End-To-End Performance Analysis of Two-Hop Asynchronous Cooperative Diversity

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***Abstract*— Mobile users with single antennas can use spatial transmission diversity through cooperative space-time encoded transmission. This paper presents an end-to-end performance analysis of two-hop asynchronous cooperative diversity with regenerative relays over Rayleigh block-flat-fading channels. We present a precoding frame-based scheme with packet-wise encoding which enables best synchronization and channel estimation. We derive the bit-error rate and the end-to-end bit-error rate expressions for binary phase-shift keying. We present the performance of the frame-error rate and the end-to-end frame-error rate. Finally, comparisons between three system configurations, differing by the amount of cooperation, are presented. The influence of the amount of cooperation is small (about 2dB), Furthermore, simulations show that the analytical results are correct at all SNRs.**

I. Introduction

Multiple antennas at the receiver and the transmitter are often used to combat the effects of fading in wireless communication system. However, implementing multiple antennas at the mobile stations is impractical for a lot of wireless applications due to the limited size of the mobile unit. So, active users can pool their resources to form a virtual antenna array (VAA) that realizes spatial diversity gain in a distributed fashion [1]. It is the cooperative diversity (CD) system. Cooperative transmission (without Space-Time Block Codes (STBC)) has been proposed in cellular networks for cooperative diversity [2] and in sensor networks for energy efficiency and fault tolerance [3]. STBC has been naturally employed for improved bandwidth efficiency besides the targeted diversity benefits [4], [5]. Unfortunately, it is difficult, and in most cases impossible, to achieve perfect synchronization among distributed transmitters. Therefore a challenge is the lack of perfect synchronization on delay and mobility of distributed transmitters. This paper focuses on performance analysis of Two-Hop asynchronous cooperative diversity system using a specific precoding, a training sequence implemented as cyclic prefix [6] [7].

In section II the system model is discussed for the three configurations. In section III, the channel and delay estimation algorithm as well as the detection scheme are discussed. The section IV shows the simulation results, and we interpret our results in section V.

All boldface letters indicate vectors (lower case) or matrices (upper case). The $tr(\mathbf{A})$ is the trace of matrix $\mathbf{A}$, $(\ )^*$, $(\ )^H$ and $(\ )^\sharp$ are the conjugate, the hermitian and the pseudo-inverse operators respectively. $\mathrm{E}[\ ]$ is the Expectation operator, $\mathbf{I}_N$ is the identity matrix and $\mathbf{I}_N(L)$ is a matrix contains the L latest rows on I_N. $\mathbf{O}_N$ is an $N \times N$ matrix with all elements equal to 0, and we use $\mathbf{o}_N$ to denote an $N \times 1$ vector with all elements equal to 0. $\mathbf{a}(n)$ is the n^{th} block symbols, and $\mathbf{a}(n,k)$ is the k^{th} element of $\mathbf{a}(n)$. The Complex Gaussian distribution with mean μ and covariance matrix $\mathbf{C}$ is denoted by $\mathcal{CN}(\mu, \mathbf{C})$. $\widetilde{\mathbf{d}}_{Ri}(n)$ and $\widetilde{\mathbf{d}}_{Ri}(n+1)$ are the decoded data by the relay terminal Ri. $\widetilde{\mathbf{d}}(n)$ and $\widetilde{\mathbf{d}}(n+1)$ are the cooperative decoded data.

II. System Models

The general system model obeys the same topology as depicted in Figure 1, i.e. a source $M1$ communicates with a target D via a given number of relaying MTs $M2$, $R1$ and $R2$. Spatially adjacent relaying MTs are grouped into VAAs, $M1$ and $M2$ form the source VAA, $R1$ and $R2$ form the relay VAA. This system is referred to as a VAA multi-stage communication system.

