}, \\ \boldsymbol{z}_2=\boldsymbol{y}_2^{\rm C}-d\left[\boldsymbol{h}_2^{\rm E} \ \ -\boldsymbol{h}_1^{\rm E}\right][s_3 \ \ s_4]^{\rm H}, \end{cases} \tag{12}$$

$\boldsymbol{h}_i^{\rm E}$ and $\boldsymbol{y}_i^{\rm C}$ $(i=1,2)$ denote the column vectors of $\boldsymbol{H}_{\rm E}$ and $\boldsymbol{Y}_{\rm C}$ respectively, and n_1 and n_2 are the equivalent additive noises following distribution $\mathcal{CN}(0, 2\,\|\boldsymbol{H}_{\rm E}\|_{\rm F}^2)$, where the factor 2 is determined by factors a and c in the FSTBC transmission given by Eq. (1). The ML estimates of s_1 and s_2 conditioned on (s_3, s_4) are calculated according to the following expressions:

$$\begin{cases} \hat{s}_1|(s_3,s_4)=\underset{s_1\in\mathcal{X}}{\arg\min}\left|r_1-\|\boldsymbol{H}_{\rm E}\|_{\rm F}^2\, s_1\right|^2, \\ \hat{s}_2|(s_3,s_4)=\underset{s_2\in\mathcal{X}}{\arg\min}\left|r_2-\|\boldsymbol{H}_{\rm E}\|_{\rm F}^2\, s_2\right|^2, \end{cases} \tag{13}$$

which can be implemented by using a threshold comparator or a lookup table. Finally, s_3 and s_4 are detected based on $\hat{s}_1$ and $\hat{s}_2$ by

$$(\hat{s}_3,\hat{s}_4)=\underset{s_3,s_4\in\mathcal{X}}{\arg\min}(\boldsymbol{k}_1^{\rm H}\boldsymbol{k}_1+\boldsymbol{k}_2^{\rm H}\boldsymbol{k}_2), \tag{14}$$

where

$$\begin{cases} \boldsymbol{k}_1=\boldsymbol{z}_1-\dfrac{\boldsymbol{H}_{\rm E}[\hat{s}_1|(s_3,s_4) \ \ \hat{s}_2|(s_3,s_4)]^{\rm T}}{\sqrt{2}}, \\ \boldsymbol{k}_2=\boldsymbol{z}_2-\dfrac{\left[\boldsymbol{h}_2^{\rm E} \ \ -\boldsymbol{h}_1^{\rm E}\right][\hat{s}_1|(s_3,s_4) \ \ \hat{s}_2|(s_3,s_4)]^{\rm H}}{\sqrt{2}}. \end{cases} \tag{15}$$

Although this method has low complexity due to the equivalent 2×2 channel and combined signal matrices, it cannot be started until D receives $\boldsymbol{Y}_{\rm d,2}$, which causes processing delay. If $\boldsymbol{Y}_{\rm d,1}$ can be preprocessed before $\boldsymbol{Y}_{\rm d,2}$ is received, the processing delay can be reduced. Therefore, the detection method with the JCML detector is proposed in the following part.

3.2 Detection method with joint conditional maximum likelihood detector

In this method, signals received at D in the two phases are first preprocessed separately. For the S-D link, the transformed signals for the estimation of s_1 and s_2 based on a given pair (s_3, s_4) are respectively transformed as

$$\begin{cases} r_1^{\rm sd}=\sqrt{2}\left[\left(\boldsymbol{h}_1^{\rm sd}\right)^{\rm H} \ \ \left(\boldsymbol{h}_2^{\rm sd}\right)^{\rm T}\right]\left[(\boldsymbol{z}_1^{\rm sd})^{\rm T} \ \ (\boldsymbol{z}_2^{\rm sd})^{\rm H}\right]^{\rm T} \\ \quad =\|\boldsymbol{H}_{\rm sd}\|_{\rm F}^2\, s_1+n_1^{\rm d,1}, \\ r_2^{\rm sd}=\sqrt{2}\left[\left(\boldsymbol{h}_2^{\rm sd}\right)^{\rm H} \ \ -\left(\boldsymbol{h}_1^{\rm sd}\right)^{\rm T}\right]\left[(\boldsymbol{z}_1^{\rm sd})^{\rm T} \ \ (\boldsymbol{z}_2^{\rm sd})^{\rm H}\right]^{\rm T} \\ \quad =\|\boldsymbol{H}_{\rm sd}\|_{\rm F}^2\, s_2+n_2^{\rm d,1}, \end{cases} \tag{16}$$

