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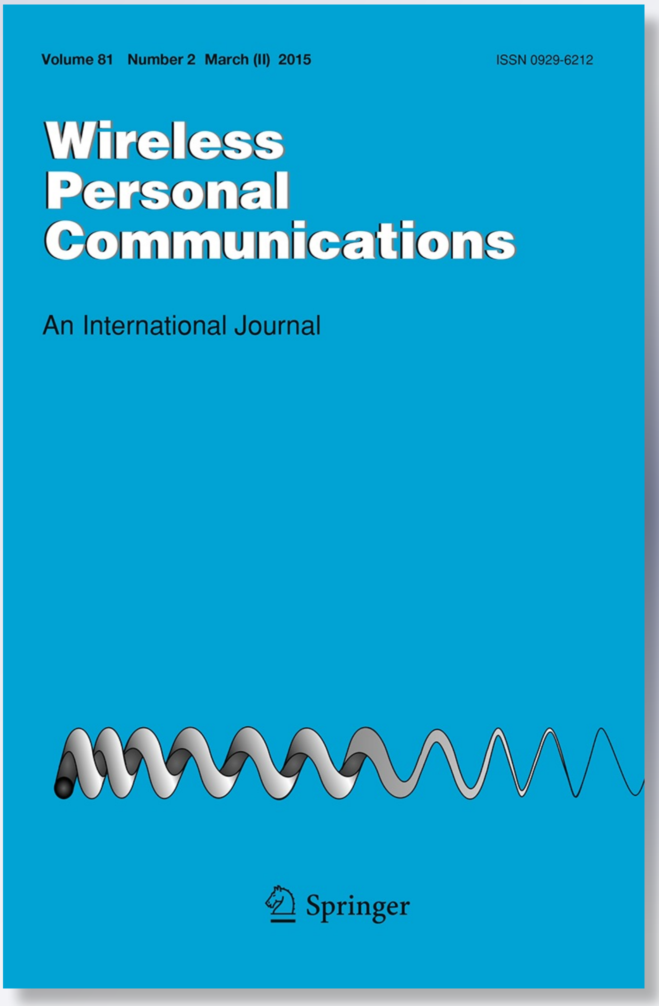

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Performance Analysis of Virtual MIMO Relaying Schemes Based on Detect–Split–Forward

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Abstract Virtual multi-input multi-output (vMIMO) schemes in wireless communication systems improve coverage, throughput, capacity, and quality of service. In this paper, we propose three uplink vMIMO relaying schemes based on detect–split–forward (DSF). In addition, we investigate the effect of several physical parameters such as distance, modulation type and number of relays. Furthermore, an adaptive vMIMO DSF scheme based on VBLAST and STBC is proposed. In order to do that, we provide analytical tools to evaluate the performance of the propose vMIMO relaying scheme.

Keywords Virtual MIMO · Distributed antenna · Relaying · Detect–split–forward · STBC · V-BLAST

1 Introduction

Since the introduction of the multiple-input multiple-output (MIMO) technology, there have been great advancements in data rate speeds and wireless network efficiency. The main purpose of MIMO implementation is to boost the transmission rate by exploiting the randomness of parallel channels. Using MIMO technology, the capacity of a propagation environment decreases with increasing the correlation of the channel coefficients. Practically, for none-line-of-sight (NLOS) and omni-directional wireless mobile communications, there are restrictions on handset manufacturing caused by wavelegths. Hence, the designers should select applicable wavelengths to realize the full potential of MIMO receivers. Obviously,

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large antenna arrays of different sizes are not always practical for handsets mobile. Furthermore, the developers of the next generation wireless systems are investing in virtual MIMO (vMIMO) [1]. Virtual MIMO (vMIMO) is a recent model adapted from the broadcasting model of wireless channels where all communication nodes (relays) support each other. The goal of vMIMO is to provide better quality-of-service (QoS) at higher data rates, especially for users who are at the cell edge. This technique acts in a way similar to multi-user (MU-MIMO) technique in the uplink side, also called network MIMO [1]. vMIMO is based on the concept of relaying over virtual antenna arrays. with results of enhancing the end-to-end link performance, offering good QoS and extending coverage range in NLOS environment. vMIMO systems execute the communication process in a distributed manner for gaining the advantages of the MIMO systems while reducing consumption of battery, improving capacity and expanding the network lifetime [2].

