Efficient space time combination technique for unsynchronized cooperative MISO transmission

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Abstract—**In the context of cooperative Multi-Input Multi-Output (MIMO) techniques for wireless sensor networks, the transmission synchronization error impact is investigated in this paper and a new space-time combination technique is proposed. Cooperative MIMO techniques have been recently studied in order to reduce the energy consumption in distributed wireless sensor networks. Differing from classical MIMO systems, the cooperative antennas are physically separated in a cooperative system which leads to the unsynchronized cooperative transmission. The transmission synchronization error generates inter-symbol interference (ISI) and decreases the desired signal amplitude at the receiver, leading to a performance degradation and an additional energy required for data transmission. For small range of synchronization error, the performance degradation is negligible and the cooperative system performance is rather tolerant. However, for large range of error, the degradation is significant. A new space time combination technique is proposed for a cooperative Multi-Input Single-Output (MISO) system using Alamouti codes. The proposed technique combines two sequences of the received signal sampled at different times in order to perform an orthogonal combination. This technique has a better tolerance to the transmission synchronization error and also a low complexity. The significant advantage of using this new combination technique over traditional Alamouti combination is illustrated by simulations over a Rayleigh fading channel.**

I. Introduction

In distributed wireless sensor network (WSN) where the energy consumption is the most important design criterion, cooperative Multi-Input Multi-Output (MIMO) techniques using space-time block codes (STBC) [1][2] can be employed to reduce the transmission energy consumption and the total energy consumption for long range transmission [3][4]. However, as the wireless nodes are physically separated in a cooperative MIMO system, the imperfect time synchronization between cooperative nodes clocks leads to an unsynchronized transmission.

The effect of this unsynchronized transmission is that the space-time coded signals from different cooperative nodes do not arrive at the same time to the receiver. After the synchronization and signal sampling process, the inter-symbol interference (ISI) of the unsynchronized sequences appears and the space-time sequences from different nodes are no longer orthogonal. Therefor, the estimated signal amplitude decreases and more interference is generated. This leads to the performance degradation and affects the energy efficiency advantage of cooperative MIMO system over Single-Input Single-Output (SISO) system. Fine synchronization techniques [5][6] can be used to obtain a better time synchronization precision but at the cost of energy and processing time.

Since space-time combination can be performed independently at each cooperative reception node, the impact of transmission synchronization error in a cooperative MIMO system is the same as in the corresponding cooperative Multi-Input Single-Output (MISO) system (e.g. the effect is the same on cooperative MIMO 2-2 and cooperative MISO 2-1 systems). Therefore, only the cooperative MISO system is investigated in this paper for the study of transmission synchronization error impact.

The performance of Alamouti diversity technique in the presence of transmission synchronization error is investigated in [7]. A cooperative MISO system using Alamouti codes has a good tolerance for the small synchronization error range, but for large error range the performance degrades quickly.

Some other space time codes like time-reversal block codes [8][9] can be used in order to limit the impact of transmission synchronization error, but the data rate is reduced, the performance is not as good as with Alamouti codes and the algorithm is more complex.

This paper presents some modifications of space time combination technique for Alamouti codes. Firstly, the receiver performs two synchronization processes which determine the time offsets and sample the received signal corresponding to the space time sequences from two cooperative nodes, then combines the two different sampled sequences to re-construct the space-time orthogonal combination. We show that the new proposed technique has a low complexity, is close to the classical Alamouti receiver structure, and has a better performance than the traditional space-time combination in the presence of transmission synchronization error.

The rest of the paper is organized as follows. The transmission synchronization error effect on cooperative MISO system is firstly presented in Section II. In Section III, the synchronization processes and the new modified space-time combination technique are proposed. The effect of transmission synchronization error on the performance of cooperative MISO system and the performance of new space time combination technique is illustrated by simulations in Section IV. Finally, conclusions and future works are given in Section V and Section VI.

