Channel And Delay Estimation Algorithm For Asynchronous Cooperative Diversity

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Abstract. Wireless Mobile Communications rely on a host of techniques, all related to one goal, sending the most possible information accross a link or a network. In recent years, both spatial and multiuser diversity have proven to be key techniques to achieve this goal. These two diversity dimensions can be exploited by the use of multiple antennas and/or the use of multiple terminals sending at the same time/frequency/code, these terminals can be seen as a multiple antenna emitter. This transmission diversity can be achieved with cooperative space-time encoded transmissions. One of the practical problems with this sort of array of transmitters is that the emitters will be asynchronous to some extent, hence the need for systems that can deal with asynchronicity, both from a signal design point of view and from a signal processing point of view. Having tackled the signal design previously, we take a look at the signal processing aspect and present a channel and delay estimation algorithm for asynchronous cooperative diversity in Block-Flat-Fading channel. The signal design is based on a precoding frame-based scheme with packet-wise encoding. This precoding is based on the addition of a cyclic prefix, implemented as a training sequence. The signal processing takes advantage of the known symbols offered by this cyclic prefix/training sequence and we show that it enables best synchronization and channel estimation which reaches the Cramer-Rao Bound. The BER performances are the same as synchronous MRC case, with full diversity order.

Keywords: Cooperative Diversity, Synchronization, Distributed Space-Time Coding, Cyclic Prefix, Time reverse, Rayleigh Block-Flat-Fading Channel.

1. 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 most wireless applications due to the limited size of the mobile unit. So, active users 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].
So far, most existing researches on cooperative transmission assume perfect synchronization among cooperative users. 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. Some scheme was proposed for synchronization [5], but the block symbols length was selected appropriately such that there is no inter-frame interference, as $(N+1) \gg 2L+D$ when N is the block symbols length, L is the impulse response length of the channel and D is the maximum of the relative delay between the two cooperative mobiles. This constraint on the block length was released in [6], by proposing a precoding based on the addition of a cyclic prefix which is implemented as a training sequence, in which the channel state information (CSI) is considered known at the receiver.

In the system considered, the data is transmitted in packets via two cooperative mobiles and the channel is considered Rayleigh block-flat-fading, constant for each frame and independent from frame to frame. The placement of training sequence, concentrated toward the edges of the date packet [6], is optimal for asynchronous interference [7].
In section 2 the system model is discussed and simple mathematical descriptions are given. In section 3 , the channel and delay estimation algorithm, the detection scheme are discussed. In section 4 is for the simulation results, and we conclude by section 5 .

Notation : 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. $\mathbb{E}[\ ]$ 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 of symbols, and $\mathbf{a}(n,k)$ is the k^{th} element of $\mathbf{a}(n)$. The n^{th} frame is denoted by $\mathbf{a}[n]$ and $\mathbf{a}[n,k]$ is his k^{th} element. The Complex Gaussian distribution with mean μ and covariance matrix $\mathbf{C}$ is denoted by $\mathcal{CN}(\mu, \mathbf{C})$.

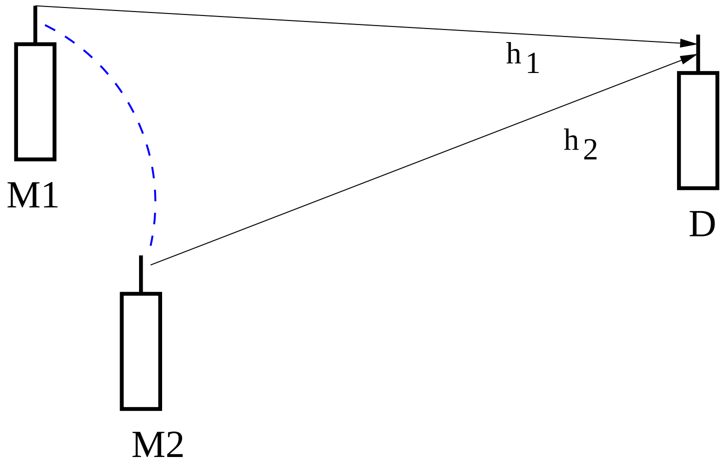

Figure 1. A virtual MISO links.