Relay structures have evolved by the introduction of virtual antenna arrays and MIMO relays [6–10]. The relaying technique, as introduced by Van der Meulen [3], has transpired through the years as the most well-known approach to improve the reliability and performance of wireless networks. It makes use of node cooperation and it allows a network to extend its coverage without exhausting its power resources. The two well-known relaying protocols, are: amplify-and forward (AF) and decode-and forward (DF) [4]. AF is the simplest as it only amplifies the received signal then forwards it. However, its drawback is that it amplifies the noise in addition to the signal. This technique, as described in the IEEE802.16j [5] standard, does not require the mobile station (MS) to be aware of intermediate relays. On the other hand, DF is a protocol that uses error detection and correction as it decodes data once received and confirms its correctness then forwards the data. This technique is generally used with hybrid automatic repeat request (HARQ) to ensure that correct data was decoded and intact [4].

The authors of [11,12] extended relaying concepts to MIMO. by considering several relay transmission and topology schemes (e.g. parallel, serial and hybrid relay) and taking into consideration practical MIMO systems. The authors of [13,14] investigated the performance of space-time block coding (STBC) with MIMO relaying using AF as an effective way to introduce spatial diversity. Virtual spatial multiplexing with AF relaying was investigated in [16] and closed-form expressions were derived for high-SNR performance of relay schemes under different design criteria. In [17], IEEE802.16e described the uplink virtual MIMO (UL-vMIMO) as follows: each user is equipped with a single antenna and shares the same channel resources with other users. By utilizing simultaneous transmissions over a common burst, vMIMO increases the peak transmission rate and improves the system performance. In [15], DF virtual relaying scheme for MIMO systems is analyzed.

In [18,19], an AF virtual spatial multiplexing scheme is proposed in which each transmitter is equipped with a single antenna. The transmitters form a virtual antenna array and send identical signals to relays that amplify-and-forward different portions of the signal at a reduced data rate to the destination. The receiver is equipped with multiple antennas in order to null and cancel the interference from the different relays and detect the original signal transmitted from the source. Another approach proposed by Kim and Cherukuri [20] is to let the relays detect a sub-stream from the original stream. Then, all relays forward their low rate sub-streams simultaneously over the same physical channel. This scheme has the advantage of controlling noise, as in digital systems, so that it is not amplified. Another advantage is that the vMIMO relay can send data with lower modulation rates which improves the bit error rate (BER). Because of the practical difficulty associated with antenna coupling, another alternative technique is proposed in [20]. In this paper we refer to the scheme of [20] as detect–split–forward (DSF) using vertical-bell laboratories layered space-time (VBLAST).

Up to the authors knowledge, there is no analysis of the error probability DSF of schemes over vMIMO. The main contribution of this paper is deriving analytical tools to evaluate the performance of DSF-vMIMO schemes. In addition, we propose a new DSF scheme based on STBC and we compare it to the spatial multiplexing DSF scheme. Furthermore, an adaptive scheme is proposed to switch between DSF-VBLAST and DSF-STBC to guarantee a minimum error rate performance. Both simulations and analysis are conducted to evaluate the system performance in terms of several physical parameters such as distance, modulation type, and number of relays.

The remainder of this paper is organized as follows. Section 2 introduces the system and channel models. The analysis of system performance and the average capacity are conducted in Sect. 3 and Sect. 4. In Sect. 5, some simulation and numerical results are presented and discussed. Finally, conclusions are given in Sect. 6.

2 System Model

We consider a $1 \times N_R \times N_D$ uplink system, where 1 indicates a source with a single antenna, N_R is number of relays, each equipped with a single antenna. N_D is number of receiving antennas at the destination. The source modulates a block of k information bits and transmits an 2^k-ary modulated symbol x, which is received by all relays. Then, each relay detects the information bits and splits them into N_R blocks of length m bits, where $mN_R = k$. At each relay, m-bit block is modulated using a lower level modulation schemes (2^m-ary symbol) and will be transmitted through N_R relays, which creates a vMIMO scheme. Two vMIMO schemes are considered to be employed at the relays, for relaying the N_R parallel 2^m-ary symbols. The first scheme uses spatial multiplexing based on VBLAST and the second scheme uses STBC.

2.1 DSF-vMIMO Schemes

To illustrate DSF vMIMO schemes, consider a $1 \times 2 \times 2$ system with 2 bps/Hz efficiency. The relays receive the following signals from the source with x being the tx'd signal

$$Y_{R_1} = h_{SR_1}x + n_{R_1} \tag{1}$$

$$Y_{R_2} = h_{SR_2}x + n_{R_2}, \tag{2}$$

where Y_{R_i} is the signal received at relay i, and h_{SR_i} is the complex Gaussian channel fading coefficient, with zero mean and variance of one, from the source to relay i. andn_{R_i} is the additive white Gaussian noise at relay i with zero-mean and variance N_o, where N_o is the noise power spectral density. Each relay detects the transmitted symbol x. The detection, splitting and forwarding of each vMIMO scheme is explained next.