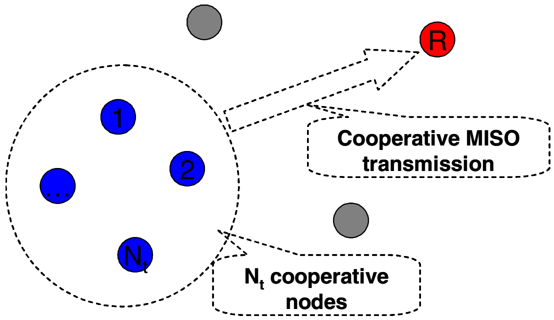

Fig. 1. Cooperative MISO scheme for wireless sensor network

II. EFFECT OF TRANSMISSION SYNCHRONIZATION ERROR

A cooperative MISO system with N_t cooperative transmission nodes and one reception node is considered as in Fig. 1. After the local data exchange and the signal space-time coding [4], all the N_t cooperative nodes must transmit their STBC symbols simultaneously to the reception node. Due to the lack of synchronous timer clocks between cooperative nodes, node k among the N_t cooperative nodes will transmit its space-time coded sequence c_k at time Δ_k and the channel transmission delay is d_k (for $k = 1..N_t$). Sequences of N_t cooperative nodes do not arrive at the reception node at the same moment. The received signal is:

$$r(t) = \sum_{l=-\infty}^{\infty} \sum_{k=1}^{N_t} \alpha_k c_k[l] p(t - lT_s - \Delta_k - d_k) + n(t), \quad (1)$$

where α_k is the channel coefficient, $c_k[l]$ is the l^{th} symbol of sequence c_k, T_s is the symbol period, $n(t)$ the white Gaussian noise and $p(t)$ is the raised cosine pulse shape. The node 1 is considered as a reference node (i.e. $\Delta_1 - d_1 = 0$). Let us define the transmission synchronization errors of cooperative nodes $\delta_k = \Delta_k + d_k - \Delta_1 - d_1$, for $k = 1...N_t$. The received signal is then:

$$r(t) = \sum_{l=-\infty}^{\infty} \sum_{k=1}^{N_t} \alpha_k c_k[l] p(t - lT_s - \delta_k) + n(t) \quad (2)$$

The effect of the transmission synchronization error is that the composite pulse shape (superposition of the pulses from each node shifted by the corresponding δ_k) seen at the receiver is no longer Nyquist. After synchronization and signal sampling process, the ISI of the unsynchronized sequences appears and the space-time sequences from different nodes are no longer orthogonal. The orthogonal space time combination can not be performed, which decreases the desired signal amplitude and generates more interference [7].

For the case of two cooperative transmit nodes using Alamouti codes, the received signal is:

$$r(t) = \sum_{l=-\infty}^{\infty} \alpha_1 c_1[l] p(t - lT_s) + \sum_{l=-\infty}^{\infty} \alpha_2 c_2[l] p(t - lT_s - \delta_2) + n(t) \quad (3)$$

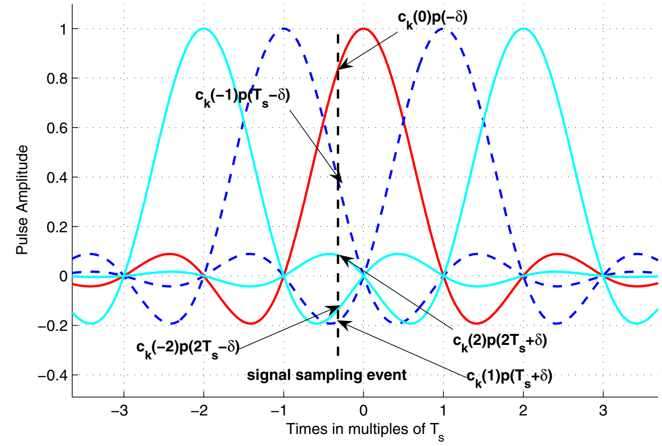

Fig. 2. ISI generated by the transmission synchronization error

For simplicity, we consider that the ISI is just created by the four nearest neighbor symbols as in Fig. 2. Let s_1 and s_2 be the two transmitted symbols in one Alamouti block, the receiver is considered be synchronized to the reference node 1. The two sampled values of the received signal are:

