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# Asynchronous Space-Time Cooperative Communications in Sensor and Robotic Networks

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***Abstract* --- For wireless sensor networks or robotic networks, cooperative communications encoded with space-time block code (STBC) are desirable to improve their energy efficiency and reliability. However, existing STBC-encoded cooperative communication schemes usually require perfect synchronization among the transmitting sensors or robots, which is difficult and even impossible to achieve in practice. In this paper, we address this problem by developing a new receiving scheme for Alamouti's STBC cooperative transmission where two asynchronous transmitting sensors or robots are employed. The new scheme uses a linear-prediction-based channel equalization technique to mitigate the effect of asynchronism. The performance of the new scheme is analyzed and demonstrated by simulations.**

***Index Terms*** *– STBC, asynchronous cooperative transmission, DSSS, linear prediction, wireless sensor network.*

## I. INTRODUCTION

It is a common belief that in the near future, many wireless sensors or robots will be deployed in an area to form sensor or robotic networks for a wide variety of applications including monitoring and surveillance. Each sensor or robot is powered by battery and is supposed to work for a relatively long time after deployment. In such cases, transmission energy efficiency and reliability becomes important because wireless transceivers usually consume a major portion of battery energy [7]. This is true considering the severe channel fading and node failure in hostile environment.

Space-time coding and processing are helpful for enhancing transmission energy efficiency and reliability [6]. In particular, space-time block codes (STBC) have attracted great attention because of their affordable linear complexity [1][2]. Among the numerous STBC schemes, Alamouti's STBC [1] is probably the most famous one due to its simplicity. However, space-time techniques are traditionally based on antenna arrays. For the sensors and robots that have no antenna arrays, STBC may still be used with cooperative transmission schemes [4][5][8] where multiple sensors or robots work cooperatively to form a virtual antenna array. Besides saving energy, STBC can also enhance fault tolerance [6] and bandwidth efficiency [8].

So far, most existing researches on cooperative transmission assume perfect synchronization among the cooperative sensors or robots, which means that the transmitting nodes' timing, carrier frequency and propagation delay are identical [8]. Unfortunately, it is difficult, and in most cases impossible, to achieve perfect synchronization among the distributed sensors or robots. This is even more a reality when low-cost, small-sized transmitters are used, such as tiny sensors. Synchronization is difficult because parameters of electronic components may be drifting and because handshaking among transmitters is usually made as infrequently as possible to save energy and bandwidth. More important, delay synchronization with respect to two or more receivers simultaneously is often impossible.

The lack of perfect delay synchronization among the cooperative transmitting sensors or robots destroys the required STBC signal structure, and prevents the transmitted symbols from being successfully detected at the receiver with the normal STBC decoder. Furthermore, it brings another side effect, i.e. channel becomes dispersive. Due to the transmitting/receiving pulse shaping filters, if the sampling time instants are not ideal, inter-symbol interference (ISI) is introduced even in flat fading environment.

In this paper, based on linear prediction, we develop a new receiving algorithm to detect the transmitted symbols for the cooperative STBC-encoded transmission when significant asynchronism exists among the cooperative transmitters. The new algorithm assumes that the receiver knows the channel and relative delays among transmitting sensors, which can be easily achieved by that the transmitters send training sequences to the receiver. Besides, as DSSS is a widely selected transmission scheme for sensor and robotic networks, we also incorporate the new algorithm into DSSS systems where the cooperative transmission is used when the transmitters are asynchronous.

The paper is organized as follows. The encoding and decoding schemes of the traditional synchronous cooperative Alamouti STBC are described in Section II. In section III, we provide the linear prediction method to solve the asynchronism problem. In section IV, we extend the proposed algorithm into the DSSS system. Simulations are given in Section V, and conclusions are provided in Section VI. Throughout this paper, we use the operator $(.)^*$, $(.)^T$ , $(.)^H$ and $\|.\|$ to denote conjugate, transpose, complex conjugate transpose, and Frobenius norm, respectively. Lower-case italic symbols, low-case bold symbols, and upper-case bold symbols denote scalar values, vectors, and matrices, respectively.

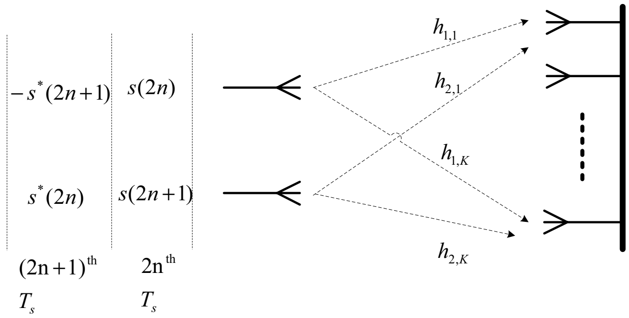


Fig. 1 Cooperative Alamouti STBC transmission scheme.