The symbols are *replicated* in *space* and *time* in a specific manner that enables the destination node to combine the received symbols in a simple manner (linear) to reap the benefits of *diversity*. The main principle underlying this block

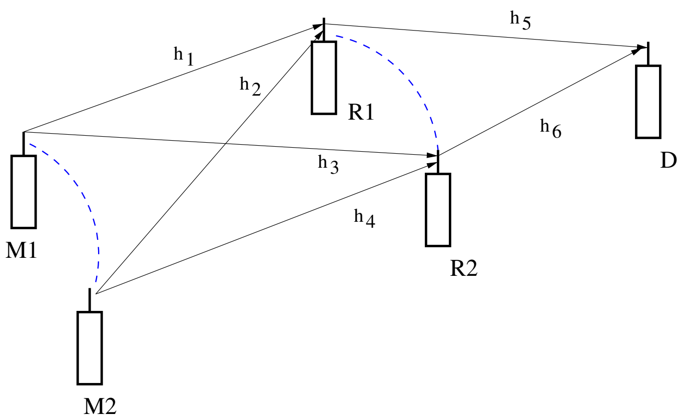

Fig. 1. VAA multi-stage communication system.

transmission system, presented in [8], is that the block of symbols to be transmitted, instead of being sent directly, is parsed into two sub-blocks of N symbols, $\mathbf{d}(n)$ and $\mathbf{d}(n+1)$, adding the training sequences $\mathbf{d}_1$ and $\mathbf{d}_2$ in each trail of the sub-blocks respectively, it can be seen in Fig. 2. We obtain two

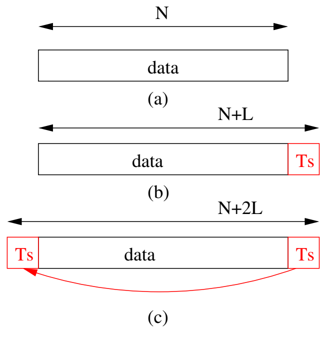

Fig. 2. A Frame description.

$(N+L)\times 1$ vectors $\mathbf{s}(n)$ and $\mathbf{s}(n+1)$, which are represented by (b) in Fig. 2. These vectors are represented in (1) and (2). We use the time reversal matrices $\mathbf{T}$ and $\mathbf{T}_s$ as linear precoding to obtain $\mathbf{s}_v(n)$ and $\mathbf{s}_v(n+1)$, which are represented in (3) and (4).

$$\mathbf{s}(n) = \begin{bmatrix} \mathbf{d}(n) \\ \mathbf{d}_1 \end{bmatrix} \quad (1)$$

$$\mathbf{s}(n+1) = \begin{bmatrix} \mathbf{d}(n+1) \\ \mathbf{d}_2 \end{bmatrix} \quad (2)$$

$$\mathbf{s}_v(n) = \begin{bmatrix} \mathbf{T}\mathbf{d}(n) \\ \mathbf{T}_s\mathbf{d}_1 \end{bmatrix} \quad (3)$$

$$\mathbf{s}_v(n+1) = \begin{bmatrix} \mathbf{T}\mathbf{d}(n+1) \\ \mathbf{T}_s\mathbf{d}_2 \end{bmatrix} \quad (4)$$

Our method consists in inserting, between any two successive blocks, a cyclic prefix as it can be seen in (c) in Fig. 2. This operation is done when pre-multiplying in the left by $\mathbf{F}_p$, then $\mathbf{s}(n)$ and $\mathbf{s}_v(n)$ are extended to $N+2L$ symbols. A distributed space time coding gives the transmitted frames $\mathbf{s}_1[n]$ and $\mathbf{s}_2[n]$ which are formed as in (5) and (6). The transmission scheme is represented in the Table I.

The precoding matrices $\mathbf{F}_p = \begin{bmatrix} I_{N+L}(L) \\ I_{N+L} \end{bmatrix}$, $\mathbf{T}$ and $\mathbf{T}_s$ are represented in Fig. 3.

$$\mathbf{s}_1[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n) \\ -(\mathbf{F}_p\mathbf{s}_v(n+1))^* \end{bmatrix} \quad (5)$$

$$\mathbf{s}_2[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n+1) \\ (\mathbf{F}_p\mathbf{s}_v(n))^* \end{bmatrix} \quad (6)$$

Each link of this system is considered a point-to-point one way communication link, and the channel is assumed Rayleigh block-flat-fading, constant during the transmission of one frame and independent from frame to frame.