2. System Model

This paper focuses on the design of a channel and delay estimation algorithm for an asynchronous cooperative diversity system using a linear block precoding with a training sequence as cyclic prefix.
The system considered has two transmit and one receive antennas, it can be seen in Figure 1 on page 3. Since multiple transmitters cooperate to communicate with a single receiver, we refer to such links as *virtual MISO links*[1]. On a virtual MISO link, multiple transmitters will transmit the same symbols to a common destination; this joint transmission improves the signal quality and therefore, the reliability of received information at the destination node. 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 transmission system 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 traning sequences $\mathbf{d}_1$ and $\mathbf{d}_2$ in each trail of the sub-blocks respectively, it can be seen in Figure 2 on page 4. We obtain two $(N+L)\times 1$ vectors $\mathbf{s}(n)$ and $\mathbf{s}(n+1)$, which are represented by (b) in Figure 2. These vectors are represented in the relations in 1. We use the time reversal matrices $\mathbf{T}$ and $\mathbf{T}_s$ as linear precoding to obtain $\mathbf{s}_v(n)$ and $\mathbf{s}_v(n+1)$,

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[1] This is an example of VAA.

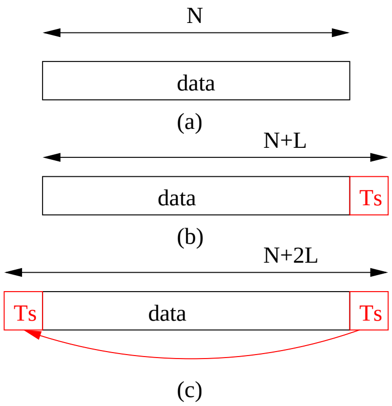

Figure 2. A Frame description.

which are represented in the relations in 2.

$$\mathbf{s}(n) = \begin{bmatrix} \mathbf{d}(n) \\ \mathbf{d}_1 \end{bmatrix} \tag{1.1}$$

$$\mathbf{s}(n+1) = \begin{bmatrix} \mathbf{d}(n+1) \\ \mathbf{d}_2 \end{bmatrix} \tag{1.2}$$

$$\mathbf{s}_v(n) = \begin{bmatrix} \mathbf{T}\mathbf{d}(n) \\ \mathbf{T}_s\mathbf{d}_1 \end{bmatrix} \tag{2.1}$$

$$\mathbf{s}_v(n+1) = \begin{bmatrix} \mathbf{T}\mathbf{d}(n+1) \\ \mathbf{T}_s\mathbf{d}_2 \end{bmatrix} \tag{2.2}$$

Our method consists in inserting, between any two successive blocks, a cyclic prefix as it can be seen in (c) in Figure 2 on page 4. 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 relations in 3. The transmission scheme is represented in Table I on page 5.

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 Figure 3 on page 5.

$$\mathbf{s}_1[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n) \\ -\left(\mathbf{F}_p\mathbf{s}_v(n+1)\right)^* \end{bmatrix} \tag{3.1}$$

$$\mathbf{s}_2[n] = \begin{bmatrix} \mathbf{F}_p\mathbf{s}(n+1) \\ \left(\mathbf{F}_p\mathbf{s}_v(n)\right)^* \end{bmatrix} \tag{3.2}$$

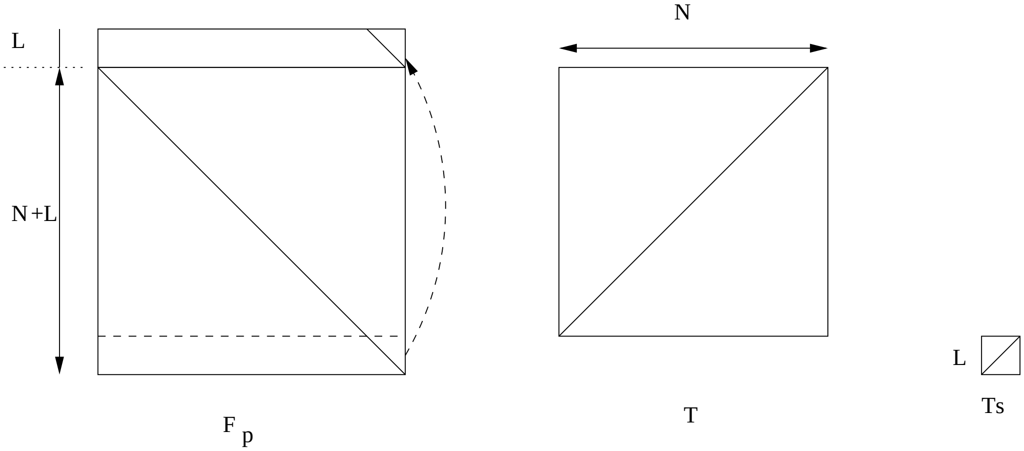

Figure 3. The precoding matrices.