2.1.1 DSF-VBLAST Scheme

The DSF-VBLAST scheme detects the 2^k-ary signal, splits it into N_R 2^m-ary parallel then forwards the signals simultaneously to the destination as shown in Fig. 1. As an example, for a 2 bps/Hz efficiency, the source modulates 4 bits using 16-QAM and sends it to the relays. Each relay detects the 16-QAM symbol and demodulates the 4 bits. Then, these 4 bits will be splitted into two blocks, each consisting of two bits. These two bits will be modulated using QPSK and then spatially multiplexed and forwarded to the destination. Since 4 bits have been transmitted using two hops, the system efficiency is 2 bps/Hz.

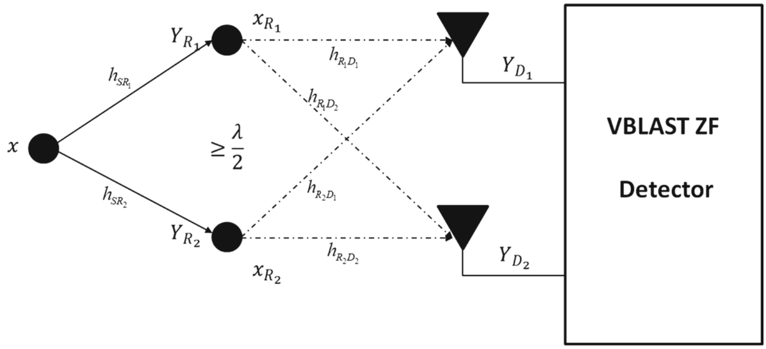

Fig. 1 System model of $1 \times 2 \times 2$ DSF-VBLAST relaying scheme

The destination receives the following vMIMO signals:

$$\begin{pmatrix} Y_{D_1} \\ Y_{D_2} \end{pmatrix} = \begin{pmatrix} h_{R_1D_1} & h_{R_2D_1} \\ h_{R_2D_2} & h_{R_1D_2} \end{pmatrix} \begin{pmatrix} \hat{x}_1 \\ \hat{x}_2 \end{pmatrix} + \begin{pmatrix} n_{D_1} \\ n_{D_2} \end{pmatrix}, \tag{3}$$

where Y_{D_j} is the signal received at antenna j at the destination, $\hat{x}_i$ is the signal transmitted from relay i, and $h_{R_iD_j}$ is the complex Gaussian channel fading coefficient, with zero mean and unit variance, between relay i and antenna j at the destination. In addition, n_{D_j} is the additive white Gaussian noise at antenna j at the destination.

The destination applies the VBLAST detection algorithm with successive interference cancellation (SIC) and it performs nulling, based on zero-forcing (ZF), cancelation and ordering.

2.1.2 DSF-STBC Scheme

To improve the diversity order and provide more link reliability, we propose a new DSF vMIMO scheme based on STBC. At the relays and after detection and splitting of the 2^k-ary symbol, into N_R $2^{k/N_R}$-ary symbols, the data symbols are forwarded using STBC as shown in Fig. 2. As an example, for a 2 bps/Hz, the source sends 6 bits using a 64-QAM symbol, x to the two relays. Then, each relay detects the 64-QAM symbol and demodulates the 6 bits and split them into two blocks, each consists of 3 bits. Each block of 3 bits will be modulated using 8PSK and then mapped to Alamouti STBC code. The STBC codes will be forwarded to the destination over two time slots. Since 6 bits have been transmitted during three time slots, the system efficiency is 2 bps/Hz. The received signals on the destination could be expressed as:

$$\begin{pmatrix} Y^2_{D_1} \\ Y^2_{D_2} \\ Y^{3*}_{D_1} \\ Y^{3*}_{D_2} \end{pmatrix} = \begin{pmatrix} h^2_{R_1D_1} & h^2_{R_1D_2} \\ h^2_{R_2D_1} & h^2_{R_2D_2} \\ h^{3*}_{R_1D_1} & -h^{3*}_{R_1D_2} \\ h^{3*}_{R_2D_1} & -h^{3*}_{R_2D_2} \end{pmatrix} \begin{pmatrix} \hat{x}_1 \\ \hat{x}_2 \end{pmatrix} + \begin{pmatrix} n^2_{D_1} \\ n^2_{D_1} \\ n^{3*}_{D_1} \\ n^{3*}_{D_1} \end{pmatrix}, \tag{4}$$

where $Y^t_{D_j}$ is the received signal at time slot t and antenna j, $h^t_{R_iD_j}$ is the channel from relay j to antenna j at the destination at tim slot t. The MIMO channel from the relay to the destination is assumed to be quasi-static complex Gaussian channel, where each cofficient has a zero mean and unit variance.