We analyze the performance of the two-hop asynchronous cooperative diversity system presented by Fig. 1 in three configurations listed below. In the first stage, every relay

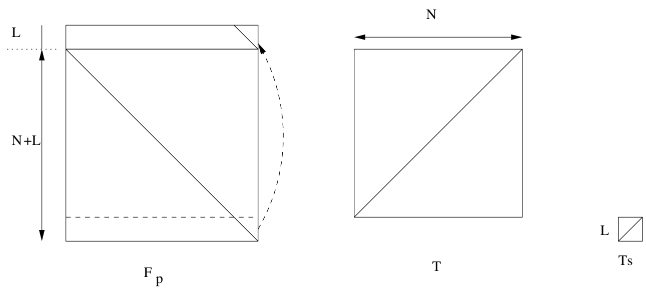

Fig. 3. The precoding matrices

TABLE I

TRANSMISSION SCHEME

	n^{th} *block symbols*	$(n+1)^{th}$ *block symbols*
ant $\mathbf{tx}_1$	$\mathbf{F}_P \times \mathbf{s}(n)$	$-(\mathbf{F}_P \times \mathbf{s}_v(n+1))^*$
ant $\mathbf{tx}_2$	$\mathbf{F}_P \times \mathbf{s}(n+1)$	$(\mathbf{F}_P \times \mathbf{s}_v(n))^*$

receives a summation of the signals of the two active mobiles in the source VAA after they travel through different paths in the channel. These channel paths induce different delays, attenuations and phase shifts. Therefore, these transmission delays and channels can be estimated from training sequences. We define τ_1 and τ_2 respectively as the arrival time of the first and the second signals received by $R1$ and We define τ_3 and τ_4 respectively as the arrival time of the first and the second signals received by $R2$. We assume without loss of generality that $\tau_1 \le \tau_2$ and $\tau_3 \le \tau_4$, and the analysis is done for $R1$.

The signal received by $R1$ is given by

$$\mathbf{r} = \mathcal{A}(\tau)\mathbf{X}\mathbf{h} + \mathbf{b} \quad (7)$$

where the total noise vector $\mathbf{b} \sim \mathcal{CN}(\mathbf{0}, N_0\ \mathbf{I}_{2N+4L})$ and

$$\mathcal{A}(\tau) = [\mathbf{O}_{2N+4L} \quad \mathbf{I}_{2N+4L} \quad \Gamma \quad \Psi] \quad (8)$$

$$\mathbf{X} = \begin{bmatrix} \mathbf{s}_1[n-1] & \mathbf{o}_{2N+4L} \\ \mathbf{s}_1[n] & \mathbf{o}_{2N+4L} \\ \mathbf{o}_{2N+4L} & \mathbf{s}_2[n-1] \\ \mathbf{o}_{2N+4L} & \mathbf{s}_2[n] \end{bmatrix} \quad (9)$$

$$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \quad (10)$$

In the equation above, $h_{1,2} \sim \mathcal{CN}(0,1)$ are the complex scalar channel parameters, $\mathbf{X}$ is the matrix obtained by stacking two consecutive frames from each transmitter. Γ and Ψ with size $(2N+4L)\times(2N+4L)$ account for the asynchronism between the two signals, and are expressed respectively as

$$\Gamma = \begin{bmatrix} \mathbf{O}_{L_\tau \times (2N+4L-L_\tau)} & \mathbf{I}_{L_\tau} \\ \mathbf{O}_{(2N+4L-L_\tau)\times(2N+4L-L_\tau)} & \mathbf{O}_{(2N+4L-L_\tau)\times(L_\tau)} \end{bmatrix} \quad (11)$$