Table I. Transmission scheme

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

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. The mobile target receives a summation of the signals of the two active mobiles after they travel through different paths in the channel. These channel paths induce different delays, attenuations and phase shifts to the signals cause fading in the channel. Therefore, the transmission delays and channels can be estimated efficiently from training sequences. We define τ_1 and τ_2 respectively as the arrival time of the first and the second signals. We assume without loss of generality that $\tau_1 \leq \tau_2$.

The received signal is given by

$$\mathbf{r} = \mathcal{A}(\tau)\mathbf{X}\mathbf{h} + \mathbf{b} \tag{4}$$

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

$$\mathcal{A}(\tau) = [\mathbf{O}_{2N+4L} \quad \mathbf{I}_{2N+4L} \quad \Gamma \quad \Psi] \tag{5.1}$$

$$\mathbf{X} = \begin{bmatrix} \mathbf{s}_1[n-1] & \mathbf{o}_{2N+4L} \\ \mathbf{s}_1[n] & \mathbf{o}_{2N+4L} \\ \mathbf{o}_{2N+4L} & \mathbf{s}_2[n-1] \\ \mathbf{o}_{2N+4L} & \mathbf{s}_2[n] \end{bmatrix} \tag{5.2}$$

$$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \tag{5.3}$$

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

$$\Gamma = \begin{bmatrix} \mathbf{O}_{L_\tau \times (2N+4L-L_\tau)} & \mathbf{I}_{L_\tau} \\ \mathbf{O}_{(2N+4L-L_\tau)\times(2N+4L-L_\tau)} & \mathbf{O}_{(2N+4L-L_\tau)\times(L_\tau)} \end{bmatrix} \tag{6.1}$$

$$\Psi = \begin{bmatrix} \mathbf{O}_{L_\tau \times (2N+4L-L_\tau)} & \mathbf{O}_{L_\tau} \\ \mathbf{I}_{2N+4L-L_\tau} & \mathbf{O}_{(2N+4L-L_\tau)\times(L_\tau)} \end{bmatrix} \tag{6.2}$$

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 $\Psi_{syn} = \mathbf{I}_{2N+4L}$.

3. Channel and Delay Estimation Algorithm

A maximum likelihood (ML) method for delay and channel estimation is proposed. We denote $\mathbf{ts_1}$ and $\mathbf{ts_2}$ as

$$\mathbf{ts_1} = \mathbf{T}_s \mathbf{d}_1 \tag{7.1}$$

$$\mathbf{ts_2} = \mathbf{T}_s \mathbf{d}_2 \tag{7.2}$$

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

$$\mathbf{ss_1} = \begin{bmatrix} \mathbf{d}_1(\tau+1:L) \\ -(\mathbf{ts_2})^* \end{bmatrix} \tag{8.1}$$

$$\mathbf{ss_2} = \begin{bmatrix} \mathbf{d}_2 \\ (\mathbf{ts_1}(1:L-\tau))^* \end{bmatrix} \tag{8.2}$$

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

$$\widetilde{\mathbf{h}}(\tau) = (\mathbf{S}(\tau))^\sharp \mathbf{z}(\tau) \tag{9}$$

then

$$\widehat{\tau} = \arg\min_{\tau < L} \|\mathbf{z} - \mathbf{S}(\tau)\widetilde{\mathbf{h}}(\tau)\|^2 \tag{10}$$

And

$$\widehat{\mathbf{h}} = \left(\mathbf{S}(\widehat{\tau})\right)^{\sharp} \mathbf{z}(\widehat{\tau}) \tag{11}$$

The Mean Square Error (MSE) of the channel estimation is defined by

$$MSE(h) = \mathbb{E}\left[\|\mathbf{h} - \widehat{\mathbf{h}}\|^2\right] \tag{12}$$

We studied the Cramer-Rao Bound for this model, we derive (see Appendix)

$$CRB = N_0 \ \left[\left(\mathbf{S}(\tau)\right)^H \mathbf{S}(\tau)\right]^{-1} \tag{13}$$