## II. SYNCHRONIZED COOPERATIVE TRANSMISSION

### A. *Synchronous Alamouti's STBC encoding scheme*

Cooperative Alamouti's STBC uses two perfectly synchronized transmitting sensors and a receiver that has $K$ antennas. Before cooperative transmission, both of the transmitting sensors possess the symbols to be transmitted. This could be done by either of the followings: (i) Both of them receive the same symbols from information sources or hear the same symbols transmitted by another sensor; (ii) One of the sensors transmits the symbols to the others. In the encoding scheme shown in the Fig.1, two successive symbols $s(2n)$ and $s(2n+1)$ are transmitted simultaneously from transmitting sensors 1 and 2, respectively, during the even $(2n)^{th}$ symbol period $2nT_s$. Then symbols $-s^*(2n+1)$ and $s^*(2n)$ are transmitted by sensors 1 and 2, respectively, during the next odd $(2n+1)^{th}$ symbol period $(2n+1)T_s$.

The channels are assumed to be quasi-static and flat fading. The channel gains are modelled as samples of independent complex Gaussian random variables with variance 0.5 per real dimension. Let the two $1\times K$ channel vectors be $\mathbf{h}_1=[h_{1,1}\ h_{1,2,\ldots}\ h_{1,K}]^T$ and $\mathbf{h}_2=[h_{2,1}\ h_{2,2,\ldots}\ h_{2,K}]^T$, respectively. The signals received at the receiving antenna array over the two consecutive periods are $\mathbf{y}(2n)$ and $\mathbf{y}(2n+1)$, respectively. It follows that

$$\mathbf{y}(2n)=[\mathbf{h}_1\ \mathbf{h}_2]\begin{bmatrix} s(2n) \\ s(2n+1) \end{bmatrix}+\mathbf{v}(2n), \tag{1}$$

$$\mathbf{y}(2n+1)=[\mathbf{h}_1\ \mathbf{h}_2]\begin{bmatrix} -s^*(2n+1) \\ s^*(2n) \end{bmatrix}+\mathbf{v}(2n+1), \tag{2}$$

where $\mathbf{v}(2n)$ and $\mathbf{v}(2n+1)$ are $K\times 1$ noise vectors whose elements are uncorrelated, zero mean circularly symmetric complex Gaussian random variable with variance $\sigma^2$.

### B. *Synchronous Alamouti's STBC decoding scheme*

Based on (1) and (2), the multi-antenna receiver forms a signal vector $\mathbf{u}(2n)$ according to

$$\mathbf{u}(2n)=\begin{bmatrix} \mathbf{y}(2n) \\ \mathbf{y}^*(2n+1) \end{bmatrix}. \tag{3}$$

It follows that $\mathbf{u}(2n)$ may be expressed as

$$\mathbf{u}(2n)=\begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 \\ \mathbf{h}_2^* & -\mathbf{h}_1^* \end{bmatrix}\begin{bmatrix} s(2n) \\ s(2n+1) \end{bmatrix}+\begin{bmatrix} \mathbf{v}(2n) \\ \mathbf{v}^*(2n+1) \end{bmatrix} = \mathbf{H}_{eff}\mathbf{s}(2n)+\mathbf{w}(2n). \tag{4}$$

Note that $\mathbf{H}_{eff}$ is orthogonal irrespective of the channel realization. If $\mathbf{z}(2n)=\mathbf{H}_{eff}^H\mathbf{u}(2n)$, we get

$$\mathbf{z}(2n)=(\|\mathbf{h}_1\|^2+\|\mathbf{h}_2\|^2)\mathbf{s}(2n)+\tilde{\mathbf{w}}(2n). \tag{5}$$

Then, the symbol vector $\mathbf{s}(2n)$ can be detected by sending the resulting $\mathbf{z}(2n)$ from (5) to a maximum likelihood detector.