$$\Psi = \begin{bmatrix} \mathbf{O}_{L_\tau \times (2N+4L-L_\tau)} & \mathbf{O}_{L_\tau} \\ \mathbf{I}_{2N+4L-L_\tau} & \mathbf{O}_{(2N+4L-L_\tau)\times(L_\tau)} \end{bmatrix} \quad (12)$$

where $L_\tau = \tau_2 - \tau_1$ is the relative delay which is bounded by L. We can remark that in synchronous case, $\Gamma_{syn} = \mathbf{O}_{2N+4L}$ and $\Psi_{syn} = \mathbf{I}_{2N+4L}$. We remember that the cooperative links in the source VAA and the relay VAA are assumed error-free due to the short communication distances between the mobiles of the same VAA compared to the inter-VAA distances. Any of the relays receives signals and functions as follows.

$$\mathbf{r}_1 = \mathcal{A}(\tau_{12})\mathbf{X}\mathbf{h}_{12} + \mathbf{b}_1 \tag{13}$$

$$\mathbf{r}_2 = \mathcal{A}(\tau_{34})\mathbf{X}\mathbf{h}_{34} + \mathbf{b}_2 \tag{14}$$

where the total noise vectors $\mathbf{b}_{1,2} \sim \mathcal{CN}(\mathbf{0}, N_0 \ \mathbf{I}_{2N+4L})$ and

$$\mathbf{h}_{12} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \tag{15}$$

$$\mathbf{h}_{34} = \begin{bmatrix} h_3 \\ h_4 \end{bmatrix} \tag{16}$$

- System 1 : $R1$ and $R2$ receive the data, estimate the channel parameters as shown in section III and decode separately the received data as shown in section III-A, before being passed onto the cooperative procedure. $R1$ uses the decoded $\widetilde{\mathbf{d}}_{R1}(n)$ to cooperate with $R2$, and the later uses $\widetilde{\mathbf{d}}_{R2}(n+1)$ to cooperate with $R1$ because we need to conserve the transmition rate. Therefore we re-transmit

$$\mathbf{s}_{1R}[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}_1(n) \\ -\left(\mathbf{F}_p\mathbf{s}_{2v}(n+1)\right)^* \end{bmatrix} \tag{17}$$

$$\mathbf{s}_{2R}[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}_2(n+1) \\ \left(\mathbf{F}_p\mathbf{s}_{1v}(n)\right)^* \end{bmatrix} \tag{18}$$

where

$$\mathbf{s}_1(n) = \begin{bmatrix} \widetilde{\mathbf{d}}_{R1}(n) \\ \mathbf{d}_1 \end{bmatrix} \tag{19}$$

$$\mathbf{s}_2(n+1) = \begin{bmatrix} \widetilde{\mathbf{d}}_{R2}(n+1) \\ \mathbf{d}_2 \end{bmatrix} \tag{20}$$

$$\mathbf{s}_{1v}(n) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}_{R1}(n) \\ \mathbf{T}_s\mathbf{d}_1 \end{bmatrix} \tag{21}$$

$$\mathbf{s}_{2v}(n+1) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}_{R2}(n+1) \\ \mathbf{T}_s\mathbf{d}_2 \end{bmatrix} \tag{22}$$

- System 2 : $R1$ and $R2$ receive the data, estimate the channel parameters as shown in section III and decode separately the received data as shown in section III-A. We conserve the structure of the Distributed STBC and we re-encode the decoded data without any cooperation in (r-VAA). Therefore we re-transmit

$$\mathbf{s}_{1R}[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}_1(n) \\ -\left(\mathbf{F}_p\mathbf{s}_v(n+1)\right)^* \end{bmatrix} \tag{23}$$

$$\mathbf{s}_{2R}[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}_2(n+1) \\ \left(\mathbf{F}_p\mathbf{s}_v(n)\right)^* \end{bmatrix} \tag{24}$$

where

$$\mathbf{s}_1(n) = \begin{bmatrix} \widetilde{\mathbf{d}}_{R1}(n) \\ \mathbf{d}_1 \end{bmatrix} \tag{25}$$

$$\mathbf{s}_2(n+1) = \begin{bmatrix} \widetilde{\mathbf{d}}_{R2}(n+1) \\ \mathbf{d}_2 \end{bmatrix} \tag{26}$$

$$\mathbf{s}_v(n) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}_{R2}(n) \\ \mathbf{T}_s\mathbf{d}_1 \end{bmatrix} \tag{27}$$

$$\mathbf{s}_v(n+1) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}_{R1}(n+1) \\ \mathbf{T}_s\mathbf{d}_2 \end{bmatrix} \tag{28}$$

