Space–Time Coded Multi-Transmission Among Distributed Transmitters Without Perfect Synchronization

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***Abstract*—For mobile users without antenna arrays, transmission diversity can be achieved with cooperative space–time encoded transmissions. However, a challenge is the lack of perfect synchronization on delay, timing and carrier frequency of distributed transmitters, which destroys the required space–time signal structure. In this letter, a new transmission scheme is proposed which employs distributed space–time block codes to achieve full diversity while tolerating imperfect synchronization. It is promising in distributed wireless networks such as sensor networks both to enhance transmission energy efficiency and to reduce synchronization cost.**

***Index Terms*—Distributed networks, sensor networks, STBC, synchronization, transmission diversity.**

I. Introduction

SPACE-TIME coding and processing are powerful techniques for transmission diversity, among which space–time block codes (STBC) [1], [2] are especially promising because of their low computational complexity. Since diversity enhances transmission energy efficiency in a fading environment, computationally efficient STBC would be desirable for mobile users in wireless networks such as *ad hoc* and sensor networks where energy efficiency is an important criterion. However, traditional STBC require physical antenna arrays that are hardly available in small-sized mobile devices. This is why STBC were proposed only for base stations [2].

In order to take the benefits of STBC on transmission energy efficiency and robustness, recently there has been great interest to extend STBC into distributed wireless networks, which is shown possible by exploiting the cooperating capability of mobile users. Ideas of cooperative transmission (without STBC encoding) have been proposed in cellular networks for cooperative diversity [3] and in sensor networks for energy efficiency and fault tolerance [4]. Then STBC have been naturally employed for improved bandwidth efficiency besides the targeted diversity benefits [5], [6].

So far, most existing researches on cooperative transmission assume perfect synchronization among cooperative users, which means that the users' timing, carrier frequency and propagation delay are identical [3], [4]. Unfortunately, it is difficult, and in most cases impossible, to achieve perfect synchronization among distributed transmitters. 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 impossible, as explained in Section II-A.

The lack of perfect delay synchronization brings another side effect, i.e., channels become dispersive. Due to the transmitting/receiving pulse shaping filters, if the sampling time instants are not ideal, intersymbol interference is introduced even in flat fading environment.

We have addressed partially the problem of imperfect synchronization in [4] and [6]. However, [4] bypasses this problem by assigning each transmitter a unique time slot, and thus no STBC are applied. Although [6] addresses delay asynchronism, it is for two transmitters only without considering timing/frequency asynchronism nor dispersive channel.

In this letter, with a focus on wireless sensor networks, we address both imperfect synchronization and channel dispersion in distributed STBC-encoded transmission. The major contribution is the development of a new STBC-encoded transmission scheme that is more general than [6] because any number of transmitters can be utilized for full diversity. This scheme is also more advantageous than other STBC schemes [2], [5] in distributed networks since imperfect synchronization can be tolerated.

This letter is organized as follows. The new scheme is introduced and analyzed in Section II. Then simulations are given in Section III. Finally, conclusions are presented in Section IV.

II. New Distributed Transmission Scheme

A. System Model

Consider a sensor network where a source sensor needs to transmit a data packet to a destination sensor through a multihop wireless network, as shown in Fig. 1(a). In each intermediate hop, the data packet is received by multiple nodes, e.g., nodes 1 to J in hop 1. Then these nodes can re-transmit it to the next hop in a cooperative manner with STBC encoding. Another scenario is that the source sensor may first transmit the packet to nearby relay sensors (with low transmission power), then they will transmit the packet cooperatively to the nodes in hop 1.

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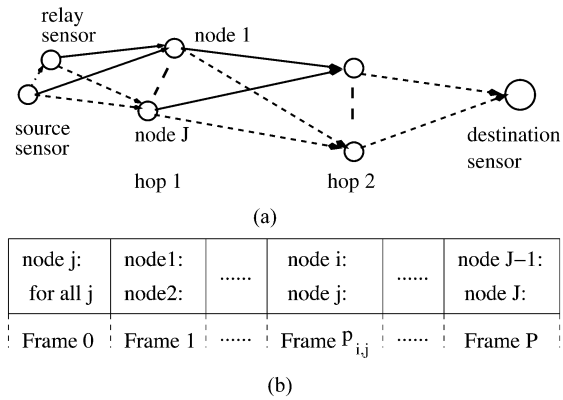

Fig. 1. (a) Multihop sensor network model with cooperative transmissions. (b) Space–time encoded transmission scheme, where a packet is subdivided into J blocks and is cooperatively transmitted by J nodes during $P+1$ time frames.