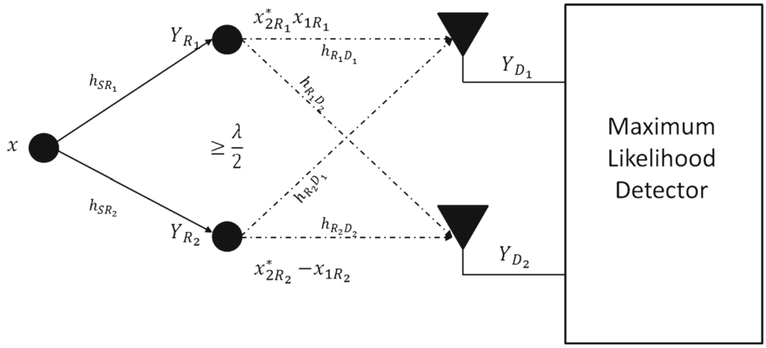

Fig. 2 System model of $1 \times 2 \times 2$ DSF-STBC relaying scheme

2.1.3 Adaptive DSF vMIMO Scheme

V-BLAST and STBC manifest the well-known tradeoff between diversity and spatial multiplexing. Such tradeoff can be exploited by making an adaptive system that switches between the two vMIMO systems. We propose a technique by which the relays determine the best scheme to be used based on relay distance from the source. As will be explained in Sect. 5.3.

3 Performance Analysis

3.1 DSF-VBLAST Scheme

To calculate the block error rate (BLER) for the DSF V-BLAST scheme, we analyze the detection process at each hop. Assume that P_{B,H_1} is the BLER of the first hop and P_{B,H_2} is the BLER of the second hop. Then the total BLER at the destination will be:

$$P_B = 1 - (1 - P_{B,H_1})(1 - P_{B,H_2}), \tag{5}$$

Since in the first hop, the source transmit the modulated symbol to N_R single antenna relays, the BLER at the first hop is

$$P_{B,H_1} = 1 - (1 - P_{e,R})^{N_R}. \tag{6}$$

where $P_{e,R}$ is the symbol error rate (SER) at each relay for M-ary modulation over fading channels [21] taking into account the appropriate signal set levels and energy after splitting. Thus SER at each relay is:

$$P_{e,R} = \left(\frac{M-1}{M}\right)\left(1 - \sqrt{\frac{1.5\gamma_R}{M^2 - 1 - 3\gamma_R}}\right), \tag{7}$$

where $M = 2^m$ is the new cardinality of the signal set after splitting and γ_R denotes the average received SNR at each relay.

Since VBLAST detection is used in the second hop, each layer of the V-BLAST scheme has a different error probability depending on its diversity order [23].

Assume that $P_{e,i}$ is the SER for layer i over Rayleigh fading channels, then the BLER of the second hop is:

$$P_{B,H_2} = 1 - \prod_{i=1}^{N_R}(1 - P_{e,i}), \tag{8}$$

For M-QAM signals, $P_{e,i}$ is [22]:

$$\begin{aligned} P_{e,i} &= 4\left(1 - \frac{1}{\sqrt{M}}\right)\left(\frac{1-\zeta_i}{2}\right)^{D_i} \sum_{j=0}^{D_i-1} \binom{D_i - 1 + j}{j} \left(\frac{1+\zeta_i}{2}\right)^j \\ &\quad -4\left(1 - \frac{1}{\sqrt{M}}\right)^2 \left\{\frac{1}{4} - \frac{\zeta_i}{\Pi}\left\{\left(\frac{\Pi}{2} - \tan^{-1}\zeta_i\right)\sum_{j=0}^{D_i-1}\binom{2j}{j}\left(\frac{1-\zeta_j}{4}\right)^j\right.\right. \\ &\quad \left.\left. + \sin(\tan^{-1}\zeta_i)\sum_{j=1}^{D_i-1}\sum_{r=1}^{j}\frac{Jrj}{(1+\beta_i)^j}[\cos(\tan^{-1})\zeta_i]^{2(j-r)+1}\right\}\right\}, \end{aligned} \tag{9}$$

where the diversity order of layer i is:

$$D_i = N_D - N_R + i, \tag{10}$$

and N_D is the total number of receiver antenna at the destination. Let d be the distance between the relays and the source, and v be the path loss, then the parameters in (9) are defined as

$$\zeta_i = \frac{\beta_i}{1+\beta_i} \tag{11}$$

$$\beta_i = \frac{3d^{-v}\gamma_D}{2N_R(M-1)} \tag{12}$$

$$J_{rj} = \frac{\binom{2j}{j}}{\binom{2(j-r)}{(j-r)}4^i(2(j-r)+1)}. \tag{13}$$

where γ_D denotes the average received SNR at each receive antenna at the destination.

