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Impact of transmission synchronization error and cooperative reception techniques on the performance of cooperative MIMO systems

Tuan-Duc Nguyen, Olivier Berder and Olivier Sentieys
IRISA - University of Rennes 1, France
Email: Firstname.Lastname@irisa.fr

***Abstract*—Wireless sensor networks where neighbor nodes can cooperate both at transmission and reception by using the cooperative multi-input multi-output (MIMO) technique are considered. Space-time diversity gain can be exploited to reduce the transmission energy consumption which is very important for average and long range transmission in wireless sensor network (WSN). However, differing from classical MIMO systems, cooperative systems suffer from the lack of synchronization between distributed nodes and the additive noise in the cooperative reception. At the cooperative transmission side, we investigate the effect of transmission synchronization error which generates inter-symbol interference (ISI), decreases the desired signal amplitude and makes the channel state information (CSI) more difficult to be estimated by the receiver. At the cooperative reception side, two strategies of wireless transmission techniques which are energy efficient and have good performance are also presented. The simulation of a cooperative MIMO system using Alamouti and Tarokh space-time block codes (STBC) over Rayleigh fading channels presents a performance degradation in the presence of transmission synchronization error and additional noise of cooperative reception techniques. For a small synchronization error range at cooperative transmission and a reasonable amplification factor in reception, the degradation is negligible and the cooperative MIMO performance is rather good.**

I. Introduction

For radio transmission over a fading channel, space-time diversity Multi-Input Multi-Output (MIMO) systems need less transmission energy for the same Bit Error Ratio (BER) requirement. The energy-efficiency of MIMO transmission is particularly useful for Wireless Sensor Network (WSN) where the energy consumption is the most important criterion. However, the direct application of multi-antenna techniques to WSN is impractical due to the limited physical size of sensor nodes which can typically support a single antenna. Fortunately, some individual nodes can cooperate in transmission and reception by using cooperative MIMO techniques [1] which allow space time diversity gain [2], reduces the energy consumption [3] [4] and increases the system capacity [5].

Since the nodes are physically separated in a cooperative MIMO system, their different respective clocks lead to un-synchronized transmission and reception. That generates ISI, decreases the desired signal amplitude at the receiver and makes it more difficult to estimate the CSI. Precise synchronization techniques in [6][7] can be used for greater precision but cost much energy and time. At the reception side, each cooperative node has to forward its received signal through a wireless channel to the destination node for signal combination which leads to additional noise in the final received signal. Consequently, due to the un-synchronized transmission and the additional noise of cooperative MIMO system, the BER is higher for the same SNR or the transmission energy has to be increased for the same BER requirement.

The principle and the energy efficiency of cooperative MIMO transmissions using Alamouti and Tarokh space-time block codes (STBC) [8] were presented in [1]. But the two articles do not consider either the impact of transmission synchronization error nor the additive noise in cooperative reception techniques. The performance of Alamouti and maximum-ratio-combining (MRC) diversity techniques in the presence of synchronization error are investigated in [9]. The cooperative MISO system has a good tolerance for the small synchronization error range, but the study is limited to two transmission antennas, the CSI is considered to be known in the receiver and the effect of synchronization error is presented for low range SNR.

The present paper extends the MIMO cooperative principle to 3 and 4 transmission antennas using Tarokh STBC [10] and the system performances are investigated also the channel estimation errors. The cooperative reception technique presented in [1] considers that a cooperative node quantizes one received symbol to N_{sb} bits and then forwards the bit sequences to the destination node, increasing the amount of data transmitted and the circuit energy consumption. In order to achieve better energy efficiency, two cooperative reception techniques derived from amplify-and-forward strategies [11] are also proposed in this paper. Their effect on the cooperative MIMO system performance is evaluated and their energy efficiency superiority over the previous cooperative reception technique is also explored.

The rest of the paper is organized as follows. Firstly, the cooperative MIMO technique is represented in next section. In section III, the performance of cooperative MISO systems using Alamouti and Tarokh STBC is analyzed in the presence of transmission synchronization error and the absence of CSI in the receiver. The performance of different cooperative reception techniques is then investigated in section IV. Finally, the performance of cooperative MIMO systems and their energy

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efficiency are illustrated by simulation results in section V.