Without loss of generality, we consider the cooperative transmission among nodes 1 to J in hop 1. Perfect synchronization among these J nodes is difficult. Although they can synchronize as much as possible using their own received signals as references, low cost implementations may still make their timing and frequency slightly different, hence cause mismatch in the long run. The major synchronization problem, however, lies in the delays of their signals when reaching at the receiving nodes in hop 2. Propagation delays may be unknown to them, while their transmission time may be different. In fact, if the transmitting nodes try to synchronize toward one receiver, they may increase asynchronism toward other receivers because of different transmission distances.

On the other hand, in most practical networks, nodes can (and are required to) maintain slot synchronization, which means that coarse slot synchronization is available. What is difficult is the fine transmission synchronization. Because of this, we assume that an upper bound on delay asynchronism is available.

Because delay asynchronism is more significant and may be out of control, to simplify the problem, we consider it first when developing new transmission schemes. Timing/frequency asynchronism is then discussed to guide system design.

Considering both imperfect delay synchronization and frequency selective fading, channels are dispersive. Let the baseband channel from node j to the receiver be $[h_j(0),\ldots,h_j(L)]$, where for notational simplicity, all channel lengths are L. Because of the requirement of packet-wise encoding as discussed in the sequel, we assume that channels are time-invariant during the transmission of a packet, but are randomly time-varying between packets.

Let the transmitted symbol sequence from node j be $\{s_j(n)\}$, the noiseless received signal from this node by the receiver is $\sum_{\ell=0}^{L} h_j(\ell)s_j(n-\ell-d_j)$, where the parameter d_j denotes asynchronous delay. Since the delays are bounded, we assume $0 \le d_j \le D$, where D is an upper bound.

Note that d_j is an integer since fractional delays are contributed to channel dispersion. In addition, we use relative delays among the cooperative nodes instead of absolute delays from the transmitters to the receiver.

B. STBC-Encoded Transmission

For cooperative transmission, the major problem is that delays d_j are unknown, although D is known. In order for the cooperative nodes to apply STBC and for the receiver to obtain the correct space–time signal structure, we will develop a special frame-based multi-transmission scheme with packet-wise encoding.

Consider the case that J nodes need to transmit the same data packet $\{s(n)\}$. Instead of transmitting it directly, each node subdivides it into J blocks which we denote as $\{s_j(n) : n = 0,\ldots,N\}$, where $j = 1,\ldots,J$. In other words, the data packet $\{s(n)\}$ has length $J(N+1)$ and is subdivided into J equal length blocks. Note that all nodes do the identical subdivision.

The J nodes then perform cooperative transmission as shown in Fig. 1(b). The entire packet (J blocks) is to be transmitted in $P+1$ time frames where

$$P+1 = \frac{J(J-1)}{2} + 1. \tag{1}$$

During the first time frame (Frame 0), all nodes participate in transmission, where each node j transmits the symbol sequence $\{s_j(0),\ldots,s_j(N)\}$, $1 \le j \le J$. Then, in each of the subsequent time frames, there are only two nodes participating in transmission. In Frame 1, the node 1 transmits the sequence $\{-s_2^*(N),\ldots,-s_2^*(0)\}$, where $(\cdot)^*$ denotes complex conjugation, whereas the node 2 transmits the sequence $\{s_1^*(N),\ldots,s_1^*(0)\}$. In general, we apply the following rule to determine the transmitting nodes and orders: in Frame $p_{i,j}$ where

$$p_{i,j} = \frac{(i-1)(2J-i)}{2} + j - i, 1 \le i \le J-1, i+1 \le j \le J \tag{2}$$

the nodes i and j transmit the sequences $\{-s_j^*(N),\ldots,-s_j^*(0)\}$ and $\{s_i^*(N),\ldots,s_i^*(0)\}$, respectively.

As special cases, for $J=2$, this scheme becomes the time-reversed (TR) scheme in [6], whereas for $J=3$ it is similar to the TR-STBC in Section IV of [7]. However, [6] considers $J=2$ with delay asynchronism only, while [7] considers only dispersive channels with perfect synchronization.