For M-PSK case, $P_{e,i}$ is [22]:

$$\begin{aligned} P_{e,i} &= \frac{M-1}{M} - \frac{\mu_t}{\sqrt{\mu_t^2+1}}\left(\frac{1}{2} + \frac{\omega_t}{\Pi}\right)\sum_{\tau=0}^{D_t-1}\binom{2\tau}{\tau}[4(\mu_t^2+1)]^{-\tau} \\ &\quad - \frac{\mu_t}{\sqrt{\mu_t^2+1}}\frac{1}{\Pi}\sin(\omega_t)\sum_{\tau=1}^{D_t-1}\sum_{i=1}^{\tau}\frac{Ji\tau}{(\mu_t^2+1)^\tau}[\cos(\omega_t)]^{2(\tau-i)+1}, \end{aligned} \tag{14}$$

where

$$\mu_t = \sqrt{\rho_t}\sin\left(\frac{\Pi}{M}\right) \tag{15}$$

$$\rho_t = d^{-v}\cdot\gamma_D \tag{16}$$

$$\omega_t = \tan^{-1}\left(\frac{\sqrt{\rho_t}\cos(\frac{\Pi}{M})}{\sqrt{\mu_t^2+1}}\right). \tag{17}$$

3.2 DSF-STBC Scheme

For M-QAM STBC, the SEP at the second hop could be calculated using (9) with a diversity order $N_D \cdot N_R$ and with one layer ($L = 1$). Therefore, the second hop BLER is $P_{B,H_2} = P_{e,1}$ with a diversity $D = N_D \cdot N_R$. Then the total BLER P_B is calculated using (5).

4 Capacity Analysis

The DSF-vMIMO capacity is presented in this section. The analysis of the capacity of DSF-vMIMO for V-BLAST and STBC is based on the fact that the instantaneous capacity of the two hop relay system is determined by the weakest link. The first hop consists of two SISO channels and the second hop consists of a MIMO channel. The second MIMO hop can be either V-BLAST or STBC. Therefore, the instantaneous capacity of DSF-VBLAST can be calculated as:

$$C_{DSF\text{-}VBLAST} = \frac{\min\left\{C_{SISO1}, C_{SISO2}, C^{ZF}_{VBLAST}\right\}}{N_H}, \tag{18}$$

and the capacity of DSF STBC is:

$$C_{DSF\text{-}STBC} = \frac{\min\left\{C_{SISO1}, C_{SISO2}, C_{STBC}\right\}}{N_H}, \tag{19}$$

where N_H is the total number of hops.

In the above equations, C_{SISO} is the instantaneous capacity of single-input single-output flat Rayleigh fading channels [23] at the first hop, which is expressed as:

$$C_{SISO} = \log_2(1 + \gamma_R |h|^2)\ bps/Hz, \tag{20}$$

where the channel coefficient h is a complex Gaussian random variable with zero mean and unit variance, and γ_R is the average SNR at each relay. For a given h, there is only one way to increase the capacity of the SISO channel and that is by increasing SNR. Also, the capacity increases logarithmically with increasing SNR.

The second hop is either a VBLAST or an STBC. For VBLAST, the instantaneous capacity with N_R relays and with ZF interference nulling and serial cancelation is given by [24]:

$$C^{ZF}_{VBLAST} = N_R.min_{j=1,2,\ldots,R_N}\left\{\log_2\left(1 + \frac{\gamma_D}{N_R \| W_{ZF,j} \|_F^2}\right)\right\}, \tag{21}$$

where $W_{ZF,j}$ is the ZF projection vector of the j^{th} relay, γ_D is the SNR per receive antenna at the destination, and $\|(\cdot)\|_F^2$ is the squared Frobenius norm.

For STBC, the instantaneous capacity rate r_c code and N_R relays is [25]

$$C_{STBC} = r_c\left\{\log_2\left(1 + \frac{\gamma_D}{N_R}\|\mathbf{H}\|_F^2\right)\right\}. \tag{22}$$

5 Numerical Results

In this section, the performance of DSF V-BLAST, DSF-STBC and a hybrid scheme are evaluated using the analytical results and verified by Monte-Carlo simulations. The channel models used in the simulation are Rayleigh flat-fading channels characterized by complex Gaussian random variables with zero-mean and 0.5 variance per dimension. In addition additive white Gaussian noise is added at each receive antenna. Both BLER performance and average capacity are evaluated.

The performance evaluation and comparisons are done as a function of spectral efficiency, which is defined as the total number of bits received at the destination divided by the total number of transmission time slots.