The error performance differences between system 1 and 2 will be visible for unequal sub-channel gains (shadowing).

- System 3 : $R1$ and $R2$ receive the data, estimate the channel parameters as shown in section III but no separately decoding is performed in (r-VAA), then an unprocessed version of the received signals are exchanged between $R1$ and $R2$. After cooperation, appropriate decoding is performed as shown in section III-B, the obtained information $\widetilde{\mathbf{d}}$ is then re-encoded in a distributed manner as follows, and re-transmitted to the destination

$$\mathbf{s}_1[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n) \\ -\left(\mathbf{F}_p\mathbf{s}_v(n+1)\right)^* \end{bmatrix} \tag{29}$$

$$\mathbf{s}_2[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n+1) \\ \left(\mathbf{F}_p\mathbf{s}_v(n)\right)^* \end{bmatrix} \tag{30}$$

where

$$\mathbf{s}(n) = \begin{bmatrix} \widetilde{\mathbf{d}}(n) \\ \mathbf{d}_1 \end{bmatrix} \tag{31}$$

$$\mathbf{s}(n+1) = \begin{bmatrix} \widetilde{\mathbf{d}}(n+1) \\ \mathbf{d}_2 \end{bmatrix} \tag{32}$$

$$\mathbf{s}_v(n) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}(n) \\ \mathbf{T}_s\mathbf{d}_1 \end{bmatrix} \tag{33}$$

$$\mathbf{s}_v(n+1) = \begin{bmatrix} \mathbf{T}\widetilde{\mathbf{d}}(n+1) \\ \mathbf{T}_s\mathbf{d}_2 \end{bmatrix} \tag{34}$$

III. Channel and Delay Estimation Algorithm

A maximum likelihood (ML) method for delay and channel estimation is proposed in [8]. We summarize it here.
We denote $\mathbf{ts_1}$ and $\mathbf{ts_2}$ as

$$\mathbf{ts_1} = \mathbf{T}_s\mathbf{d}_1 \tag{35}$$

$$\mathbf{ts_2} = \mathbf{T}_s\mathbf{d}_2 \tag{36}$$

Therefore we define $\mathbf{S}(\tau) = [\mathbf{ss_1}\mathbf{ss_2}]$ where

$$\mathbf{ss_1} = \begin{bmatrix} \mathbf{d}_1(\tau+1:L) \\ -\left(\mathbf{ts_2}\right)^* \end{bmatrix} \tag{37}$$

$$\mathbf{ss_2} = \begin{bmatrix} \mathbf{d}_2 \\ \left(\mathbf{ts_1}(1:L-\tau)\right)^* \end{bmatrix} \tag{38}$$

For this deterministic model, we denote $\mathbf{z}(\tau) = \mathbf{r}[n, N+L+\tau+1 : N+3L]$, therefore we can write

$$\widetilde{\mathbf{h}}(\tau) = (\mathbf{S}(\tau))^{\sharp}\mathbf{z}(\tau) \tag{39}$$

then

$$\widehat{\tau} = \arg\min_{\tau<L} \|\mathbf{z} - \mathbf{S}(\tau)\widetilde{\mathbf{h}}(\tau)\|^2 \tag{40}$$

and

$$\widehat{\mathbf{h}} = \left(\mathbf{S}(\widehat{\tau})\right)^{\sharp} \mathbf{z}(\widehat{\tau}) \tag{41}$$