where

$$\begin{cases} \boldsymbol{z}_1^{\rm sd}=\boldsymbol{y}_1^{\rm d,1}-b\boldsymbol{H}_{\rm sd}[s_3 \ \ s_4]^{\rm T}, \\ \boldsymbol{z}_2^{\rm sd}=\boldsymbol{y}_2^{\rm d,1}-d\left[\boldsymbol{h}_2^{\rm sd} \ \ -\boldsymbol{h}_1^{\rm sd}\right][s_3 \ \ s_4]^{\rm H}, \end{cases} \tag{17}$$

$\boldsymbol{h}_i^{\rm sd}$ and $\boldsymbol{y}_i^{\rm d,1}$ $(i=1,2)$ are the column vectors of $\boldsymbol{H}_{\rm sd}$ and $\boldsymbol{Y}_{\rm d,1}$ respectively, and $n_1^{\rm d,1}$ and $n_2^{\rm d,1}$ are the equivalent additive noises for Phase I which follow distribution $\mathcal{CN}(0, 2\,\|\boldsymbol{H}_{\rm sd}\|_{\rm F}^2\,\sigma_{\rm d}^2)$. While for the S-R-D link, $\boldsymbol{Y}_{\rm d,2}$ should be whitened beforehand due to the noise accumulation at R, and the whitened signal is yielded by the following equation:

$$\overline{\boldsymbol{Y}}_{\rm d,2}=\boldsymbol{W}\boldsymbol{Y}_{\rm d,2}=\overline{\boldsymbol{H}}_{\rm srd}\boldsymbol{X}+\overline{\boldsymbol{N}}_{\rm srd}, \tag{18}$$

where $\overline{\boldsymbol{H}}_{\rm srd} = \boldsymbol{W}\boldsymbol{H}_{\rm srd}$, and $\overline{\boldsymbol{N}}_{\rm srd} = \boldsymbol{W}\boldsymbol{N}_{\rm srd}$ is the zero-mean complex Gaussian noise matrix with covariance $\boldsymbol{I}_{N_{\rm d}}$. Then the transformed signals for the estimates of s_1 and s_2 based on (s_3, s_4) are respectively given as follows:

$$\begin{cases} r_1^{\rm srd} = \sqrt{2}\left[\left(\overline{\boldsymbol{h}}_1^{\rm srd}\right)^{\rm H} \ \left(\overline{\boldsymbol{h}}_2^{\rm srd}\right)^{\rm T}\right]\left[\left(\boldsymbol{z}_1^{\rm srd}\right)^{\rm T} \ \left(\boldsymbol{z}_2^{\rm srd}\right)^{\rm H}\right]^{\rm T} \\ \quad = \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2 s_1 + n_1^{\rm d,2}, \\ r_2^{\rm srd} = \sqrt{2}\left[\left(\overline{\boldsymbol{h}}_2^{\rm srd}\right)^{\rm H} \ -\left(\overline{\boldsymbol{h}}_1^{\rm srd}\right)^{\rm T}\right]\left[\left(\boldsymbol{z}_1^{\rm srd}\right)^{\rm T} \ \left(\boldsymbol{z}_2^{\rm srd}\right)^{\rm H}\right]^{\rm T} \\ \quad = \left\|\bar{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2 s_2 + n_2^{\rm d,2}, \end{cases} \tag{19}$$

where

$$\begin{cases} \boldsymbol{z}_1^{\rm srd} = \overline{\boldsymbol{y}}_1^{\rm d,2} - b\overline{\boldsymbol{H}}_{\rm srd}[s_3 \ \ s_4]^{\rm T}, \\ \boldsymbol{z}_2^{\rm srd} = \overline{\boldsymbol{y}}_2^{\rm d,2} - d\left[\overline{\boldsymbol{h}}_2^{\rm srd} \ \ -\overline{\boldsymbol{h}}_1^{\rm srd}\right][s_3 \ \ s_4]^{\rm H}, \end{cases} \tag{20}$$