5.1 DSF-VBLAST Scheme

Figure 3 compares the BLER of a DSF-VBLAST system with 2 bpz/Hz spectral efficiency using 16-QAM at the first hop and QPSK at the second hop. The results in this figure illustrate the accuracy of our analysis by comparing it to simulations for the first and second hops in addition to the total BLER. Figure 4 shows the BLER performance of $1 \times 2 \times 2$ DSF-VBLAST with several spectral efficiencies as shown in Table 1. In Fig. 5, we show the effect of doubling the number of relays where it is doubled from 2 to 4 to 8 while keeping the same spectral efficiency at 4 bps/Hz. A gain of 2 dB is obtained as the number of relays doubled from 2 to 4. The reason is that increasing the number of relays lowers the modulation level at the second hop from 16-QAM to QPSK to BPSK and that leads to a better performance.

5.2 DSF-STBC Scheme

For DSF-STBC scheme, Fig. 6 compares analytical and simulated BLER performance of $1 \times 2 \times 2$ DSF-STBC at 2 and 2.66 spectral efficiencies (Table 2). The relays are placed at a normalized distance of 0.3 from the source. This figure confirms the accuracy of our analysis for DSF-STBC.

5.3 Comparison of DSF-vMIMO Schemes

Figure 7 compares the BLER performance of DSF-VBLAST and DSF-STBC schemes. The result shows the effect of relay location on the performance of both systems and the inherent

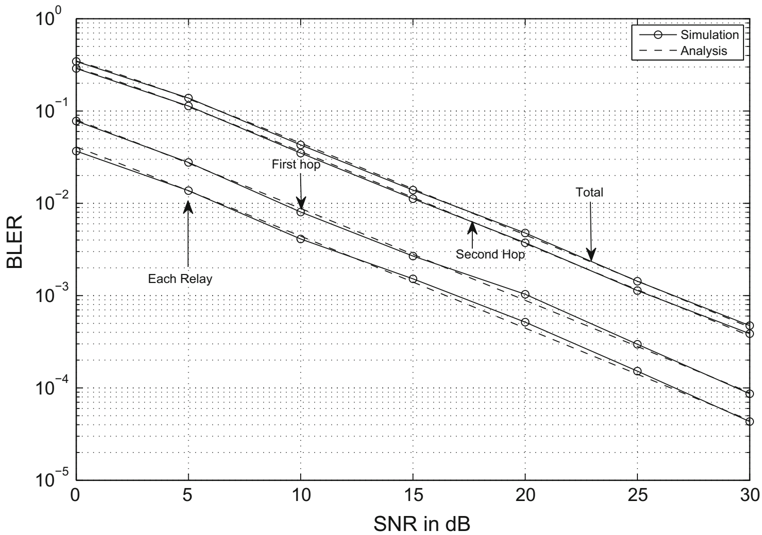

Fig. 3 BLER performance of DSF-VBLAST at 2 bps/Hz

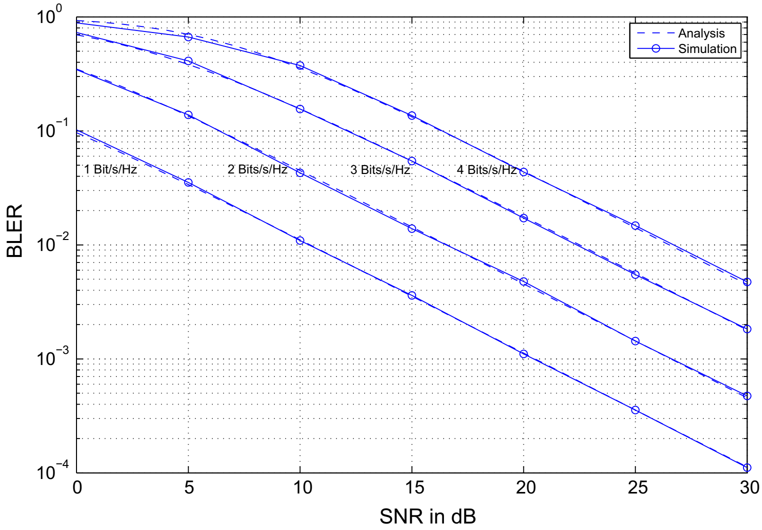

Fig. 4 BLER performance comparison of DSF-VBLAST relaying schemes for $1 \times 2 \times 2$ vMIMO system

Table 1 $1 \times 2 \times 2$ DSF-VBLAST

Number of time slots	Modulation at 1st Hop	Modulation at 2nd Hop	Spectral efficiency (bps/Hz)
2	QPSK	BPSK	1
2	16-QAM	QPSK	2
2	64-QAM	8PSK	3
2	256-QAM	16-QAM	4