A. Detection scheme for one receiver

We denote $\mathbf{r}_a$, $\mathbf{r}_b$ and $\mathbf{y}$ as

$$\mathbf{r}_a = \mathbf{r}[n, L+1 : N+L+\tau] \quad (42)$$

$$\mathbf{r}_b = \mathbf{r}[n, N+3L+1 : 2N+3L+\tau] \quad (43)$$

$$\mathbf{y} = [\mathbf{r}_a^T \ \mathbf{r}_b^T] \quad (44)$$

The combiner builds the following two combined signals that are sent to the maximum likelihood detector:

$$\widetilde{\mathbf{d}}(n,k) = \widehat{\mathbf{h}}_1^*(n)\mathbf{y}(n,k) + \widehat{\mathbf{h}}_2(n)\mathbf{y}^*(n,l+1-k) \quad (45)$$

$$\widetilde{\mathbf{d}}(n+1,k) = \widehat{\mathbf{h}}_2^*(n)\mathbf{y}(n,\tau+k) - \widehat{\mathbf{h}}_1(n)\mathbf{y}^*(n,l-\tau+1-k) \quad (46)$$

where l is the number of bits which $\mathbf{y}$ contains.

B. Detection scheme for two cooperative receivers

We receive $\mathbf{r}_1$ and $\mathbf{r}_2$ and we denote $\mathbf{r}_{1a}$, $\mathbf{r}_{1b}$ and $\mathbf{y}_1$ as

$$\mathbf{r}_{1a} = \mathbf{r}_1[n, L+1 : N+L+\tau_1] \quad (47)$$

$$\mathbf{r}_{1b} = \mathbf{r}_1[n, N+3L+1 : 2N+3L+\tau_1] \quad (48)$$

$$\mathbf{y}_1 = [\mathbf{r}_{1a}^T \ \mathbf{r}_{1b}^T] \quad (49)$$

and we denote $\mathbf{r}_{2a}$, $\mathbf{r}_{2b}$ and $\mathbf{y}_2$ as

$$\mathbf{r}_{2a} = \mathbf{r}_2[n, L+1 : N+L+\tau_2] \quad (50)$$

$$\mathbf{r}_{2b} = \mathbf{r}_2[n, N+3L+1 : 2N+3L+\tau_2] \quad (51)$$

$$\mathbf{y}_2 = [\mathbf{r}_{2a}^T \ \mathbf{r}_{2b}^T] \quad (52)$$

The combiner builds the following two combined signals that are sent to the maximum likelihood detector :

$$\begin{aligned}\widetilde{\mathbf{d}}(n,k) &= \widehat{\mathbf{h}}_1^*(n)\mathbf{y}_1(n,k) + \widehat{\mathbf{h}}_2(n)\mathbf{y}_1^*(n,l_1+1-k) \\ &+ \widehat{\mathbf{h}}_3^*(n)\mathbf{y}_2(n,k) + \widehat{\mathbf{h}}_4(n)\mathbf{y}_2^*(n,l_2+1-k)\end{aligned} \quad (53)$$

$$\begin{aligned}\widetilde{\mathbf{d}}(n+1,k) &= \widehat{\mathbf{h}}_2^*(n)\mathbf{y}_1(n,\tau_1+k) - \widehat{\mathbf{h}}_1(n)\mathbf{y}_1^*(n,\nu_1) \\ &+ \widehat{\mathbf{h}}_4^*(n)\mathbf{y}_2(n,\tau_2+k) - \widehat{\mathbf{h}}_3(n)\mathbf{y}_2^*(n,\nu_2)\end{aligned} \quad (54)$$

where l_1 and l_2 are the numbers of bits which $\mathbf{y}_1$ and $\mathbf{y}_2$ contain respectively, and $\nu_i = l_i - \tau_i + 1 - k$.

IV. Performance analysis and simulations

For equal sub-channel gains γ, the moment generating function (MGF) of the instantaneously experienced SNR for a system with t transmit antennas, r receive antennas and λ is the channel energy, can be expressed as

$$\phi_{\frac{1}{R}\frac{\lambda}{t}\frac{S}{N}}(s) = \frac{1}{(1 - \frac{1}{R}\frac{\gamma}{t}\frac{S}{N} \times s)^u} \quad (55)$$

where R is the transmission rate and $u = t \times r$.