$\overline{\boldsymbol{h}}_i^{\rm srd}$ and $\overline{\boldsymbol{y}}_i^{\rm d,2}$ $(i = 1, 2)$ denote the column vectors of $\overline{\boldsymbol{H}}_{\rm srd}$ and $\overline{\boldsymbol{Y}}_{\rm d,2}$ respectively, and $n_1^{\rm d,2}$ and $n_2^{\rm d,2}$ are the equivalent additive noises for Phase II following distribution $\mathcal{CN}(0, 2\left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2)$. Based on the foregoing discussion, the sufficient statistics for s_1 and s_2 are

$$\begin{cases} r_1^{\rm C} = r_1^{\rm sd}/\sigma_{\rm d}^2 + r_1^{\rm srd} \\ \quad = \left(\left\|\boldsymbol{H}_{\rm sd}\right\|_{\rm F}^2/\sigma_{\rm d}^2 + \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2\right) s_1 + n_1^{\rm C}, \\ r_2^{\rm C} = r_2^{\rm sd}/\sigma_{\rm d}^2 + r_2^{\rm srd} \\ \quad = \left(\left\|\boldsymbol{H}_{\rm sd}\right\|_{\rm F}^2/\sigma_{\rm d}^2 + \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2\right) s_2 + n_2^{\rm C}, \end{cases} \tag{21}$$

where $n_1^{\rm C} = n_1^{\rm d,1}/\sigma_{\rm d}^2 + n_1^{\rm d,2}$, $n_2^{\rm C} = n_2^{\rm d,1}/\sigma_{\rm d}^2 + n_2^{\rm d,2}$, with variance equal to $2(\left\|\boldsymbol{H}_{\rm sd}\right\|_{\rm F}^2/\sigma_{\rm d}^2 + \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2)$. Then based on the given pair (s_3, s_4), s_1 and s_2 are respectively estimated as

$$\begin{cases} \hat{s}_1^{\rm C}|(s_3, s_4) \\ \quad = \underset{s_1\in\mathcal{X}}{\arg\min}\left|r_1^{\rm C} - \left(\left\|\boldsymbol{H}_{\rm sd}\right\|_{\rm F}^2/\sigma_{\rm d}^2 + \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2\right)s_1\right|^2, \\ \hat{s}_2^{\rm C}|(s_3, s_4) \\ \quad = \underset{s_2\in\mathcal{X}}{\arg\min}\left|r_2^{\rm C} - \left(\left\|\boldsymbol{H}_{\rm sd}\right\|_{\rm F}^2/\sigma_{\rm d}^2 + \left\|\overline{\boldsymbol{H}}_{\rm srd}\right\|_{\rm F}^2\right)s_2\right|^2. \end{cases} \tag{22}$$

With the estimated $\hat{s}_1^{\rm C}$ and $\hat{s}_2^{\rm C}$, the JCML detector for pair (s_3, s_4) is formulated by

$$(\hat{s}_3, \hat{s}_4) = \underset{s_3,s_4\in\mathcal{X}}{\arg\min}\left((\boldsymbol{k}_1^{\rm C})^{\rm H}\boldsymbol{k}_1^{\rm C} + (\boldsymbol{k}_2^{\rm C})^{\rm H}\boldsymbol{k}_2^{\rm C}\right), \tag{23}$$