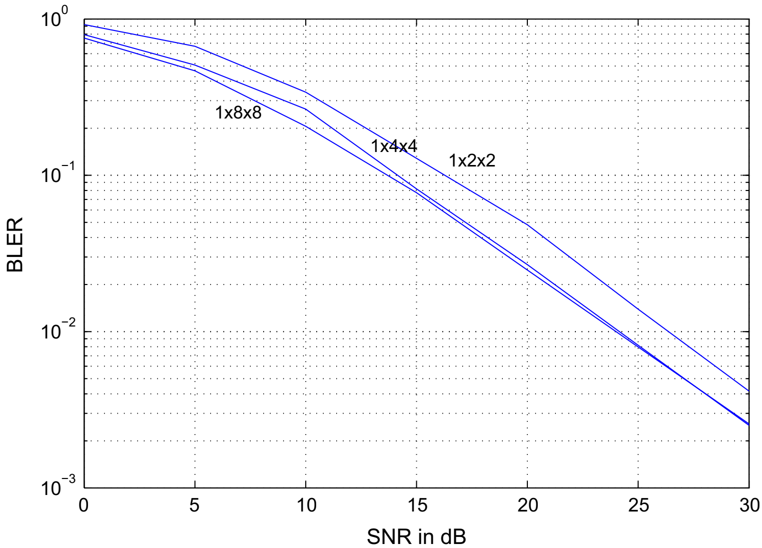

Fig. 5 Effect of number of relays on the performance of DSF-VBLAST scheme at 4 bps/Hz

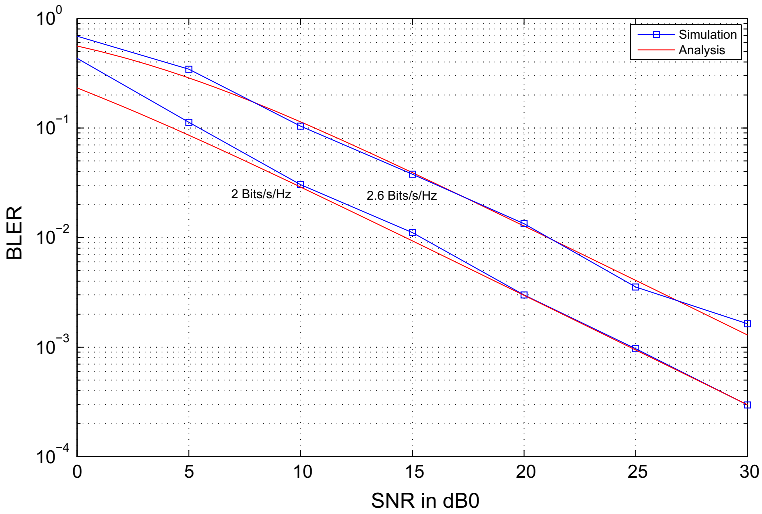

Fig. 6 BLER performance of DSF-STBC relaying schemes at 0.3 normalized distance from the source

Table 2 $1 \times 2 \times 2$ DSF-STBC

Number of time slots	Modulation at 1st Hop	Modulation at 2nd Hop	Spectral efficiency (bps/Hz)
3	QPSK	BPSK	0.66
3	16-QAM	QPSK	1.33
3	64-QAM	8PSK	2
3	256-QAM	16-QAM	2.66

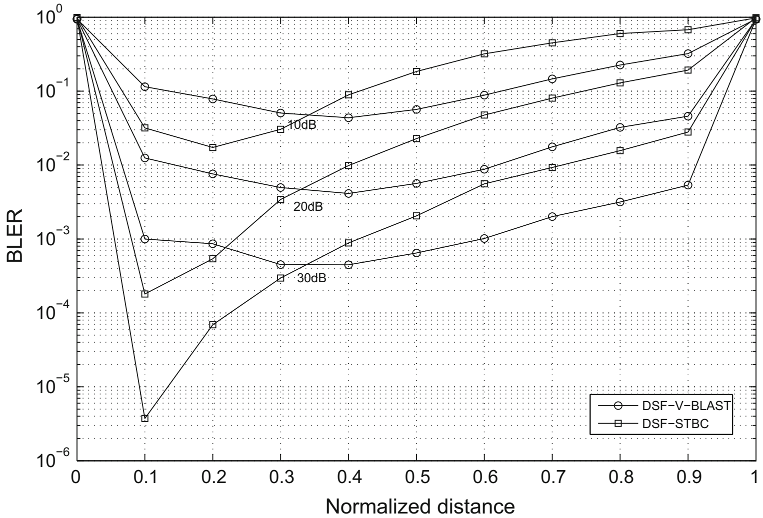

Fig. 7 Effect of the source-relay distance on the BLER performance of DSF-vMIMO relaying schemes

tradeoffs. The performance is examined at low, medium, and high SNRs and the normalized distance is changed from zero to one. The result shows that when the relays are closer to the