II. Cooperative MIMO for Wireless Sensor Networks

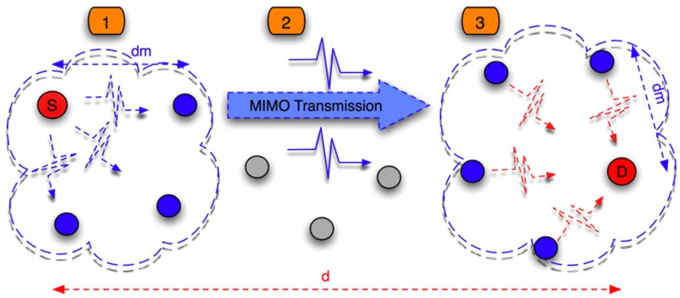

Fig. 1. Cooperative MIMO scheme for wireless sensor networks

As illustrated by Fig. 1, the cooperative MIMO transmission from source node S to destination node D over distance d is composed of three phases : 1) local data exchange, 2) cooperative MIMO transmission and 3) cooperative reception.

On the transmission side, node S can cooperate with its neighbors and exchange its data (the distance between cooperating nodes d_m is much smaller than distance d). STBC techniques are then employed to encode and transmit the data simultaneously to the destination node or multi-destination cooperative nodes like traditional MIMO systems (each cooperative node plays role of one antenna of the MIMO system). On the reception side, the cooperative neighbors of destination node D receive the MIMO modulated symbols and then sequentially retransmit them to the destination node D for joint MIMO signals combination.

As the nodes are physically separated in a cooperative MIMO system, the system performance suffers from the transmission synchronization error on the cooperative transmission side and the additional noise on the cooperative reception side. Due to performance degradation, the cooperative MIMO system BER is higher than the traditional MIMO system BER with the same number of transmission-reception antennas.

III. Effect of transmission synchronization error

As the space-time combination can be performed independently at each cooperative reception node, the effect of transmission synchronization error in cooperative MIMO system is the same as in corresponding cooperative MISO system (ex. effect is the same for cooperative MIMO 4-3 and cooperative MISO 4-1 system). Therefore, the cooperative MISO system with N_t cooperative transmission nodes is considered in this section for simplicity.

In cooperative MISO system, all N_t cooperative nodes must transmit their STBC symbols simultaneously to the destination. Due to the lack of synchronous clocks between cooperative nodes, node k among the N_t cooperative nodes will transmit its space-time coded sequence c_k at Δ_k and the channel transmission delay is d_k (for $k = 1..N_t$). Signal sequences of N_t cooperative nodes do not arrive at a 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 l^{th} symbol of sequence c_k, T_s the symbol period, $n(t)$ the white Gaussian noise and $p(t)$ the raised cosine pulse shape with roll-off factor of 0.25. The node 1 (node S) is considered like 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 $k = 1...N_t$, so the received signal is:

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

The effect of 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 the synchronization process, there will be the ISI of the non-synchronized sequences and the space-time coded sequences from different cooperative nodes are no longer orthogonal. We have not the orthogonal space time combination, which decreases the desired signal amplitude and generates more interference [9].

For the case of 2 cooperative transmit nodes:

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

For simplicity, we consider the ISI is just created by the four

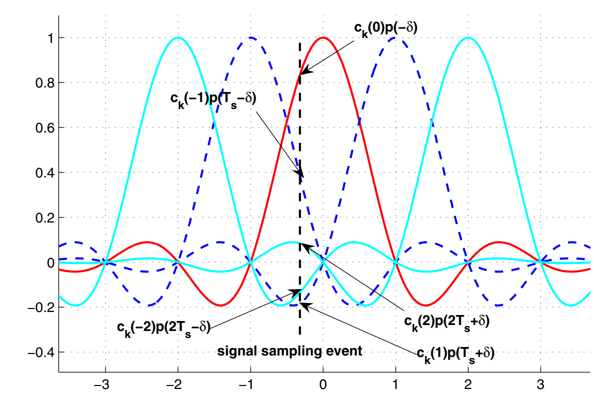

Fig. 2. ISI generated by the transmission synchronization error ($T_s = 1$)

nearest neighbor symbols as in Fig. 2. Let s_1 and s_2 be the two transmitted symbols in one Alamouti block, the two received symbols are:

$$r(T_s) = \alpha_1 c_1[1] + \alpha_2 c_2[1] p(-\delta_2) + ISI(c_2[1]) + n(T_s)$$
$$r(2T_s) = \alpha_1 c_1[2] + \alpha_2 c_2[2] p(-\delta_2) + ISI(c_2[2]) + n(2T_s) \quad (4)$$