where

$$\begin{cases} \boldsymbol{k}_1^{\rm C} = \boldsymbol{z}_1^{\rm C} - \dfrac{\boldsymbol{H}_{\rm C}\left[\hat{s}_1^{\rm C}|(s_3, s_4) \ \ \hat{s}_2^{\rm C}|(s_3, s_4)\right]^{\rm T}}{\sqrt{2}}, \\ \boldsymbol{k}_2^{\rm C} = \boldsymbol{z}_2^{\rm C} - \dfrac{\left[\boldsymbol{h}_2^{\rm C} \ \ -\boldsymbol{h}_1^{\rm C}\right]\left[\hat{s}_1^{\rm C}|(s_3, s_4) \ \ \hat{s}_2^{\rm C}|(s_3, s_4)\right]^{\rm H}}{\sqrt{2}}, \\ \boldsymbol{z}_1^{\rm C} = \left[\dfrac{(\boldsymbol{z}_1^{\rm sd})^{\rm T}}{\sigma_{\rm d}} \ \ (\boldsymbol{z}_1^{\rm srd})^{\rm T}\right]^{\rm T}, \\ \boldsymbol{z}_2^{\rm C} = \left[\dfrac{(\boldsymbol{z}_2^{\rm sd})^{\rm T}}{\sigma_{\rm d}} \ \ (\boldsymbol{z}_2^{\rm srd})^{\rm T}\right]^{\rm T}, \\ \boldsymbol{H}_{\rm C} = \left[\dfrac{\boldsymbol{H}_{\rm sd}^{\rm T}}{\sigma_{\rm d}} \ \ \overline{\boldsymbol{H}}_{\rm srd}^{\rm T}\right]^{\rm T}. \end{cases} \tag{24}$$

Here, $\boldsymbol{h}_i^{\rm C}$ $(i = 1, 2)$ denote the column vectors of $\boldsymbol{H}_{\rm C}$. The process of the detection method with the JCML detector is summarized in Algorithm 1.

Algorithm 1 Detection method with the joint conditional maximum likelihood detector

1: **for** $m = 1 : |\mathcal{X}|$ **do**
2: Select s_3^m from $\mathcal{X}$;
3: **for** $n = 1 : |\mathcal{X}|$ **do**
4: Select s_4^n from $\mathcal{X}$;
5: Compute $r_1^{\rm sd}$, $r_2^{\rm sd}$, $r_1^{\rm srd}$, and $r_2^{\rm srd}$ according to Eqs. (16)–(20) based on pair (s_3^m, s_4^n);
6: Compute the statistics of s_1 and s_2 based on (s_3^m, s_4^n) according to Eq. (21);
7: Estimate s_1 and s_2 based on (s_3^m, s_4^n) according to Eq. (22);
8: Calculate the metric for (s_3^m, s_4^n) as $m_{(s_3^m, s_4^n)} = (\boldsymbol{k}_1^{\rm C})^{\rm H}\boldsymbol{k}_1^{\rm C} + (\boldsymbol{k}_2^{\rm C})^{\rm H}\boldsymbol{k}_2^{\rm C}$ based on Eq. (24);
9: **end for**
10: **end for**
11: Select the pair $(\hat{s}_3, \hat{s}_4)$ with the minimum metric as the detection of s_3 and s_4 and output the corresponding estimates of s_1 and s_2;

Note that the complexity orders of these detection methods are both $\mathcal{O}(|\mathcal{X}|^2)$, which is much lower than that of traditional ML detection, i.e., $\mathcal{O}(|\mathcal{X}|^4)$, especially for high-order constellations. In the detection method with the JCML detector, the calculations for each search of pair (s_3, s_4) are related to $N_{\rm r}$ and $N_{\rm d}$; thus, its complexity may be a little higher than that of the detection method with MLC. However, the method with the JCML detector processes the signals received in two phases separately, which is perfectly suitable for parallel implementations. Furthermore, $\boldsymbol{z}_1^{\rm sd}$, $\boldsymbol{z}_2^{\rm sd}$, $r_1^{\rm sd}$, and $r_2^{\rm sd}$ can be calculated before receiving $\boldsymbol{Y}_{\mathrm{d},2}$ at D and thereby the detection delay can be reduced at the cost of extra storage of these variables for each pair (s_3, s_4) at D.