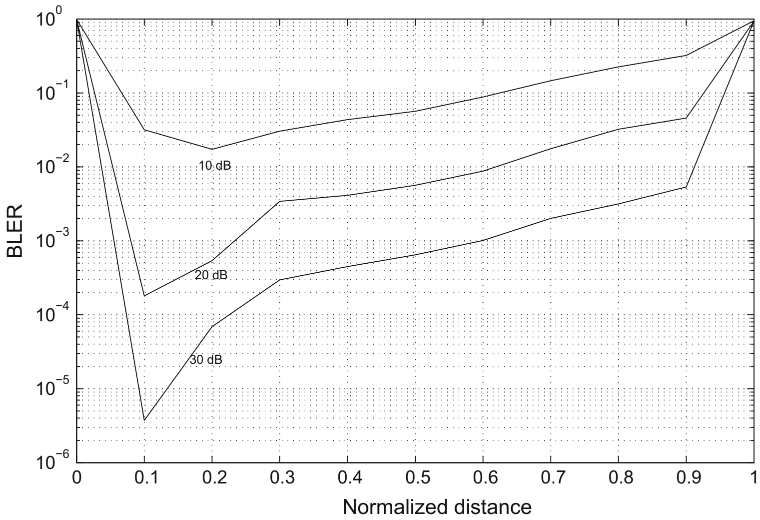

Fig. 8 BLER performance of the hybrid vMIMO relaying scheme for $1 \times 2 \times 2$ system at 2 bps/Hz

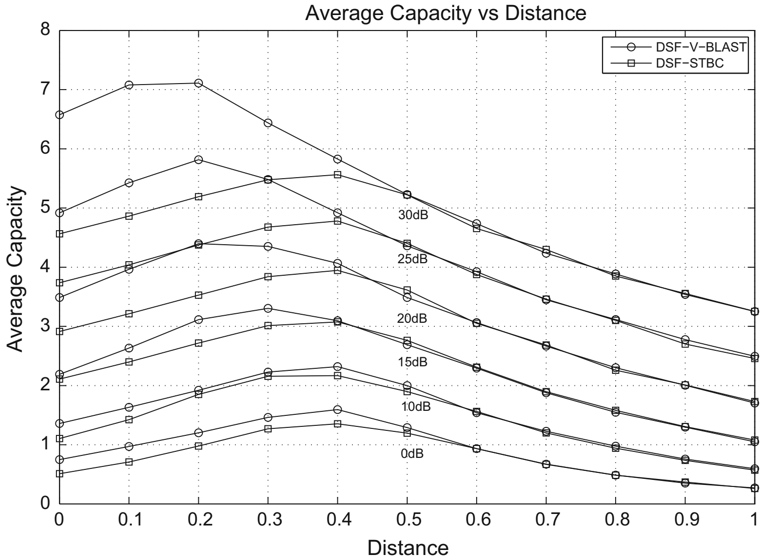

Fig. 9 Average capacity of DSF-vMIMO relaying schemes at different source-relay distances

source, the DSF-STBC performs better than DSF-V-BLAST. However, when the relays are placed further than 0.4, the performance of DSF-VBLAST becomes better. From this result, we propose to design a hybrid system where the relays use adaptive techniques to determine the best scheme to be used based on the distance from the source. The BLER performance of the adaptive DSF-vMIMO is shown in Fig. 8.

We also compare the average capacities of DSF-VBALST and DSF-STBC schemes, as shown in Fig. 9. Since both systems consist of SISO and MIMO hops, at a certain distance, the SISO channel dominates the overall channel capacity. The results in Fig. 9 show that at a distance greater than $d = 0.5$, the DSF-VBLAST channel capacity will perform the same as the DSF-STBC since both systems are dominated by the weakest channel, which is the SISO channel at the first hop.

6 Conclusion

In this paper, we proposed and analyzed detect–split–forward uplink virtual MIMO relying schemes based on VBLAST and STBC. The analysis presented in this paper matched the simulation results and it showed the effect of several physical parameters such as distance, modulation type and number of relays. An adaptive system that benefits from performance tradeoffs between VBLAST and STBC is introduced and evaluated depending on the distance of the relays from the source.

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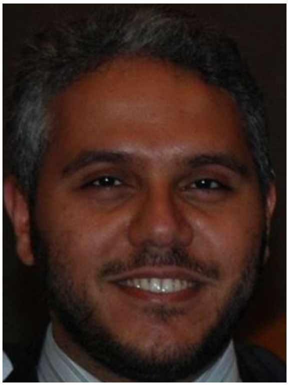

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