$$\begin{aligned} r_1[1] &= r(t = T_s) \\ &= \alpha_1 c_1[1] + \alpha_2 c_2[1] p(-\delta_2) + ISI(c_2[1]) + n(T_s) \\ r_1[2] &= r(2T_s) \\ &= \alpha_1 c_1[2] + \alpha_2 c_2[2] p(-\delta_2) + ISI(c_2[2]) + n(2T_s) \quad (4) \end{aligned}$$

where the inter symbol interference terms are:

$$\begin{aligned} ISI(c_2[1]) &= \alpha_2 (c_2[-1] p(2T_s - \delta_2) + c_2[0] p(T_s - \delta_2) \\ &\quad + c_2[2] p(T_s + \delta_2) + c_2[3] p(2T_s + \delta_2)) \\ ISI(c_2[2]) &= \alpha_2 (c_2[0] p(2T_s - \delta_2) + c_2[1] p(T_s - \delta_2) \\ &\quad + c_2[3] p(T_s + \delta_2) + c_2[4] p(2T_s + \delta_2)) \quad (5) \end{aligned}$$

with space-time coded symbols $[c_1[1]\ c_1[2]] = [s_1\ \ -s_2^*]$ and $[c_2[1]\ c_2[2]] = [s_2\ s_1^*]$. For the rest of this paper, $n(T_s)$, $n(2T_s)$ and $ISI(c_2[1])$, $ISI(c_2[2])$ are replaced by n_1^1, n_2^1 and ISI_1^1, ISI_2^1. After the space time combination, the estimated symbols are:

$$\begin{aligned} \tilde{s_1} &= \alpha_1^* r_1[1] + \alpha_2 r_1^*[2] = (||\alpha_1||^2 + ||\alpha_2||^2 p(-\delta_2)) s_1 \\ &\quad + \alpha_1^* \alpha_2 (1 - p(-\delta_2)) s_2 + \alpha_1^* (ISI_1^1 + n_1) + \alpha_2 (ISI_2^1 + n_2)^* \\ \tilde{s_2} &= \alpha_2^* r_1[1] - \alpha_1 r_1^*[2] = (||\alpha_1||^2 + ||\alpha_2||^2 p(-\delta_2)) s_2 \\ &\quad + \alpha_1 \alpha_2^* (1 - p(-\delta_2)) s_1 + \alpha_2^* (ISI_1^1 + n_1) - \alpha_1 (ISI_2^1 + n_2)^* \quad (6) \end{aligned}$$

If the synchronization error $\delta_2 = 0$ (i.e. we have perfect transmission synchronization), the traditional Alamouti system performance is achieved. The two estimated symbols are:

$$\begin{aligned} \tilde{s_1} &= (||\alpha_1||^2 + ||\alpha_2||^2) s_1 + \alpha_1^* (n_1) + \alpha_2 (n_2)^* \\ \tilde{s_2} &= (||\alpha_1||^2 + ||\alpha_2||^2) s_2 + \alpha_2^* (n_1) - \alpha_1 (n_2)^* \quad (7) \end{aligned}$$

Otherwise, with the presence of synchronization error δ_2, the desired symbol amplitude decreases and an interference between s_1 and s_2 appears after the space-time combination in the formula (6). The performance is affected depending on the level of synchronization error range, so that the error rate of cooperative MISO system will be higher than of traditional MISO system.

III. New space time combination technique

In formula (6), besides the ISI generated after synchronization and sampling process, the performance degradation is caused mainly by the non-orthogonal space-time combination of the received values. By using a modified synchronization and combination process, the orthogonal space-time combination of received signal can be re-constructed.