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where the inter symbol interference terms are:

$$ISI(c_2[1]) = \alpha_2(c_2[-1]p(2T_s-\delta_2) + c_2[0]p(T_s-\delta_2) + c_2[2]p(T_s+\delta_2) + c_2[3]p(2T_s+\delta_2)) \quad (5)$$

$$ISI(c_2[2]) = \alpha_2(c_2[0]p(2T_s-\delta_2) + c_2[1]p(T_s-\delta_2) + c_2[3]p(T_s+\delta_2) + c_2[4]p(2T_s+\delta_2)) \quad (6)$$

with $[c_1[1]\ c_1[2]] = [s_1\ \ -s_2^*]$ and $[c_2[1]\ c_2[2]] = [s_2\ s_1^*]$. For the rest of this paper, $ISI(c_2[1])$,$ISI(c_2[2])$ are replaced by ISI_1,ISI_2 and $r(T_s)$,$r(2T_s)$,$n(T_s)$,$n(2T_s)$ are replaced by r_1,r_2,n_1,n_2. After space time combination, the estimated symbols are:

$$\tilde{s_1} = \alpha_1^* r_1 + \alpha_2 r_2^* = (||\alpha_1||^2 + ||\alpha_2||^2 p(-\delta_2))s_1 + \alpha_1^*\alpha_2(1-p(-\delta_2))s_2 + \alpha_1^*(ISI_1+n_1) + \alpha_2(ISI_2+n_2)^*$$
$$\tilde{s_2} = \alpha_2^* r_1 - \alpha_1 r_2^* = (||\alpha_1||^2 + ||\alpha_2||^2 p(-\delta_2))s_2 + \alpha_1\alpha_2^*(1-p(-\delta_2))s_1 + \alpha_2^*(ISI_1+n_1) - \alpha_1(ISI_2+n_2)^* \quad (7)$$

Due to the synchronization error δ_2, the desired symbols amplitude decreases, ISI is generated and we do not have the orthogonal combination.

For channel estimation, at the beginning of each fading block (frame in case of static fading) of antenna i, a training sequences W_i which is orthogonal from each other is inserted ($i = 1..N_t$). Due to the un-synchronized transmission, the training sequences from different nodes in the received signal are no longer orthogonal and ISI appears. The precision of CSI estimation procedures, depending on the synchronization error range, will affect the total performance of cooperative MISO system.

So that, in the presence of cooperative synchronization error, the BER will increase due to the ISI, the non-orthogonal combination and the less precise channel estimation. The degradation depends on the synchronization error range and increases with the number of cooperative transmit nodes.

IV. Cooperative reception techniques

The cooperative reception technique presented in [1] considers that the cooperative node quantizes one received symbol to $N_{sb} = 10$ bits and then forwards the bit sequences to the destination node D. For small distance range SISO transmission, the circuit energy dominates the total system consumption. The strategy of quantizing one symbol to N_{sb} bits will increase the amount of data to be transmitted, the transmission time and the circuit energy consumption, which increases the total consumption and affects the energy efficiency of cooperative reception techniques. In [11], decode-and-forward and amplify-and-forward techniques of cooperative transmission can be applied in cooperative reception for a better energy efficient cooperative reception.

Because of the small received SNR in each cooperative reception nodes it is better to transmit (amplify and forward or combine, amplify and forward) the analog symbols' values (which requires just some small modification in the receiver DSP circuit) than to transmit the decoded digital bits to the destination node D.

For the case of 2 transmit antennas, the space time received symbols at each cooperative node j are:

$$R^j = [r_1^j\ r_2^j] = [\alpha_{j,1}s_1 + \alpha_{j,2}s_2 \quad -\alpha_{j,1}s_2^* + \alpha_{j,2}s_1^*] + [n_1^j\ n_2^j] \quad (8)$$

After that, the space time combination can be performed in each cooperative node or destination node that leads to 2 strategies of cooperative reception.