### C. *Average receiving signal-to-noise ratio analysis*

The average signal-to-noise ratio (SNR) at the input to the symbol detector is the most and best understood performance measure of a digital communication system subject to fading impairment because it is directly related to the symbol error rate (SER). In the paper, we adopt it as the performance measure. From (5), without loss of generality, the symbols are assumed to be i.i.d random variable with unit variance, then the signal power in $\mathbf{z}(2n)$ is $(\|\mathbf{h}_1\|^2+\|\mathbf{h}_2\|^2)^2\mathbf{I}_2$, and the noise power is $E\{\tilde{\mathbf{w}}(2n)\tilde{\mathbf{w}}(2n)^H\}=\sigma^2(\|\mathbf{h}_1\|^2+\|\mathbf{h}_2\|^2)\mathbf{I}_2$, where $\mathbf{I}_2$ is a 2×2 identity matrix. Hence the effective average SNR for detecting either $s(n)$ or $s(n+1)$ is

$$SNR_{syn}=(\|\mathbf{h}_1\|^2+\|\mathbf{h}_2\|^2)/\sigma^2. \tag{6}$$

From (6), we can see that the cooperative Alamouti's STBC transmission scheme achieves full $2K$ diversity gain because of all channel coefficients are utilized.

## III. ASYNCHRONOUS COOPERATIVE TRANSMISSION

In section II, we see that Alamouti's STBC scheme requires perfect synchronization among the cooperative transmitters to achieve the optimal diversity gain specified in (6). However, that is just the ideal case. In practice, perfect synchronization is very hard, even impossible to realize in distributed systems because low cost implementation of the sensors may make their timing and frequency slightly different, hence may cause mismatch in the long run. The major synchronization problem is reflected in the delays of their signals when reaching at the receiver. Propagation delays are usually unknown to the transmitters, while their transmission time may also be different.

The imperfect delay synchronization will destroy the coding structure and make the receiver unable to detect the original signal successfully. For example, if the relative delay $d$ between the two transmitting sensor is a non-zero even integer value, then when the first sensor transmits the symbol $s(2n)$, the second sensor transmits the symbol $s(2n+d+1)$ instead of $s(2n+1)$. Similarly in the next symbol period, the first transmitter transmits the symbol $-s^*(2n+1)$ while the second sensor transmits symbol $s^*(2n+d)$. Because four symbols instead of two are involved in the two consecutive received signal vectors, the orthogonal channel matrix $\mathbf{H}_{eff}$ provided by the special signal structure in (4) is totally destroyed and thus the decoding procedure in Section II-B can not be directly applied.

In this section, we propose a new receiving scheme that can tolerate the delay asynchronism. This scheme first constructs special received signal vectors, then uses linear-prediction-based equalization technique to remove the asynchronous effect, and finally, applies the procedure similar to traditional synchronized STBC decoding scheme to estimate the transmitted symbols.

*A. Construct sample vectors for even delay*

We let $d_i$ denote the delay from the transmitting sensor $i$ to the receiver, where $i\in\{1,2\}$ is the index of the transmitting sensor. To save the space, in this paper, we consider only the case when the relative delay is even, i.e., $d_1$-$d_2$ = (0, ±2, ±4, ±6,…) because the case of the relative delay being odd integers can be similarly treated. Here, in order to detect a symbol at the receiver, such as $s(2n)$, we construct appropriate signal vectors as follows.

In the $(2n)^{th}$ symbol period, the first transmitting sensor transmits the symbol $s(2n)$, whereas the second sensor transmits the symbol $s(2n+d_1-d_2+1)$. The received signal vector $\mathbf{y}(2n+d_1)$ can be therein expressed by

$$\mathbf{y}(2n+d_1)=[\mathbf{h}_1\ \mathbf{h}_2]\begin{bmatrix} s(2n) \\ s(2n+d_1-d_2+1)\end{bmatrix}+\mathbf{v}(2n+d_1). \qquad (7)$$

On the other hand, in the $(2n+d_1-d_2+1)^{th}$ symbol period, the first transmitting sensor transmits the symbol $-s^*(2n+d_1-d_2+1)$, while the second sensor transmits the symbol $s^*(2n+2d_1-2d_2)$. The received signal vector $\mathbf{y}(2n+2d_1-d_2+1)$ can be similarly expressed by

$$\mathbf{y}(2n+2d_1-d_2+1)=[\mathbf{h}_1\ \mathbf{h}_2]\begin{bmatrix} -s^*(2n+d_1-d_2+1) \\ s^*(2n+2d_1-2d_2)\end{bmatrix} +\mathbf{v}(2n+2d_1-d_2+1). \qquad (8)$$

Examining (7) and (8), we can find that the symbol $s(2n+d_1-d_2+1)$ is contained in both the signal vectors $\mathbf{y}(2n+d_1)$ and $\mathbf{y}(2n+2d_1-d_2+1)$, which leaves us space to use some equalization technique to estimate $s(2n)$ by cancelling $s(2n+d_1-d_2+1)$ from $\mathbf{y}(2n+d_1)$.