4 Diversity analysis

As we know, diversity order is related to the number of uncorrelated channels (Winters, 1998). In the detection method with the JCML detector, we can see from the first equation in Eq. (16) that $2N_{\mathrm{d}}$ uncorrelated channels are included in the S-D link for the estimate of s_1, which correspond to the elements of $\boldsymbol{H}_{\mathrm{sd}}$. However, for the case of the S-R-D link, it is difficult to directly observe the number of uncorrelated channels for the estimate of s_1 from the first equation in Eq. (19). We therefore rewrite $\overline{\boldsymbol{H}}_{\mathrm{srd}}$ as $\overline{\boldsymbol{H}}_{\mathrm{srd}} = \alpha\overline{\boldsymbol{H}}\boldsymbol{H}_{\mathrm{sr}}$, where $\overline{\boldsymbol{H}} = \boldsymbol{W}\boldsymbol{H}_{\mathrm{rd}}$. Since the dimensions of $\boldsymbol{W}$ and $\boldsymbol{H}_{\mathrm{rd}}$ are $N_{\mathrm{d}} \times N_{\mathrm{d}}$ and $N_{\mathrm{d}} \times N_{\mathrm{r}}$ respectively, $\overline{\boldsymbol{H}}$ is an $N_{\mathrm{d}} \times N_{\mathrm{r}}$ matrix whose rank is equal to $\min\{N_{\mathrm{d}}, N_{\mathrm{r}}\}$ (Horn and Johnson, 1985). The element of $\overline{\boldsymbol{H}}_{\mathrm{srd}}$ is the product of α, the row vector in $\overline{\boldsymbol{H}}$, and the column vector in $\boldsymbol{H}_{\mathrm{sr}}$, and all the elements of $\boldsymbol{H}_{\mathrm{sr}}$ are uncorrelated. Therefore, for each column of $\overline{\boldsymbol{H}}_{\mathrm{srd}}$, the number of uncorrelated channels is equal to the rank of $\overline{\boldsymbol{H}}$. Then there are $2\min\{N_{\mathrm{d}}, N_{\mathrm{r}}\}$ uncorrelated channels in $\overline{\boldsymbol{H}}_{\mathrm{srd}}$. To sum up, the estimate of s_1 benefits from $2(N_{\mathrm{d}} + \min\{N_{\mathrm{d}}, N_{\mathrm{r}}\})$-order diversity, so is that of s_2. Additionally, instead of estimating s_1 and s_2, s_3 and s_4 can be estimated with a given pair (s_1, s_2), according to Sezginer and Sari (2007). So, it can be deduced that the diversity order for s_3 and s_4 is also $2(N_{\mathrm{d}} + \min\{N_{\mathrm{d}}, N_{\mathrm{r}}\})$.

In the detection method with MLC, the coefficient of the estimated symbols is $\|\boldsymbol{H}_{\mathrm{E}}\|_{\mathrm{F}}^2$ according to Eq. (11). $\|\boldsymbol{H}_{\mathrm{E}}\|_{\mathrm{F}}^2$ can be calculated as follows:

$$\begin{aligned}\|\boldsymbol{H}_{\mathrm{E}}\|_{\mathrm{F}}^2 &= \mathrm{tr}\left[\boldsymbol{H}_{\mathrm{sd}}^{\mathrm{H}}\boldsymbol{H}_{\mathrm{sd}}/\sigma_{\mathrm{d}}^2 + \boldsymbol{H}_{\mathrm{srd}}^{\mathrm{H}}\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W}\boldsymbol{H}_{\mathrm{srd}}\right] \\ &= \mathrm{tr}\left[\boldsymbol{H}_{\mathrm{sd}}^{\mathrm{H}}\boldsymbol{H}_{\mathrm{sd}}/\sigma_{\mathrm{d}}^2\right] + \mathrm{tr}\left[\boldsymbol{H}_{\mathrm{srd}}^{\mathrm{H}}\boldsymbol{W}^{\mathrm{H}}\boldsymbol{W}\boldsymbol{H}_{\mathrm{srd}}\right] \\ &= \|\boldsymbol{H}_{\mathrm{sd}}\|_{\mathrm{F}}^2/\sigma_{\mathrm{d}}^2 + \left\|\overline{\boldsymbol{H}}_{\mathrm{srd}}\right\|_{\mathrm{F}}^2,\end{aligned} \tag{25}$$

which is identical to that of the detection method with the JCML detector. The diversity order for the detection method with MLC is therefore $2(N_{\mathrm{d}} + \min\{N_{\mathrm{d}}, N_{\mathrm{r}}\})$. From Eq. (25), it can be additionally inferred that the detection methods with JCML and MLC have the same error performance, which can be verified by the simulation in the following part.