The analysis in [9] allows expressing the BER of BPSK in closed form as

$$\begin{aligned}P_{t,r}(e) &= \phi_{\frac{1}{R}\frac{\lambda}{t}\frac{S}{N}}(-1)\left[\frac{1}{2\sqrt{\pi}}\frac{\Gamma(u+1/2)}{\Gamma(u+1)}\right] \times \\ &{}_2F_1\left(u, 1/2; u+1; (1+\frac{1}{R}\frac{\gamma}{t}\frac{S}{N})^{-1}\right)\end{aligned} \quad (56)$$

where ${}_2F_1(a,b;c;x)$ is the Gauss hypergeometric function with 2 parameters of type 1 and 1 parameter of type 2. It has been implemented using the series representations

$${}_2F_1(a,b;c;x) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n n!} x^n \quad (57)$$

where

$$(a)_n = \frac{\Gamma(a+n)}{\Gamma(a)} \quad (58)$$

Fig 4 depicts the efficiency of the channel and delay estimation algorithm derived in section III.

In systems 1 and 2, the partial cooperation at the first relaying stage results in two parallel MISO channels. Assuming an error free input into the relay VAA, each of these MISO channels causes independent BERs, denoted by P_{R1} and P_{R2} respectively. Each of these MISO channels consists of channels with equal average attenuations γ. The second stage spans a single MISO channel with a BER P_D. To obtain the exact end-to-end BER is not trivial, as an error in the first stage may propagate to D; however, it may also be corrected at the next stage.

Therefore, the probability that an error which occured in link $\{M1, R1\}$ with probability $P_{R1} = P_{2,1}(e)$ propagates through the O-MIMO channel spanned by $\{R1, D\}$ and $\{R2, D\}$ is approximated as $P_{R1} \times \gamma/(\gamma+\gamma)$, where the strength of the erroneous channel $\{R1, D\}$ is normalized by the total strength of both sub-channels. To capture the probability that such an error propagates until the destination D, all possible paths in the network have to be found and the original probability of error weighed with the ratios between the respective path gains. The end-to-end BER can be expressed as

$$P_{e2e}(e) \approx \left[\frac{1}{2}P_{R1} + \frac{1}{2}P_{R2}\right] + P_D \quad (59)$$

where $P_{R1} = P_{R2} = P_D = P_{2,1}(e)$.

In system 3, the full cooperation at each stage is assumed. Each of the two relaying stages experiences independent BERs. A bit from the source $M1$ is received correctly at the target D only when at all stages the bit has been transmitted correctly. The end-to-end BER can therefore be expressed as

$$P_{e2e}(e) = 1 - [(1 - P_{2,2}(e))(1 - P_{2,1}(e))] \quad (60)$$

Fig 5 depicts the end-to-end bit-error rate P_{e2e} versus the SNR in (dB) labelled on the system schemes exhibiting a spectral efficiency of 1 bit/s/Hz. Here, the solid lines represent the analytically derived P_{e2e}, whereas the markers correspond to specific points obtained by means of simulations. For all configurations, the simulations clearly corroborate the analytical results. Furthermore, the third configuration, with full cooperation at each stage, obviously enhances the end-to-end performances.

Each frame contains 288 symbols in which 224 for data. Therefore the cyclic prefix contain 16 symbols for training sequence.

Fig 6 depicts the end-to-end frame-error rate versus the SNR in (dB) labelled on the system schemes exhibiting a spectral efficiency of 1 bit/s/Hz.