This can be realized by linear prediction. To prepare the linear prediction, the receiver forms a signal vector $\mathbf{y}_1(2n)$ according to

$$\mathbf{y}_1(2n)=\begin{bmatrix} \mathbf{y}(2n+d_1) \\ \mathbf{y}^*(2n+2d_1-d_2+1)\end{bmatrix}, \qquad (9)$$

It follows from (7) and (8) that $\mathbf{y}_1(2n)$ may be expressed as

$$\mathbf{y}_1(2n)=\begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & 0 \\ 0 & -\mathbf{h}_1^* & \mathbf{h}_2^*\end{bmatrix}\begin{bmatrix} s(2n) \\ s(2n+d_1-d_2+1) \\ s(2n+2d_1-2d_2)\end{bmatrix} +\begin{bmatrix} \mathbf{v}(2n+d_1) \\ \mathbf{v}^*(2n+2d_1-d_2+1)\end{bmatrix}. \qquad (10)$$

*B. Linear prediction algorithm*

Linear prediction (LP) is a commonly used mathematical operation where current values of a digital signal are estimated as linear functions of previous samples or future samples. In our case, we use a linear prediction matrix $\mathbf{P}_1$ to estimate the symbol $s(2n)$ from the signal vector $\mathbf{y}_1(2n)$, which gives

$$\mathbf{e}_1(2n)=[\mathbf{I}\quad -\mathbf{P}_1]\mathbf{y}_1(2n), \qquad (11)$$

where $\mathbf{I}$ is a $K\times K$ identity matrix. Equation (11) denotes the prediction error between the symbol $s(2n)$ and the linear combination of the past symbols. Substituting (10) into (11), we have

$$\mathbf{e}_1(2n)=[\mathbf{I}\quad -\mathbf{P}_1]\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}\begin{bmatrix} s(2n) \\ \tilde{\mathbf{s}}_1(2n)\end{bmatrix}+[\mathbf{I}\quad -\mathbf{P}_1]\mathbf{v}_1(2n), \qquad (12)$$

where we defined submatrices $\mathbf{H}_1=[\mathbf{h}_2\ \mathbf{0}]$, $\mathbf{H}_2=[\mathbf{h}_1^*\ \mathbf{h}_2^*]$, and vectors $\tilde{\mathbf{s}}_1(2n)=[s(2n+d_1-d_2+1), s(2n+2d_1-2d_2)]^T$ and $\mathbf{v}_1(2n)=[\mathbf{v}(2n+d_1), \mathbf{v}^*(2n+2d_1-d_2+1)]^T$, respectively.

The optimal linear prediction matrix $\mathbf{P}_1$ can be found by minimizing the power of prediction error $\mathbf{e}_1(2n)$ expressed in (12) by

$$\min\left\{\mathrm{E}\|\mathbf{e}_1(2n)\|^2\right\}=\min\left\{\mathrm{tr}(\mathrm{E}[\mathbf{e}_1(2n)\mathbf{e}_1^H(2n)])\right\}$$
$$=\min\left\{\mathrm{tr}\left([\mathbf{I}\quad -\mathbf{P}_1]E[\mathbf{y}_1(2n)\mathbf{y}_1^H(2n)]\begin{bmatrix}\mathbf{I} \\ -\mathbf{P}_1^H\end{bmatrix}\right)\right\}$$
$$=\min\left\{\mathrm{tr}\left([\mathbf{I}\quad -\mathbf{P}_1]\mathbf{R}_y\begin{bmatrix}\mathbf{I} \\ -\mathbf{P}_1^H\end{bmatrix}\right)\right\}, \qquad (13)$$

where $\mathbf{R}_y$ is the received signal correlation matrix

$$\mathbf{R}_y=\mathrm{E}[\mathbf{y}_1(2n)\mathbf{y}_1^H(2n)]. \qquad (14)$$

From (10) and (14), $\mathbf{R}_y$ can be further represented as

$$\mathbf{R}_y=\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}\mathrm{E}\left\{\begin{bmatrix} s(2n) \\ \tilde{\mathbf{s}}_1(2n)\end{bmatrix}\begin{bmatrix} s(2n) \\ \tilde{\mathbf{s}}_1(2n)\end{bmatrix}^H\right\}\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}^H$$
$$=\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}^H. \qquad (15)$$

Plugging the expression of $\mathbf{R}_y$ in (15) back into (13), the minimization problem (13) then becomes the determination of $\mathbf{P}_1$ to minimize the trace of the following matrix

$$[\mathbf{I}\quad -\mathbf{P}_1]\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}\begin{bmatrix} \mathbf{h}_1 & \mathbf{H}_1 \\ 0 & \mathbf{H}_2\end{bmatrix}^H\begin{bmatrix}\mathbf{I} \\ -\mathbf{P}_1^H\end{bmatrix}. \qquad (16)$$