C. Joint STBC Decoding and Equalization

Since the delays and channels can be estimated by the receiver, e.g., through training [6], we assume that they are known to the receiver. The received baseband signal in Frame 0 is

$$x_0(n) = \sum_{j=1}^{J}\sum_{\ell=0}^{L} h_j(\ell)s_j(n-\ell-d_j) + v_0(n) \tag{3}$$

where the noise $v_0(n)$ is assumed to be AWGN, and $s_j(n) = 0$ for $n < 0$ or $n > N$. Note that because d_j and L are bounded, we can select the block length N appropriately such that there is no inter-frame interference.

Stack samples into $L+1$ dimensional vectors $\mathbf{x}_0(n) = [x_0(n),\ldots,x_0(n-L)]^T$, where $(\cdot)^T$ denotes transposition. Define symbol vectors $\mathbf{s}_j(n) = [s_j(n),\ldots,s_j(n-2L)]^T$ and noise vectors $\mathbf{v}_0(n) = [v_0(n), \ldots, v_0(n-L)]^T$. From (3), we obtain

$$\mathbf{x}_0(n) = \sum_{j=1}^{J} \mathcal{H}_j \mathbf{s}_j(n-d_j) + \mathbf{v}_0(n) \tag{4}$$

where the channel matrices are

$$\mathcal{H}_j = \begin{bmatrix} h_j(0) & \cdots & h_j(L) & & \\ & \ddots & & \ddots & \\ & & h_j(0) & \cdots & h_j(L) \end{bmatrix}. \tag{5}$$

Note that in (4), we can utilize all valid sample vectors $\mathbf{x}_0(n)$ with

$$\min_{1 \le j \le J} d_j \le n \le N + 2L + \max_{1 \le j \le J} d_j. \tag{6}$$

In each of the subsequent frames $p_{i,j} \in [1, P]$, where $1 \le i \le J-1$ and $i+1 \le j \le J$, the received signal is

$$x_{p_{i,j}}(n) = \sum_{\ell=0}^{L} h_i(\ell) \left[-s_j^*(N-n+d_i+\ell)\right] + \sum_{\ell=0}^{L} h_j(\ell) s_i^*(N-n+d_j+\ell) + v_{p_{i,j}}(n). \tag{7}$$

Similarly, we construct sample vectors $\mathbf{x}_{p_{i,j}}(n) = [x_{p_{i,j}}(N-n+d_i+d_j+L), \ldots, x_{p_{i,j}}(N-n+d_i+d_j+2L)]^H$, where $(\cdot)^H$ denotes conjugate transpose. Then from (7), we have

$$\mathbf{x}_{p_{i,j}}(n) = \tilde{\mathcal{H}}_j \mathbf{s}_i(n-d_i) - \tilde{\mathcal{H}}_i \mathbf{s}_j(n-d_j) + \mathbf{v}_{p_{i,j}}(n) \tag{8}$$

where $\mathbf{v}_{p_{i,j}}(n)$ is the corresponding noise vector and

$$\tilde{\mathcal{H}}_j = \begin{bmatrix} h_j^*(L) & \cdots & h_j^*(0) & & \\ & \ddots & & \ddots & \\ & & h_j^*(L) & \cdots & h_j^*(0) \end{bmatrix}. \tag{9}$$

The reason that we use the special transmission scheme in Fig. 1(b) and the special received signal structure (4) and (8) is that they provide us with efficient decoding and equalization, whose computational complexity is linear. The transmitted signals can be jointly decoded and detected via a procedure consisting of a linear combiner and a linear equalizer.

The linear combiner is to add the received sample vectors in all frames together

$$y_j(n) = \tilde{\mathbf{h}}_j^T \mathbf{x}_0(n) - \sum_{i=1}^{j-1} \mathbf{h}_i^T \mathbf{x}_{p_{i,j}}(n) + \sum_{k=j+1}^{J} \mathbf{h}_k^T \mathbf{x}_{p_{j,k}}(n), \quad j = 1, \ldots, J \tag{10}$$

where $\mathbf{h}_j = [h_j(0), \ldots, h_j(L)]^T$ and $\tilde{\mathbf{h}}_j = \left[h_j^*(L), \ldots, h_j^*(0)\right]^T$. It gives the desired signal (relative to only one symbol block) from the received mixtures. Note that j in (10) is corresponding to the index of symbol blocks, not cooperative users.