5 Simulation results

The SEP performances of the proposed detection methods and the different transmission schemes are evaluated in this section via computer simulation. For all simulations, an AF relay-aided D2D system as depicted in Section 2 is adopted. In this system, the radio channels between various pairs of antennas for S-D, S-R, and R-D links are modeled as independent Rayleigh channels, and therefore the elements of $\boldsymbol{H}_{\mathrm{sd}}$, $\boldsymbol{H}_{\mathrm{sr}}$, and $\boldsymbol{H}_{\mathrm{rd}}$ are i.i.d. CSCG random variables with distributions $\mathcal{CN}(0, \sigma_{\mathrm{sd}}^2)$, $\mathcal{CN}(0, \sigma_{\mathrm{sr}}^2)$, and $\mathcal{CN}(0, \sigma_{\mathrm{rd}}^2)$, respectively. Assuming that the noises at R and D are normalized as $\sigma_{\mathrm{r}}^2 = \sigma_{\mathrm{d}}^2 \equiv 1$, the signal-to-noise ratios (SNRs) for links S-D, S-R, and R-D are respectively equal to $\mathrm{SNR}_{\mathrm{sd}} = \sigma_{\mathrm{sd}}^2$, $\mathrm{SNR}_{\mathrm{sr}} = \sigma_{\mathrm{sr}}^2$, and $\mathrm{SNR}_{\mathrm{rd}} = \sigma_{\mathrm{rd}}^2$. As relay is generally used when the quality of the S-D link is worse than that of the S-R-D link, we set $\mathrm{SNR}_{\mathrm{sd}} = \mathrm{SNR}_{\mathrm{sr}}/2 = \mathrm{SNR}_{\mathrm{rd}}/2$ for all simulations. The SEP performances are averaged over 10^9 Monte-Carlo experiments, and for each experiment, 100 symbols are sent. Quadrature phase shift keying (QPSK) and 16QAM constellations are adopted.

Fig. 2 compares the SEP of the proposed detection methods with the traditional ML detection method. It is easy to see that the two proposed detection methods, i.e., detections with JCML and MLC, achieve nearly identical SEP performances to that of traditional ML detection for various constellations. Therefore, these detection methods are equivalent in terms of SEP performance. On this basis, we consider only the detection with JCML, which has a comparatively low complexity and is suitable for parallel processing, in the following simulations for the transmission with FSTBC.

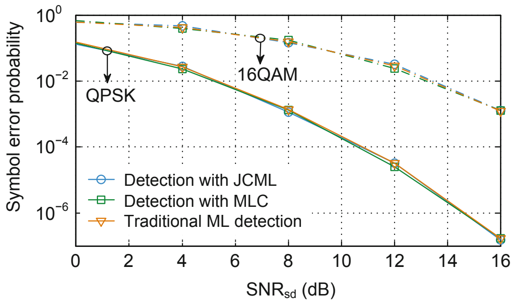

Fig. 2 Comparison of symbol error probability (SEP) performances for different detection methods with $N_{\mathrm{r}} = N_{\mathrm{d}} = 2$ (16QAM: 16-quadrature amplitude modulation; QPSK: quadrature phase shift keying)

Fig. 3 presents the SEP of different transmission schemes, including the SM relay-aided D2D transmission (RA D2D with $\boldsymbol{X}_1$), D2D transmission with FSTBC (D2D with $\boldsymbol{X}_2$), and relay-aided D2D transmission with FSTBC (RA D2D with $\boldsymbol{X}_2$). Additionally, two benchmark curves are plotted in Fig. 3 as the diversity order references, i.e., $\text{SNR}_{\text{sd}}^{-8}$ and $\text{SNR}_{\text{sd}}^{-4}$. As illustrated in Fig. 3, the relay-aided D2D transmission with FSTBC outperforms the SM relay-aided D2D transmission at the high SNR regime, and it achieves the highest diversity order (diversity order is equal to the slope of the SEP curves at the high SNR regime) equal to eight, which is double those of other transmission schemes by costing about the same complexity based on the previous analysis.