By taking the derivative of trace of (16) with respect to $\mathbf{P}_1$ and making it equal to zero, we have

$$\mathbf{H}_1-\overline{\mathbf{P}}_1\mathbf{H}_2=0,\quad \text{or}\quad \overline{\mathbf{P}}_1=\mathbf{H}_1\mathbf{H}_2^+, \qquad (17)$$

where $(.)^+$ denotes matrix pseudo-inverse. From (12), when the prediction matrix $\mathbf{P}_1=\overline{\mathbf{P}}_1$, the minimum prediction error will be

$$\overline{\mathbf{e}}_1(2n)=[\mathbf{I}\quad -\overline{\mathbf{P}}_1]\mathbf{y}(2n)$$
$$=\mathbf{h}_1 s(2n)+[\mathbf{I}\quad -\overline{\mathbf{P}}_1]\mathbf{v}_1(2n). \qquad (18)$$

The symbol $s(2n)$ can be directly estimated by (18). However, if only $\overline{\mathbf{e}}_1(2n)$ were used, the utilized diversity gain would be only from the first transmitting sensor by the channel vector $\mathbf{h}_1$. The gain from the second transmitting sensor (by channel vector $\mathbf{h}_2$) would be lost. Therefore, in order to achieve full diversity, we need also consider the contribution from the second transmitter.

To utilize channel vector $\mathbf{h}_2$, we can construct another received signal vector which also contains the symbol $s(2n)$, i.e.,

$$\mathbf{y}_2(2n) = \begin{bmatrix} \mathbf{y}(2n+2d_2-d_1) \\ \mathbf{y}^*(2n+d_2+1) \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & 0 \\ 0 & -\mathbf{h}_1^* & \mathbf{h}_2^* \end{bmatrix} \begin{bmatrix} s(2n+2d_2-2d_1) \\ s(2n+d_2-d_1+1) \\ s(2n) \end{bmatrix} + \begin{bmatrix} \mathbf{v}(2n+2d_2-d_1) \\ \mathbf{v}^*(2n+2d_2+1) \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{H}_3 & 0 \\ \mathbf{H}_4 & \mathbf{h}_2^* \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{s}}_2(2n) \\ s(2n) \end{bmatrix} + \mathbf{v}_2(2n) . \quad (19)$$

Based on (19), a new linear prediction problem can be used,

$$\mathbf{e}_2(2n) = [-\mathbf{P}_2 \quad \mathbf{I}]\mathbf{y}_2(2n) , \quad (20)$$

We can perform the similar steps as (12)-(17) to get the optimal $\overline{\mathbf{P}}_2$ and prediction error $\overline{\mathbf{e}}_2(2n)$ as

$$\overline{\mathbf{P}}_2 = \mathbf{H}_4\mathbf{H}_3^+ , \quad (21)$$

$$\overline{\mathbf{e}}_2(2n) = \mathbf{h}_2^* s(2n) + [-\overline{\mathbf{P}}_2 \quad \mathbf{I}]\mathbf{v}_2(2n) . \quad (22)$$

Combining the results of (18) and (22), the overall prediction error is

$$\overline{\mathbf{e}}(2n) = \begin{bmatrix} \overline{\mathbf{e}}_1(2n) \\ \overline{\mathbf{e}}_2(2n) \end{bmatrix} = \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2^* \end{bmatrix} s(2n) + \begin{bmatrix} [\mathbf{I} \quad -\overline{\mathbf{P}}_1] & 0 \\ 0 & [-\overline{\mathbf{P}}_2 \quad \mathbf{I}] \end{bmatrix} \begin{bmatrix} \mathbf{v}_1(2n) \\ \mathbf{v}_2(2n) \end{bmatrix} . \quad (23)$$

With the knowledge of channels, the symbol $s(2n)$ can be estimated as

$$\hat{s}(2n) = [\mathbf{h}_1^H \quad \mathbf{h}_2^T]\overline{\mathbf{e}}(2n) = (\|\mathbf{h}_1\|^2 + \|\mathbf{h}_2\|^2)s(2n) + \tilde{\mathbf{v}}(2n) . \quad (24)$$

The above procedure is for estimating the even numbered symbols $s(2n)$. For odd numbered symbols $s(2n+1)$, we can get similar results by using the steps similar to getting $s(2n)$.