Proposition: The combiner (10) gives

$$y_j(n) = \mathbf{g}^T \mathbf{s}_j(n-d_j) + w_j(n), \quad j = 1, \ldots, J \tag{11}$$

where $\mathbf{g}^T = \sum_{j=1}^{J} \tilde{\mathbf{h}}_j^T \mathcal{H}_j$, and the noise $w_j(n) = \tilde{\mathbf{h}}_j^T \mathbf{v}_0(n) - \sum_{i=1}^{j-1} \mathbf{h}_i^T \mathbf{v}_{p_{i,j}}(n) + \sum_{k=j+1}^{J} \mathbf{h}_k^T \mathbf{v}_{p_{j,k}}(n)$ is still Gaussian with zero mean.

Proof: First, let us see how $\mathbf{s}_j(n-d_j)$ is contained in (10). From (4), the item containing $\mathbf{s}_j(n-d_j)$ in $\mathbf{x}_0(n)$ is $\mathcal{H}_j \mathbf{s}_j(n-d_j)$. From (8), the item containing $\mathbf{s}_j(n-d_j)$ in $\mathbf{x}_{p_{i,j}}(n)$, $1 \le i \le j-1$, is $-\tilde{\mathcal{H}}_i \mathbf{s}_j(n-d_j)$. Similarly, the item containing $\mathbf{s}_j(n-d_j)$ in $\mathbf{x}_{p_{j,k}}(n)$, $j+1 \le k \le J$, is $\tilde{\mathcal{H}}_k \mathbf{s}_j(n-d_j)$. Therefore, $\mathbf{s}_j(n-d_j)$ is included in (10) as $\sum_{j=1}^{J} \tilde{\mathbf{h}}_j^T \mathcal{H}_j \mathbf{s}_j(n-d_j)$.

Similarly, $\mathbf{s}_\ell(n-d_\ell)$, where $\ell \ne j$ and $1 \le \ell \le J$, is contained in $\mathbf{x}_0(n)$ as $\mathcal{H}_\ell \mathbf{s}_\ell(n-d_\ell)$, in $\mathbf{x}_{p_{i,j}}(n)$ as $\tilde{\mathcal{H}}_j \mathbf{s}_\ell(n-d_\ell)$ (only if $i = \ell$), and in $\mathbf{x}_{p_{j,k}}(n)$ as $-\tilde{\mathcal{H}}_j \mathbf{s}_\ell(n-d_\ell)$ (only if $k = \ell$). Since $\left(\tilde{\mathbf{h}}_j^T \mathcal{H}_\ell - \mathbf{h}_\ell^T \tilde{\mathcal{H}}_j\right) \mathbf{s}_\ell(n-d_\ell) = 0$, signals $\mathbf{s}_\ell(n-d_\ell)$ for all $\ell \ne j$ are nullified from (10).

The property of noise $w_j(n)$ is obvious from (10). □

Equations (10) and (11) tell us that although with imperfect synchronization on delays and dispersive channels, the received STBC-encoded signal can still be separated and decoded. Each of the J parallel outputs $y_j(n)$ is the convolution of the symbol block $\{s_j(n)\}$ with the same composite channel $\mathbf{g}$. Since $\mathbf{g}$ is the summation of the convolution of each channel $\{h_j(n)\}$ and its time-reversed complex-conjugated version, (10) is a maximal ratio combiner, which means optimal diversity is preserved.

We need to find only one equalizer to estimate $s_j(n)$ from $y_j(n)$ for all j. For example, via training, a low complexity MMSE linear equalizer $\mathbf{f}$ can be estimated such that $\hat{s}_j(n-d_f) = \mathbf{f}^H \mathbf{y}_j(n)$ can be used for symbol estimation, where d_f is the appropriate equalization delay [4].

D. Diversity, Bandwidth Efficiency, and Block Length

From (11), the output of the combiner preserves diversity $J(L+1)$, where J is the number of cooperative nodes and $L+1$ is the number of taps in each channel. Hence, full diversity can be achieved if the optimal maximum likelihood detection is applied on (11) to detect symbols.