3.1. DETECTION SCHEME

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

$$\mathbf{r}_a = \mathbf{r}[n, L+1 : N+L+\tau] \tag{14.1}$$

$$\mathbf{r}_b = \mathbf{r}[n, N+3L+1 : 2N+3L+\tau] \tag{14.2}$$

$$\mathbf{y} = [\mathbf{r}_a^T \ \mathbf{r}_b^T] \tag{14.3}$$

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

$$\widetilde{\mathbf{d}}(n,k) = \widehat{\mathbf{h}}_1^*(n)\mathbf{y}(n,k) + \widehat{\mathbf{h}}_2(n)\mathbf{y}^*(n, l+1-k) \tag{15.1}$$

$$\widetilde{\mathbf{d}}(n+1,k) = \widehat{\mathbf{h}}_2^*(n)\mathbf{y}(n, \tau+k) - \widehat{\mathbf{h}}_1(n)\mathbf{y}^*(n, l-\tau+1-k) \tag{15.2}$$

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

4. Simulations

Figure 4 shows the MSE of the channel estimation performance, for which we derive $tr(CRB)$ for comparisons. We can remark that the CRB is reached. We derive the performance for constant delay (A) and burst transmission (B) schemes.

The BER performance of BPSK for our transmit diversity scheme is showed in Figure 5. The simulations show that the performances are the same as for the MRC scheme. The average probability of error of the MRC can be found in closed form by successive integration by parts [8]

$$P_b = \left(\frac{1-\mu}{2}\right)^L \ \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left(\frac{1+\mu}{2}\right)^l \tag{16}$$

Where $\mu = \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}$ and $\overline{\gamma}$ is the average SNR per bit per antenna. For our case $L = 2$, is presented in Figure 5 on page 9. Our scheme achieve

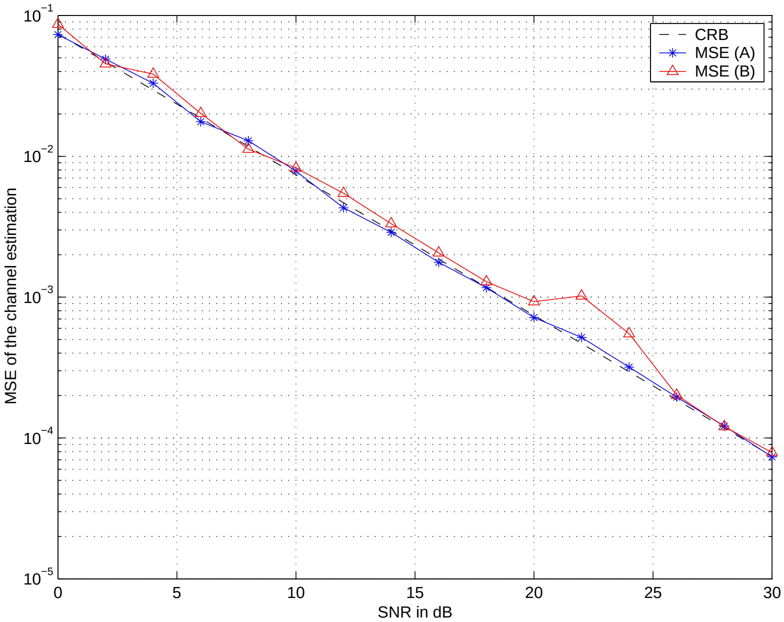

Figure 4. The performance of the channel estimation.

a full diversity order.
Each frame contains 288 symbols in which 224 for data. Therefore the cyclic prefix contain 16 symbols for training sequence. For burst transmission, each burst contain 100 frames. As showed in Figure 6 on page 10, the FER performance can attain 10^{-5} for $SNR = 30dB$, for constant delay (A) and burst transmission (B) schemes.

5. Conclusions

In this paper, we proposed a precoding frame-based scheme with packet-wise encoding, which is implemented as $CP - training$ sequence. This scheme tolerates a relative delay as large as the cyclic prefix length, and the transmission delay and channel can be estimated efficiently from training sequences with a maximum likelihood (ML) method. The MSE of the channel estimation reaches the Cramer-Rao Bound and the BER performances are the same as synchronous MRC case, with full diversity order.