*C. Average SNR analysis*

Under the same assumptions that we made in Section II-C, from (23) and (24), the signal power in (24) is equal to $(\|\mathbf{h}_1\|^2 + \|\mathbf{h}_2\|^2)^2$, and the noise power, i.e., $\mathrm{E}\{\tilde{\mathbf{v}}(2n)\tilde{\mathbf{v}}(2n)^H\}$, is equal to

$$\sigma^2(\|\mathbf{h}_1\|^2 + \|\mathbf{h}_2\|^2 + \mathbf{h}_1^H\overline{\mathbf{P}}_1\overline{\mathbf{P}}_1^H\mathbf{h}_1 + \mathbf{h}_2^T\overline{\mathbf{P}}_2\overline{\mathbf{P}}_2^H\mathbf{h}_2^*) . \quad (25)$$

The resulting average SNR at the input to the decoder for the asynchronous cooperative transmission then becomes

$$SNR_{asyn} = \frac{(\|\mathbf{h}_1\|^2 + \|\mathbf{h}_2\|^2)^2}{\sigma^2(\|\mathbf{h}_1\|^2 + \|\mathbf{h}_2\|^2 + \mathbf{h}_1^H\overline{\mathbf{P}}_1\overline{\mathbf{P}}_1^H\mathbf{h}_1 + \mathbf{h}_2^T\overline{\mathbf{P}}_2\overline{\mathbf{P}}_2^H\mathbf{h}_2^*)} . \quad (26)$$

Since the matrices $\overline{\mathbf{P}}_1\overline{\mathbf{P}}_1^H$ and $\overline{\mathbf{P}}_2\overline{\mathbf{P}}_2^H$ are positive definite, we have $\mathbf{h}_1^H\overline{\mathbf{P}}_1\overline{\mathbf{P}}_1^H\mathbf{h}_1 > 0$ and $\mathbf{h}_2^T\overline{\mathbf{P}}_2\overline{\mathbf{P}}_2^H\mathbf{h}_2^* > 0$. Comparing (25) and (6), we see that $SNR_{asyn} < SNR_{syn}$ and the proposed decoding scheme makes the asynchronous cooperatively transmitted symbols decodable with the price of lowering average SNR, which causes the symbol error rate higher than that for the synchronized transmission in Section II. The degree of degradation of symbol error rate is shown in the simulations.

*D. Analysis of dispersive channel case*

Communication signals are typically pulse-shaped with, e.g., raised cosine filters. The sampling time at the receivers should be optimal, e.g., at exactly integer number of symbol intervals, such as $t=nT_s$, in order to avoid inter-symbol interference. If this optimal condition is satisfied, then the channel has a single tap only in flat fading environment. This is called timing phase synchronization. However, if the two transmitted signals are with different delays, then there is no such optimal sampling time instant. In this case, a negative effect is that the channel becomes multi-tap instead of single-tap, which we call dispersive channel. Dispersive channel means inter-symbol interference. This is another side-effect of asynchronism among the cooperative transmitters because dispersive channels are created even in flat-fading environment. Besides degrading performance, dispersive channel also prevents the application of traditional STBC decoders.

In this section we take the dispersive channel into consideration, where the integer (in the unit of one symbol interval) part of the delay asynchronism contributes to delay $d_1$ and $d_1$ shown in Section III A-C, whereas the fractional part contributes to making channel dispersive. In this case, each channel consists of more than one tap, which induces ISI. We have to use a multi-tap channel model.

Considering the case with 2 transmitters and $K$ receiving antennas, the channels are $h_{ij}(m)$, $m$=0,…,L, where L is the total number of taps, $i$ denotes the $i^{\text{th}}$ transmitter, and $j$ denotes the $j^{\text{th}}$ receiver. With respect to this channel model, however, there is a simplification we can make. The receiver can in fact synchronize to one of the transmitters. For example, by using the optimal sampling time instants corresponding to the first transmitters, channel $h_{1j}(m)$ can be made single-tap, just as in Section II. The channels of the second transmitter, i.e., $h_{2j}(m)$, are still dispersive. Then we can develop similar procedures as described in Section III.A-C to estimate the transmitted symbols. The only difference is that we have to make sure the prediction matrix is non-singular which means we need to have larger $K$. Details can be found in [9].

## IV. Extension to DSSS System

Single-user DSSS transmissions have wide applications in practice, e.g., in ad hoc networks, wireless LAN, and sensor networks, where the spreading is primarily used for mitigating noise and other unknown interference. As an example, for the sensor networks working in the public ISM frequency band, each node can be interfered by many other devices which occupy the same band.

Traditionally, because only a single user with a single spreading code is used, MAI (Multi-access interference) is usually not a concern. However, when STBC-encoded cooperative transmission is used, we have effectively two or more transmitters (users). If the cooperative transmitters are not perfectly synchronized, then cross-interference among them can be created, which has a similar negative effect as MAI. In this case, we require that the new receiving algorithm can mitigate MAI as well while conducting symbol estimation. This objective can be successfully realized by our proposed method.