A. *Strategy 1 (forward-and-combine)*

Each cooperative node amplifies its space time received symbols and then forwards its analog sequence to the destination D (the short distance channel between two cooperative nodes is considered additive white Gaussian noise (AWGN) channel). The amplification process ensures the amplification factor K_1 of the received signal R'^j at destination node D.

$$R'^j = K_1[r_1^j\ r_2^j] + [n_1'^j\ n_2'^j] \Rightarrow \tilde{R}^j = [r_1^j\ r_2^j] + [n_1'^j\ n_2'^j]/K_1 \quad (9)$$

for $j = 2..N_r$. Let us define the effective Gaussian noise $n_{i\,e}^jff = n_i^j + n_i'^j/K_1$ with $i = 1, 2$. After the space time combination, we have the estimated symbols:

$$\tilde{s_1} = \sum_{j=1}^{N_r}(||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_1 + \sum_{j=1}^{N_r}(\alpha_{j,1}^* n_{1e}^j ff + \alpha_{j,2} n_2^{j*}{}_e ff)$$
$$\tilde{s_2} = \sum_{j=1}^{N_r}(||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_2 + \sum_{j=1}^{N_r}(\alpha_{j,2}^* n_{1e}^j ff - \alpha_{j,1} n_2^{j*}{}_e ff) \quad (10)$$

B. *Strategy 2 (combine-and-forward)*

The space time combination is done at each cooperative node and the combined symbols are:

$$\tilde{s}_1^j = (||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_1 + \alpha_{j,1}^* n_1^j + \alpha_{j,2} n_2^{j*}$$
$$\tilde{s}_2^j = (||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_2 + \alpha_{j,2}^* n_1^j - \alpha_{j,1} n_2^{j*} \quad (11)$$

Then each cooperative node amplifies its combined symbols value and forwards it to destination node D. The amplification process ensures the amplification factor K_2 of the received signal is:

$$R'^j = K_2[\tilde{s}_1^j\ \tilde{s}_2^j] + [n_1'^j\ n_2'^j] \Rightarrow \tilde{R}^j = [\tilde{s}_1^j\ \tilde{s}_2^j] + [n_1'^j\ n_2'^j]/K_2 \quad (12)$$

The final space time combined symbols are the addition of all received $\tilde{R}^j$:

$$[\tilde{s}_1\ \tilde{s}_2] = \sum_{j=1}^{N_r}\tilde{R}^j = \sum_{j=1}^{N_r}[\tilde{s}_1^j\ \tilde{s}_2^j] + \sum_{j=2}^{N_r}[n_1'^j\ n_2'^j]/K_2 \quad (13)$$

We have the estimated symbols:

$$\tilde{s_1} = \sum_{j=1}^{N_r}(||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_1 + \sum_{j=1}^{N_r}(\alpha_{j,1}^* n_1^j + \alpha_{j,2} n_2^{j*} + n_1'^j/K_2)$$
$$\tilde{s_2} = \sum_{j=1}^{N_r}(||\alpha_{j,1}||^2 + ||\alpha_{j,2}||^2)s_2 + \sum_{j=1}^{N_r}(\alpha_{j,2}^* n_1^j - \alpha_{j,1} n_2^{j*} + n_2'^j/K_2) \quad (14)$$

From (10) and (14), we can observe that the effective noise due to the cooperative reception techniques depends on the number of cooperative reception nodes N_r and the amplification factor

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K_1 (or K_2). For $K_1 = K_2$, the power of effective noise in case 2 is smaller than in case 1. However, we must use more energy to amplify and transmit in case 2 because the power of input symbols in case 2 is greater than in case 1 (for $N_t = 2$ and $N_t = 4$, the average power is 3 times and 5 times greater). However, if the number of cooperative transmission nodes is 3 or 4, we must use the STBC of Tarokh with the rate 3/4 for complex symbols. So for case 2, we have 4/3 times less analog symbols to be transmitted than for case 1. That will reduce by 4/3 times the circuit energy consumption in cooperative reception.

By using the two proposed cooperative reception techniques rather than the quantization technique proposed in [1], the transmission time can be reduced to N_{sb}/M where M is the number of bits/symbol of modulation technique used in cooperative transmission in [1]. The reduced cooperative reception consumption will lead to a better energy efficient cooperative MIMO system.