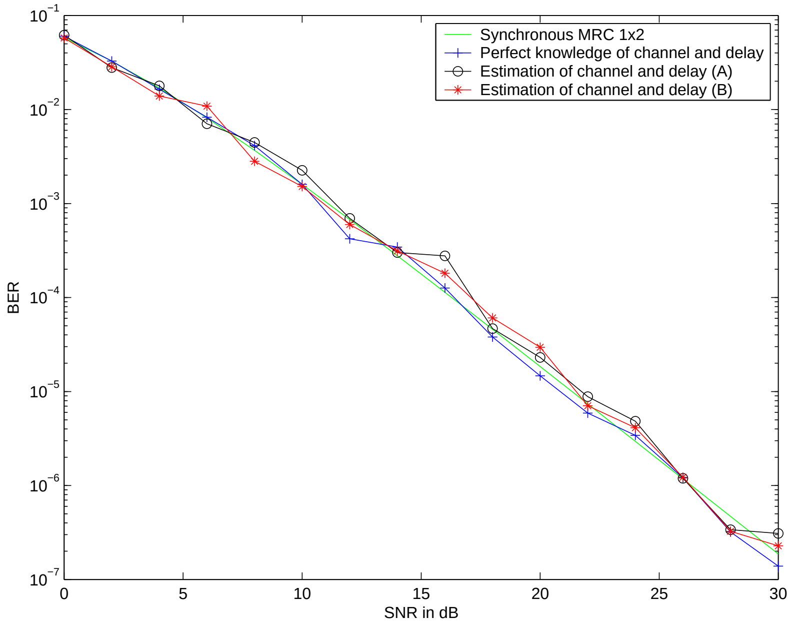

Figure 5. BER performance of the asynchronous cooperative diversity system with channel and delay estimations and perfect knowledge of delay and channel parameters.

Appendix

The complex Fisher Information Matrix is :

$$J(h) = \frac{1}{N_0} \left(\frac{\partial \mathbf{r}_s^H}{\partial h^*} \right) \left(\frac{\partial \mathbf{r}_s^H}{\partial h^*} \right)^H \tag{17}$$

Where $\mathbf{r}_s = \mathbf{S}(\tau)\mathbf{h}$ is the signal part of $\mathbf{r}$. Therefore, we have :

$$\left(\frac{\partial \mathbf{r}_s^H}{\partial h^*} \right) = \frac{\partial \mathbf{h}^H (\mathbf{S}(\tau))^H}{\partial \mathbf{h}^*} = (\mathbf{S}(\tau))^H \tag{18.1}$$

$$\left(\frac{\partial \mathbf{r}_s^H}{\partial h^*} \right)^H = \mathbf{S}(\tau) \tag{18.2}$$

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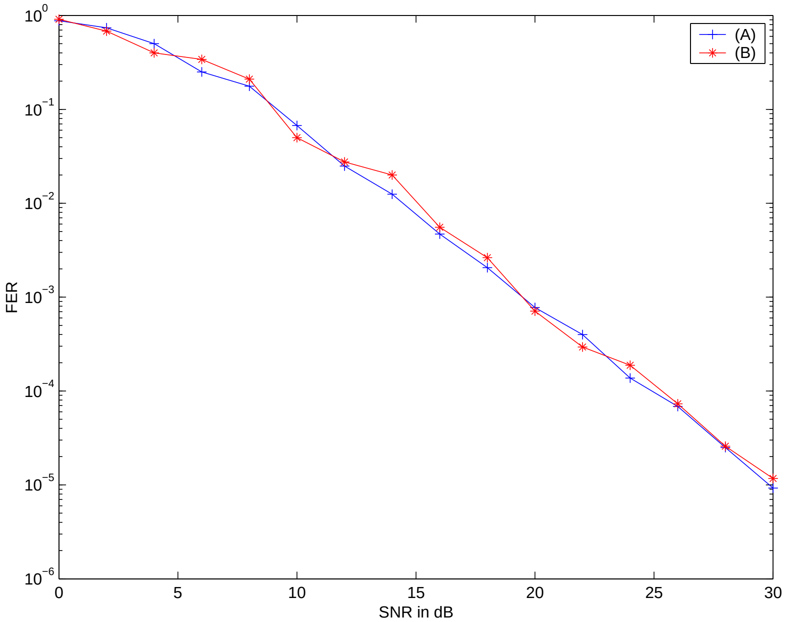

Figure 6. FER performance of the asynchronous cooperative diversity system with channel and delay estimations.

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Author's Vitae

Kamel Tourki was born in Antibes, France, in December 1977. He received the Engineering degree in telecommunications from the Ecole Nationale d'ingnieurs de Tunis, Tunisia, in 2003; and the Master degree in Signal Processing and Digital Communications from the University of Nice (UNSA), in 2004. Since October 2004, he is pursuing his Ph.D. thesis in signal processing at I3S Laboratory under the supervision of Prof. Luc Deneire. His general research interests include signal processing for wireless communication systems, space-time coding, multiple antenna techniques, and cooperative diversity.

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