A. Synchronization technique

Let us consider that the receiver can determine the time offset that helps to synchronize perfectly the sequences from two cooperative transmission antennas. For example, each cooperative node uses a different known preamble for the signal synchronization at the receiver (the preamble sequences are orthogonal to each other). The receiver can perform the correlation between the received signal and the known preamble of each cooperative node, determine the peak of correlation and the time offset corresponding to each arriving sequence. After that, the received signal is sampled sequentially with two time offsets and the two different sampled sequences corresponding to two arriving sequences from two cooperative nodes are obtained.

The two sampled sequences are registered to two different memory banks for the space time combination in the next step. So, for one Alamouti block of two transmitted symbols, instead of registering two analog values the receiver needs to register four analog values from the received signal.

$$r(t) = \sum_{l=-\infty}^{\infty} \alpha_1 c_1[l] p(t - lT_s) + \sum_{l=-\infty}^{\infty} \alpha_2 c_2[l] p(t - lT_s - \delta_2) + n(t) \tag{8}$$

Considering that the receiver synchronizes (determines the time offsets) perfectly to the two sequences from cooperative nodes, the two sampled values corresponding to node 1 are presented in formulas (4), (5). And the two sampled values corresponding to node 2 are:

$$\begin{aligned} r_2[1] &= r(t = T_s + \delta_2) \\ &= \alpha_1 c_1[1] p(\delta_2) + ISI(c_1[1]) + n(T_s + \delta_2) + \alpha_2 c_2[1] \\ r_2[2] &= r(t = 2T_s + \delta_2) \\ &= \alpha_1 c_1[2] \delta_2 + ISI(c_1[2]) + n(2T_s + \delta_2) + \alpha_2 c_2[2] \end{aligned} \tag{9}$$

where the inter symbol interference terms are:

$$\begin{aligned} ISI(c_1[1]) &= \alpha_1 (c_1[-1] p(2T_s - \delta_2) + c_1[0] p(T_s - \delta_2) \\ &\quad + c_1[2] p(T_s + \delta_2) + c_1[3] p(2T_s + \delta_2)) \\ ISI(c_1[2]) &= \alpha_1 (c_1[0] p(2T_s - \delta_2) + c_1[1] p(T_s - \delta_2) \\ &\quad + c_1[3] p(T_s + \delta_2) + c_1[4] p(2T_s + \delta_2)) \end{aligned} \tag{10}$$

The space time combination technique of Alamouti codes can be modified in order to re-construct the orthogonal space-time combination from the two above sampling sequences.

B. New space-time combination technique

For the next formulas, $n(T_s + \delta_2)$, $n(2T_s + \delta_2)$, $ISI(c_1[1])$, $ISI(c_1[2])$ are replaced by n_1^2, n_2^2, ISI_1^2, ISI_2^2 and the symmetry of the pulse shape value $p(-\delta_2) = p(\delta_2)$ is remarked. The two sampling sequences are space-time combined and the two estimated symbols are:

$$\begin{aligned} \tilde{s_1} &= \alpha_1^* r_1[1] + \alpha_2 r_2^*[2] = ||\alpha_1||^2 s_1 + \alpha_1^* \alpha_2 s_2 p(-\delta_2) \\ &+ \alpha_1^* (ISI_1^1 + n_1^1) - \alpha_1^* \alpha_2 s_2 p(\delta_2) + ||\alpha_2||^2 s_1 + \alpha_2 (ISI_2^2 + n_2^2)^* \\ &= (||\alpha_1||^2 + ||\alpha_2||^2) s_1 + \alpha_1^* (ISI_1^1 + n_1^1) + \alpha_2 (ISI_2^2 + n_2^2)^* \\ \tilde{s_2} &= \alpha_2^* r_2[1] - \alpha_1 r_1^*[2] = \alpha_1 \alpha_2^* s_1 p(-\delta_2) + \alpha_2^* (ISI_1^2 + n_1^2) \\ &+ ||\alpha_2||^2 s_2 + ||\alpha_1||^2 s_2 - \alpha_1 \alpha_2^* s_1 p(\delta_2) - \alpha_1 (ISI_2^1 + n_2^1)^* \\ &= (||\alpha_1||^2 + ||\alpha_2||^2) s_2 + \alpha_2^* (ISI_1^2 + n_1^2) - \alpha_1 (ISI_2^1 + n_2^1)^* \end{aligned} \tag{11}$$

In comparison with formula (6), the amplitude of desired symbol in formula (11) does not decrease and the interference between two symbols s_1 and s_2 does not appear after space time combination (i.e. the orthogonal space-time combination is achieved). The signal to interference noise ratio (SINR) increases with the new proposed combination technique so that the cooperative MISO system performance will be better than the traditional Alamouti combination in the presence of transmission synchronization error.