V. Simulation Results

Simulations of cooperative MIMO performance using Alamouti codes and Tarokh STBC in the presence of synchronization error, channel estimation error and cooperative reception noise are presented. The system uses an uncoded quadrature phase shift keying (QPSK) modulation and the channel is considered to be Rayleigh fading and independent for each frame of 120 symbols. The traditional channel estimation which the training sequences are Walsh orthogonal codes with a length of 32 symbols was employed. Alamouti codes was used for the case of 2 transmission nodes and Tarokh STBC rate 3/4 for the case of 3 and 4 transmission nodes. For the reliability of result, at least 10^6 frames have been sent for assuring the $BER = 10^{-5}$.

The cooperative reception nodes are considered to be perfectly synchronized to the source node S for simplicity and the independent evaluation of cooperative transmission synchronization error impact. The difference between the delays of each MISO transmission channel is negligible in comparison with the different clock timer. The contribution of transmission delay is sometimes neglected or included in the different timer clock. Neglecting timer drift in the nodes clock, the clock jitters 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 clock. For our simulation, the synchronization error δ_k is considered to have a uniform distribution in $[-\Delta T_{syn}/2, \Delta T_{syn}/2]$ with ΔT_{syn} the synchronization error range.

A. Effect of Transmission Synchronization Error

In Fig. 3, simulation results of cooperative MISO 2-1 and MISO 4-1 systems with 2 and 4 transmit nodes (coop 2-1, coop 4-1) are presented for the synchronization error ranges $\Delta T_{syn} = 0.2T_s, 0.5T_s$ and the presence of channel estimation error in the receiver.

We can see that for the case of synchronization error range $\Delta T_{syn} = 0.2T_s$, the cooperative MISO system is rather tolerant and the performance degradation is acceptable until $\Delta T_{syn} = 0.5T_s$. For the $BER = 10^{-4}$, in cooperative MISO 2-1, $0.3dB$ and $3dB$ are lost for a synchronization error range of $0.2T_s$ and $0.5T_s$, respectively. And in cooperative MISO 4-1, $0.5dB$ and $3.9dB$ are lost for error range of $0.2T_s$ and $0.5T_s$, respectively. The performance degradation is increased

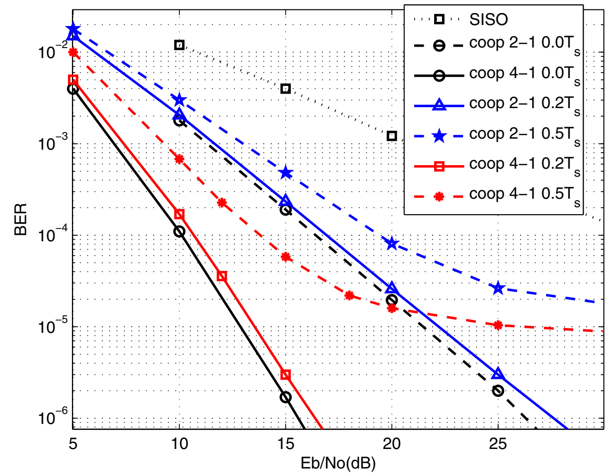

Fig. 3. Effect of transmission synchronization and channel estimation errors

with the number of cooperative transmit antennas. Moreover, ΔT_{syn} as large as $0.5T_s$, we begin to see some performance saturation of cooperative MISO in large Eb/N_0 range due to the ISI generated by the synchronization error, the non-orthogonal combination and channel estimation error. And for a large synchronization error range as $0.7T_s$, the cooperative MIMO performance degrades quickly.

B. Effect of Cooperative Reception Techniques

For the compromise of performance and energy consumption of cooperative reception technique, let us consider the amplification factors of the forward-combine technique (strategy 1) $K_1 = \sqrt{4}$ and $K_1 = \sqrt{8}$ ($6dB$ and $9dB$ energy amplification). In order to ensure the same cooperative transmission energy, we choose the amplification factors of combine-forward technique (strategy 2) $K_2 = K_1/\sqrt{3}$ and $K_2 = K_1/\sqrt{5 \times 3/4}$ respectively for $N_t = 2$ and $N_t = 4$. The performance of cooperative MIMO systems in the presence of the synchronization error range $\Delta T_{syn} = 0.2T_s$ is presented in Fig. 4. The performance degradation of cooperative MIMO systems using strategy 1 (R1 in Fig. 4) with 2 and 4 cooperative reception nodes is acceptable for the amplification factor $K1 = \sqrt{4}$ and negligible for $K1 = \sqrt{8}$. The degradation increases when the number of cooperative reception nodes increases or the amplification factor decreases.