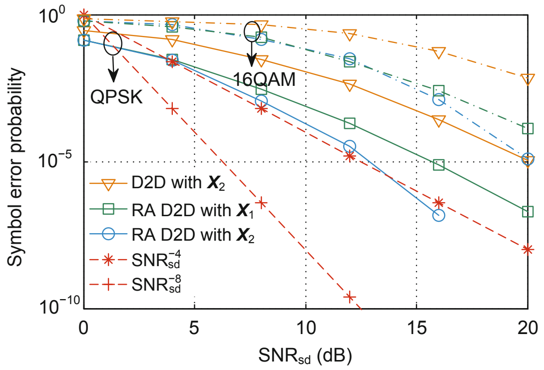

Fig. 3 Comparison of symbol error probability (SEP) performances for different transmission schemes with $N_{\text{r}} = N_{\text{d}} = 2$ (16QAM: 16-quadrature amplitude modulation; QPSK: quadrature phase shift keying)

Figs. 4 and 5 investigate the effects of N_{d} and N_{r} on the SEP of the proposed detection methods, respectively. Diversity order benchmarks, namely, $\text{SNR}_{\text{sd}}^{-4}$, $\text{SNR}_{\text{sd}}^{-6}$, and $\text{SNR}_{\text{sd}}^{-8}$, are also provided in these figures. In Figs. 4 and 5, N_{r} and N_{d} are respectively set to 2. As shown in Fig. 4, the increase of N_{d} leads to a higher diversity gain when $N_{\text{d}} \le N_{\text{r}}$ for different constellations, while when $N_{\text{d}} > N_{\text{r}}$, only SEP improvement can be obtained by increasing N_{d} and the diversity gain is not changed. Similar properties for the effect of N_{r} can be found in Fig. 5. Through these simulations, we verify that the diversity order of the proposed detection methods is determined by the minimum of N_{d} and N_{r}. Comparing Figs. 4 and 5, it can be found that the influence of N_{d} on diversity gain is more than that of N_{r}, which is in agreement with the analysis in Section 4.

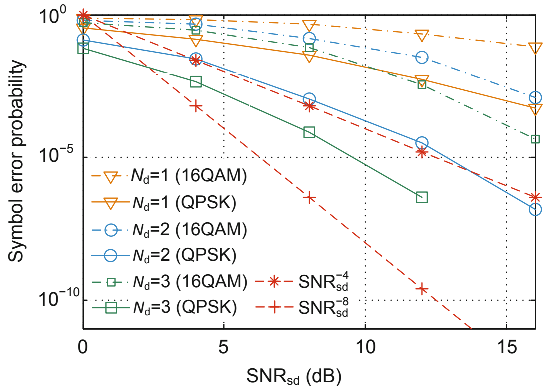

Fig. 4 Effect of N_{d} on the symbol error probability (SEP) performance of the proposed detection methods with $N_{\text{r}} = 2$ (16QAM: 16-quadrature amplitude modulation; QPSK: quadrature phase shift keying)

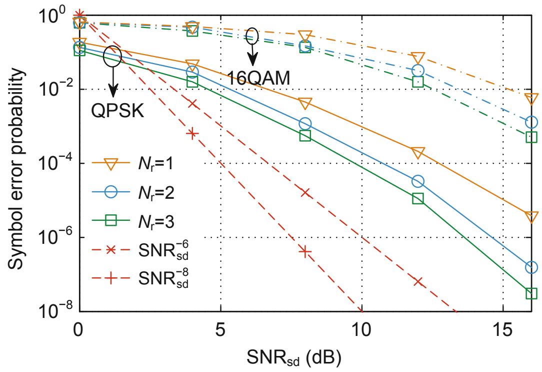

Fig. 5 Effect of N_{r} on the symbol error probability (SEP) performance of the proposed detection methods with $N_{\text{d}} = 2$ (16QAM: 16-quadrature amplitude modulation; QPSK: quadrature phase shift keying)

6 Conclusions

We have presented two low-complexity detection methods for the AF relay-aided D2D system with FSTBC transmission. By using the orthogonal structure of the selected FSTBC transmission, the complexity order of the proposed detection methods was reduced to the square root of that for the traditional ML detector. Furthermore, the detection method with the JCML detector was perfectly suitable for parallel processing in order to reduce the processing delay. The diversity orders of the proposed detection methods were also provided. Simulation results demonstrated the outstanding SEP performance of the FSTBC transmission scheme with the proposed detection methods and verified their diversity analysis.

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