Some other space-time codes like time-reversal block codes have good tolerance towards the transmission synchronization errors, but with the drawbacks such as the reduced data rate and more complex combination algorithm. With this new proposed combination technique, we retain the full data rate and the low complexity algorithm of traditional Alamouti codes. The receiver has to synchronize two times the received signal and register two times the sampled values, but the over processing time and the memory resource cost are negligible in modern receivers.

IV. Simulation results

Simulations of cooperative MISO performance using Alamouti codes (two cooperative transmission nodes) in the presence of transmission synchronization error are performed. The system uses an uncoded quadrature phase shift keying (QPSK) modulation, the channel is considered to be Rayleigh fading and independent for each frame of 120 symbols and the raised cosine pulse shape $p(t)$ has a roll-off factor of 0.25. For the reliability of result, 10^6 frames have at least been sent for assuring the bit-error-ratio $BER = 10^{-5}$ and frame-error-ratio $FER = 10^{-4}$.

The receiver is considered to be synchronized perfectly to the desired space-time coded sequences for an independent evaluation of the cooperative transmission synchronization error impact and the proposed combination technique performance.

Neglecting the timer drift in node clocks, the clock errors of different cooperative nodes are considered fixed between two runs of synchronization process and have a random distribution law (Gaussian, uniform,. . .) around the reference node. For our simulation, the transmission synchronization error δ_2 is considered having uniform distribution in $[-\Delta T_{syn}/2, \Delta T_{syn}/2]$ with ΔT_{syn} the synchronization error range.

A. Effect of transmission synchronization errors

In Fig. 3, simulation results of the cooperative MISO 2-1 technique (two cooperative transmission nodes, labeled coop 2-1 in Fig.3), the non-cooperative MISO 2-1 technique (the two transmit antennas are in the same transmission node) and the SISO technique are presented for synchronization errors $\Delta T_{syn} = 0.2T_s, 0.5T_s, 0.6T_s$ and $0.7T_s$.

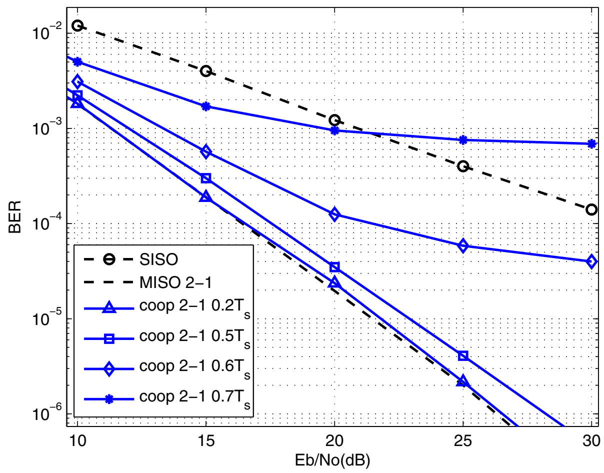

Fig. 3. Effect of transmission synchronization errors

For the case of synchronization error $\Delta T_{syn} = 0.2T_s$, the cooperative MISO system using traditional Alamouti combination is rather tolerant and the performance degradation is acceptable until $\Delta T_{syn} = 0.5T_s$. For $\Delta T_{syn} = 0.7T_s$, the degradation is significant and the performance of cooperative 2-1 system is not as good as SISO system. So, for large range of transmission synchronization error, the cooperative MISO techniques do not have any advantage over the SISO technique.