Bandwidth efficiency is determined by J (the number of cooperative nodes) and the overhead required to tolerate asynchronism. Since (6) gives $0 \le n \le N + 2L + D$, we need to choose frame length to be at least $N + 2L + D + 1$ in order to avoid inter-frame interference. On the other hand, because $P+1$ frames are used to transmit $J(N+1)$ symbols, the rate (or bandwidth efficiency) of this transmission scheme is

$$R_c = \frac{J(N+1)}{\left(\frac{J(J-1)}{2} + 1\right)(N+1+2L+D)} \tag{12}$$

which gives

$$\frac{2}{J} \frac{N+1}{N+1+2L+D} \le R_c \le \frac{2}{J-1} \frac{N+1}{N+1+2L+D}. \tag{13}$$

The rate is within $[2/J, 2/(J-1)]$ if $N+1 \gg 2L+D$, which is the case when the symbol block length is large. For $J = 2, 3, 4, 5$, the rates R_c are 1, 3/4, 4/7, 5/11, respectively. These rates are comparable to those of traditional STBC based on orthogonal designs [2]. The proposed scheme is thus promising, especially because of the fact that most diversity gains can be

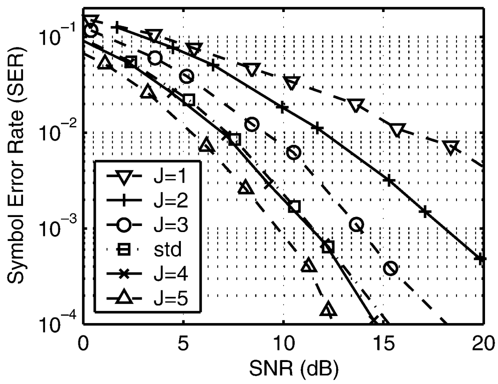

Fig. 2. SER as function of SNR for the proposed scheme with $J = 2$ to five nodes, for the single-transmission $J = 1$, and for the standard TR-STBC (std) with four transmitters.

obtained with only a few transmitters. On the other hand, although the rate drops below 1/2 for larger J, it is still twice of those repeated transmission schemes such as [3], [4].

We can increase block length N or reduce delay upper bound D to enhance bandwidth efficiency. However, the choice of these two parameters is limited by the imperfect synchronization on carrier frequency and timing. The choice of N depends on two factors: timing (or more specifically, symbol-interval) offset among the transmitting nodes, and time-variation of the channels. The former introduces unequal symbol intervals among cooperative nodes. If N is too large, the relative delays d_j at $n = 0$ may not be the same as those at $n = N$. The latter, on the other hand, makes the channels in Frame 0 not as same as those in Frame P. Both of them destroy the signal structure in (4) and (8). Therefore, we have to choose N appropriately for desirable tradeoff between bandwidth efficiency and synchronization cost.

Timing offset is caused by the fact that the transmitting nodes have no perfectly accurate clocks, whereas channel time-variation is caused by carrier frequency offset and movement-induced Doppler shifting. They can be alleviated by periodic network clock/frequency synchronization. Note that such synchronization procedure also brings smaller delay bound D. However, it reduces both energy and bandwidth efficiency in the upper layers of the network.

III. Simulations

We compare our new scheme with the traditional single-transmission scheme $(J = 1)$, and the standard TR-STBC (std) [7], in terms of symbol error rate (SER). They all use QPSK with the same total transmission power. For the new scheme, since the received signal-to-noise ratio (SNR) in Frame 0 is higher than those in the subsequent frames, we consider the average SNR. We use $N = 500$, $L = 3$, $D = 10$, and equalizer length 14. Using Rayleigh faded one-ray propagation and raised cosine pulse shaping with sampling time mismatch, we generate random channels, which are then truncated to four taps. Delays d_j are randomly generated for our scheme. For the TR-STBC, the delays are less than one symbol interval, i.e., $d_j = 0$, because TR-STBC does not work for $d_j \geq 1$. We use 1000 Monte-Carlo runs to evaluate each SER with respect to the average SNR.

Results in Fig. 2 show that the new transmission scheme has lower SER than the single-transmission scheme under the same total transmission power. Specifically, to achieve SER of 0.005, the required SNR of the new scheme is 5 dB less for $J = 2$ to 13 dB less for $J = 5$. This can be exploited to enhance transmission energy efficiency. In addition, with the same $J = 4$ transmitters, our scheme has identical performance as TR-STBC, which demonstrates that our scheme does not suffer from diversity loss in order to tolerate imperfect synchronization.

IV. Conclusions

In this letter, we proposed a new distributed STBC-encoded transmission scheme with which any number of mobile users can cooperatively transmit a single packet. The new scheme tolerates imperfect synchronization on delay, timing and carrier frequency among cooperative nodes. Full transmission diversity can be achieved with linear computational complexity. It is useful for distributed wireless networks such as sensor networks to enhance transmission energy efficiency and to reduce synchronization overhead and cost.

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