For an amplification factor of $K1 = \sqrt{8}$ and the $BER = 10^{-4}$ requirement, we lost $0.1dB$ or $2dB$ by using cooperative reception strategy 1 or strategy 2 (R2 in Fig. 4) in cooperative

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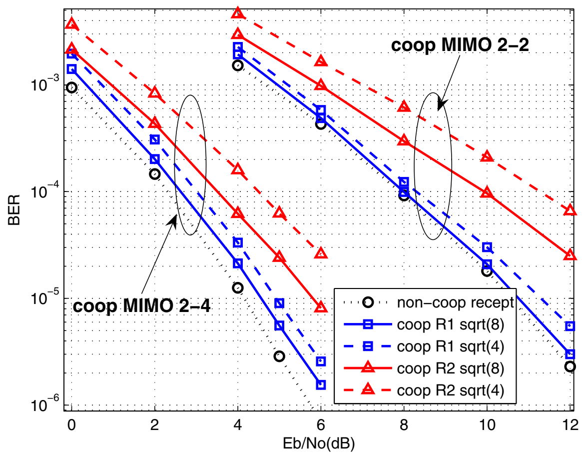

Fig. 4. Performance of cooperative reception techniques, $\Delta T_{syn} = 0.2T_s$

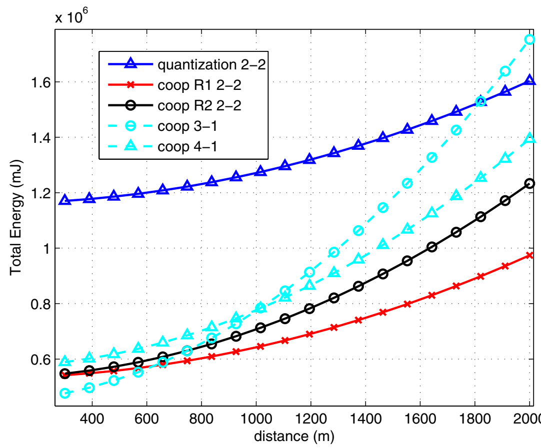

Fig. 5. Total energy consumption of cooperative MIMO with different reception techniques vs. cooperative MISO, $\Delta T_{syn} = 0.2T_s, BER = 10^{-5}$

MIMO 2-2 systems. And in a cooperative MIMO 2-4 system, we lost $0.2dB$ or $1.2dB$ by using cooperative reception strategy 1 or strategy 2.

BER performance of strategy 1 is better than strategy 2 because of the smaller effective Gaussian noise. However in strategy 2, most of the signal processing and combination calculations are distributed among the cooperative nodes. For some ad-hoc WSN applications, that is better than strategy 1 where all calculations are centralized in the destination node D and the energy consumption of D will be more than other cooperative reception nodes. Considering the energy consumption model with the same system parameters as in [3], the energy consumption of cooperative MIMO systems using quantization reception technique and our two proposed cooperative reception strategies is presented in Fig. 5 (including the energy consumption of cooperative MISO 3-1 and 4-1 with synchronization error $\Delta T_s = 0.2T_s$). In comparison with the quantization technique used in [1], the two proposed strategies can significantly reduce the transmission time in cooperative reception, which reduces the cooperative energy consumption and total energy consumption.

For distances greater than 600 m, we can see the energy consumption advantage of cooperative MIMO 2-2 over the cooperative MISO 3-1 and 4-1.

VI. Conclusion

The effects of synchronization error, channel estimation error and cooperative reception techniques on the performance of cooperative MIMO were investigated in this paper. The performance degradation increases with the synchronization error range and the number of cooperative transmission and reception nodes. However, the cooperative MIMO system is rather tolerant for small ranges of synchronization error and the degradation is negligible for synchronization error range as small as $0.2T_s$.

Two cooperative reception techniques were also proposed for better energy-efficiency than the previous cooperative reception technique. The first one consists of performing the whole space-time combination at the destination node, and in the second one signal processing and space time combination are done independently at each cooperative node. The cooperative MIMO system performance degradation due to the noise of cooperative reception techniques decreases as the amplification factor increases and is negligible for an amplification factor of cooperative reception technique equal to $9dB$.

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