Let the input symbol sequence be $b(k)$, the spreading coding be $c(g)$. Then the spreaded symbol sequence is

$$s(kG+g) = b(k)c(g), \quad k = 0,1,\ldots, \quad g = 0,\ldots,G-1 \tag{27}$$

Here, we assume that the spreading code has length $G$.

Compared with the symbol sequence in Section II and III, in this section the spreaded symbol sequence is $s(n)=s(kG+g)$. In case of perfect synchronization and flat-fading, we can perform traditional transmission and STBC decoding, which gives the estimated symbol $s(n)$. Then we can despread $s(n)$ to obtain $b(k)$ as

$$\hat{b}(k) = \frac{1}{G}\sum_{g=0}^{G-1} s(kG+g)c^*(g). \tag{28}$$

In this case, both spatial diversity and the spreading gain are optimally exploited. In particular, there is no extra interference due to the added STBC encoding/decoding procedure.

The situation becomes more complex when the two transmitters can not be synchronized. However, if we consider the spreaded sequence $s(n)$ only, then it is obvious that the algorithm in Section III can still be used to estimate $s(n)$, which removes the effect of delay and dispersive channel. Then the spreading/despreading can be conducted just as synchronized case (27)-(28). For details, please refer to [10].

## V. SIMULATIONS

In Fig. 2 and Fig. 3 we compared our new asynchronous transmission scheme with Alamouti scheme in both synchronous and asynchronous cases where symbol error rate (SER) was used as criteria. Each run contained 100 QPSK symbols, whereas each curve is the average result of 1000 runs. Channel coefficients were randomly generated over every frame. Relative transmission delay was set to $d_1$-$d_2$=2. Fig. 2 is for single-tap channel while Fig. 3 is for two-tap channels. They both use 2 receiving antennas. We can see that in both cases asynchronism prevents the traditional STBC decoding scheme from working, but our method can still correctly estimate symbols with reasonable SER. In Fig. 4 and Fig. 5 we consider DSSS transmission with processing gain $G$=15. Fig. 4 is for single-tap and Fig. 5 is for 2-tap channels. Again, our proposed algorithm has significant performance improvement.

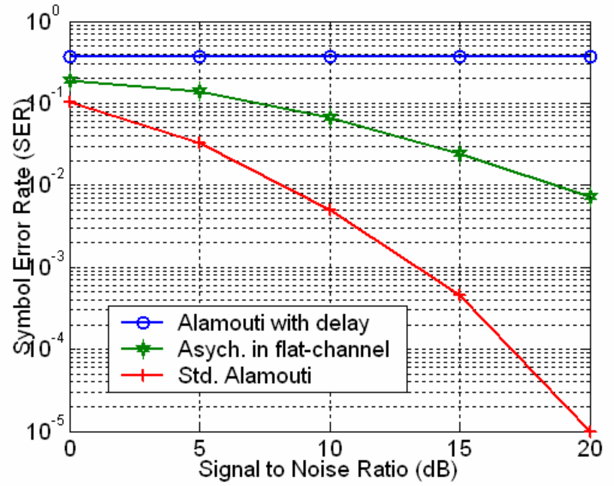


Fig. 2 Comparison between the traditional STBC and the proposed method with single-tap channels. o: traditional STBC with asynchronous transmitters. *: proposed method with asynchronous transmitters. +: traditional STBC with ideal synchronous transmitters.

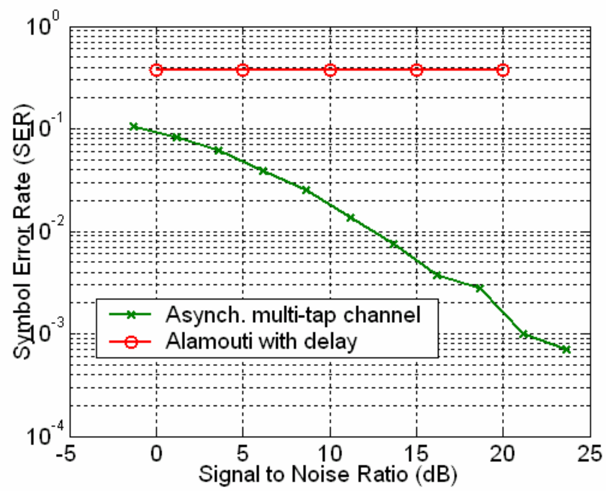


Fig. 3 Comparison between the traditional STBC and the proposed method with multi-tap channels. o: traditional STBC with asynchronous transmitters. *: proposed method with asynchronous transmitters.