B. New space time combination technique performance

In Fig. 4 and Fig. 5, we have the BER) and FER simulation results of the new proposed space-time combination technique versus the traditional Alamouti combination technique in the presence of transmission synchronization error ranges as large as $\Delta T_{syn} = 0.5T_s, 0.6T_s$ and $0.7T_s$.

The performance degradation of the new combination technique is smaller than of the traditional technique. For $\Delta T_{syn} = 0.5T_s$ and $BER = 10^{-5}$ requirement (or $FER = 10^{-3}$ requirement), the gain of $1.1dB$ (or $1.2dB$) can be obtained by using the new combination technique.

For synchronization error ΔT_{syn} larger than $0.5T_s$, the performance of traditional combination technique decreases quickly, but the performance of the new combination technique remains acceptable until $\Delta T_{syn} = 0.7T_s$. The advantages of

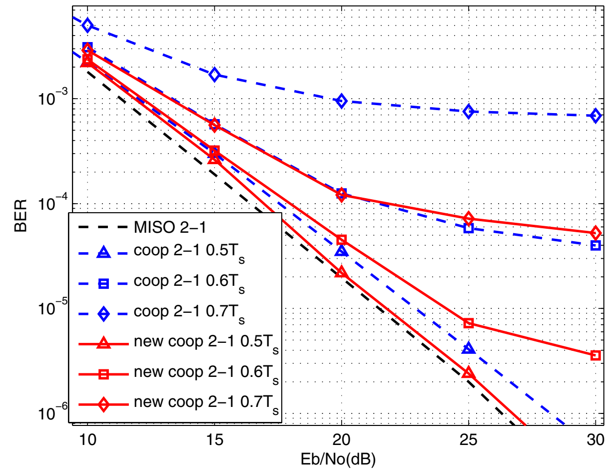

Fig. 4. BER results of new combination vs. traditional combination

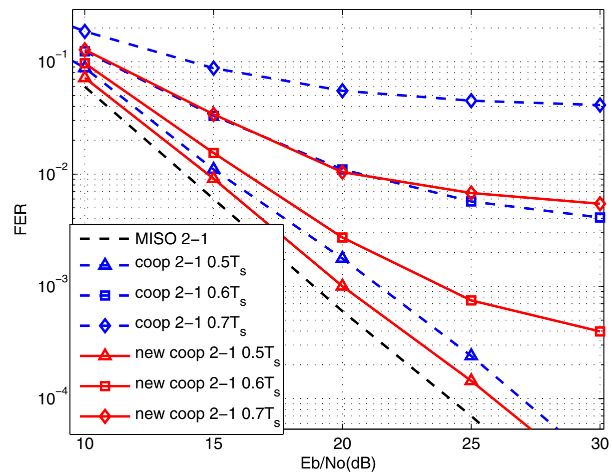

Fig. 5. FER results of new combination vs. traditional combination

using new proposed combination technique over traditional technique in the presence of transmission synchronization error are illustrated clearly by those simulation results.

V. Conclusion

The effect of transmission synchronization error in cooperative MISO systems is investigated in this paper. The performance degradation increases with the synchronization error range. The cooperative MISO system is rather tolerant for small range of synchronization error, however for large range of error, the degradation is significant and the performance advantage of cooperative MISO system over the SISO system is reduced.

A new combination technique which has better performances than the traditional combination technique in the presence of large range synchronization error and has low complexity is also proposed. By using this new technique, more performance can be obtained and the tolerance to the transmission synchronization error of cooperative MISO technique increases. Consequently, less transmission energy is needed or less precise clock synchronization process can be used for cooperative MISO system.

VI. Future work

For cooperative MISO systems with three and four cooperative transmission nodes using Tarokh STBC, similar techniques limiting the synchronization error impact have also been studied. However, since interference increases with the number of unsynchronized nodes, the significant gain like in case of two transmission nodes has not yet been obtained. So, other solutions for cooperative MISO systems with three and four transmission nodes continue to be investigated in future works.

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