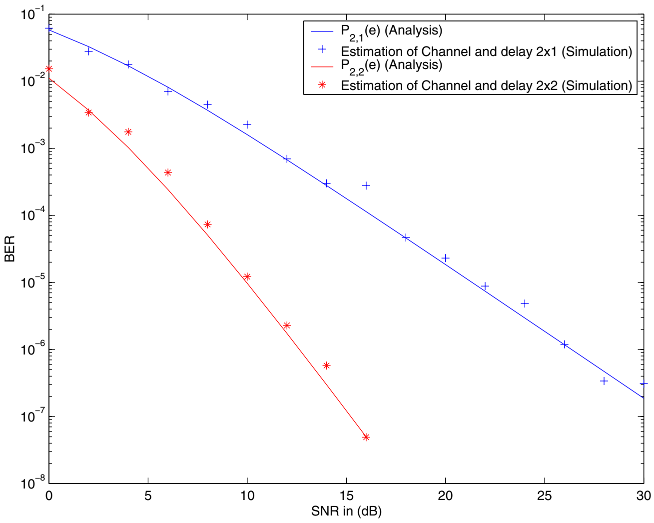

Fig. 4. BER performance of the first stage asynchronous cooperative diversity system with channel and delay estimations.

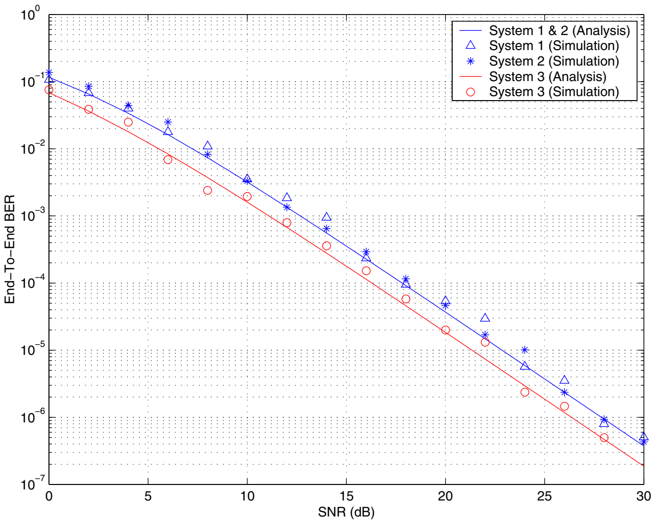

Fig. 5. Comparison between end-to-end bit-error rate of the three configurations.

V. Conclusion

We analyze the performance of two-hop asynchronous cooperative diversity, where the emphasis has been on transceivers utilizing space-time block coding. The error probability of such transceivers has been derived for three communication scenarios. As mentioned before, we have an equal sub-channel case, and, systems 1 and 2 present a partial cooperation at the relaying stage, but system 3 is a full cooperation scenario. The performance enhancements by the full cooperation at each stage is at the expense of additional transceiver complexity to realize the cooperation; also, additional bandwidth and power

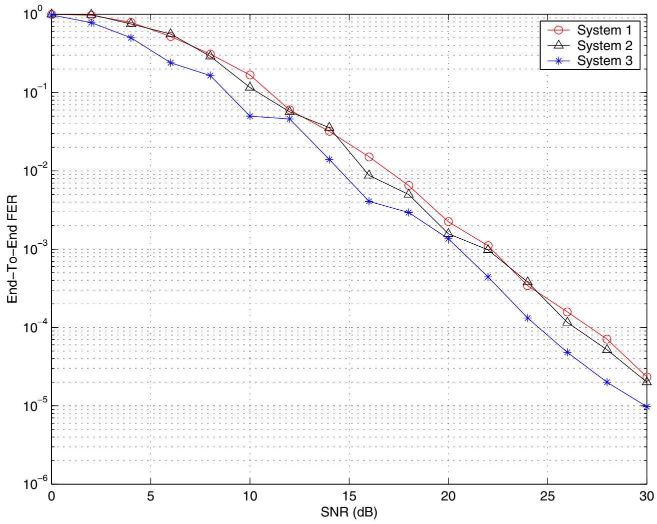

Fig. 6. Comparison between end-to-end frame-error rate of the three configurations.

are required to accomplish the relaying process. The shadowed links will be considered for a future work.

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