## VI. CONCLUSIONS

In this paper, a new receiving algorithm is developed for STBC-encoded cooperative transmissions to resolve the problem of asynchronism among the transmitters. A linear-prediction-based equalization technique is used to mitigate delay asynchronism and channel dispersion. The proposed algorithm is useful for cooperative wireless sensor networks or robotic networks to enhance transmission energy efficiency and reliability.

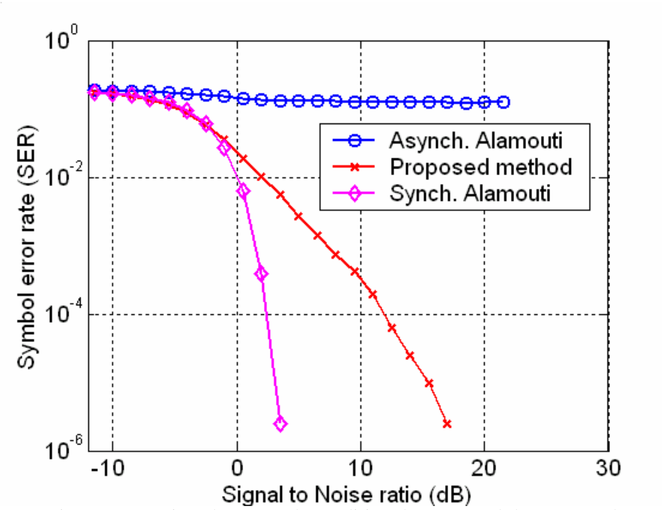


Fig. 4 Comparison between the traditional STBC and the proposed method in DSSS with single-tap channels. o: traditional STBC+DSSS with asynchronous transmitters. +: proposed method with asynchronous transmitters.

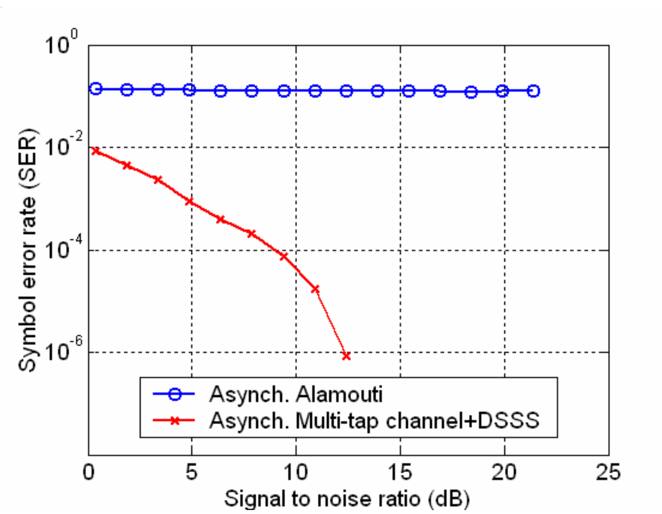


Fig.5 Comparison between the traditional STBC and the proposed method in DSSS with multi-tap channels. o: traditional STBC+DSSS with asynchronous transmitters. +: proposed method with asynchronous transmitters.

## REFERENCES


[1] S. M. Alamouti, "A simple transmitter diversity scheme for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, pp. 1451-1458, Oct.1998.

[2] V. Tarokh, H. Jafarkhani and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 45, no. 7, pp. 1456-1467, July 1999.

[3] X. Li, "Space-time coded multi-transmission among distributed transmitters without perfect synchronization," *IEEE Signal Process. Lett.*, vol. 11, no. 12, pp. 948-951, Dec. 2004.

[4] X. Li, M. Chen and W. Liu, "Application of STBC-encoded cooperative transmissions in wireless sensor networks," *IEEE Signal Process. Lett.*, vol. 12, no. 2, pp. 134-137, Feb. 2005.

[5] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperative diversity, Part I, II," *IEEE Trans. Commun*., vol. 51, no. 11, pp. 1927-1948, Nov. 2003.

[6] X. Li and N. E. Wu, "Power efficient wireless sensor networks with distributed transmission-induced space spreading," in *Proceedings of the 37th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, Nov. 2003.

[7] I. F. Akyildiz, etc, "A survey on sensor networks," *IEEE Commun*. Mag., vol. 40, no. 8, pp. 102-114, Aug. 2002.

[8] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415-2425, Oct. 2003.

[9] F. Ng, "*Asynchronous transmission with space-time block codes*," MS thesis, Binghamton University, Jan. 2005

[10] J.-T. Hwu, "*Asynchronous space-time direct-sequence spread-spectrum transmissions for ad hoc sensor networks*," MS thesis, Binghamton University, Mar. 2005.