Synchronization for Cooperative MIMO in Wireless Sensor Networks

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Abstract. The application of Wireless Sensor Networks (WSNs) is hindered by the limited energy budget available for the member nodes. Energy aware solutions have been proposed for all tasks involved in WSNs, such as processing, routing, cluster formation and communication. With communication being responsible for a large part of the energetic demand of WSNs energy efficient communication is paramount. The application of MIMO (Multiple-Input Multiple-Output) techniques in WSNs emerges as a efficient alternative for long range communications, however, MIMO communication require precise synchronization in order to achieve good performance. In this paper the problem of transmission synchronization for WSNs employing Cooperative MIMO is studied, the main problems and limitations are highlighted and a synchronization method is proposed.

Keywords: multiple-in multiple-out (MIMO) systems, wireless sensor networks (WSNs), synchronization

1 Introduction

Recently wireless sensor networks have emerged as the tool of choice for a large number of emerging applications.Their usage ranges from military applications, such as battlefield surveillance and targeting, to health care applications, such as automating drug applications in hospitals [1]. However, the large scale application of WSNs is still hindered by the limited energy budget available to the nodes that compose such network and due to the fact that, since WSNs are first choices for deployment in harsh and hard to reach environments, replacing individual nodes, or their batteries, may become unpractical. Extensive research has been conducted with the aim of maximizing the energy efficiency of WSNs [2].

Solutions aiming to minimize energy consumption in WSNs have been proposed trough different layers, with energy efficiency being analyzed for all tasks involved in WSNs. Energy efficient protocols for medium access control have been proposed on [3, 4], while many proposals focus on enhancing energy efficiency in the network layer, by means of energy efficient routing protocols [5, 6]. Other proposals consider energy aware processing approaches for communications among sensor nodes in WSN, as presented in [7], as well as alternatives solutions on the physical layer [8, 9].

Since communication is responsible for a large part of the energetic demand in WSNs, special attention has been given to the study of energy efficient communication methods, with multi-hop communication being a widely used technique to obtain improved energy efficiency and maximize network life time by spreading energy consumption over different nodes [10]. Multi-hop takes advantage of the cooperative nature of WSNs in order to split the distance involved in communication by employing intermediary nodes to forward data packets. Since free space loss is not linear, splitting the distance results in reduced power demand, thus minimizing energy consumption. However care must be taken when applying multi-hop in order to avoid reduced energy efficiency, as presented in [10].

Also taking advantage of the cooperative nature of WSNs, the formation of Cooperative MIMO clusters have been proposed. In this context, the work presented in [11] proposes a cooperative MIMO system used in the communication amongst the sensor nodes, in [12] cooperative MIMO transmissions are studied, and (Single-Input Multiple-Output) SIMO and (Multiple-Input Single-Output) MISO cases are taken into account. In [13] a energy analysis considering single-hop, multi-hop and cooperative MIMO is presented. Results obtained in these works show that cooperative MIMO is only advantageous when long distances are involved. Nevertheless, the advantages of cooperative MIMO are not restricted to energy efficiency. The faster data rates achievable with MIMO system allow the interaction between fast moving mobile as well as traditional static nodes [14, 15]. Cooperative MIMO also allows the application of antenna array techniques such as beam forming or direction of arrival estimation can be employed.

The application of Cooperative MIMO results in reduced hardware complexity on single nodes, allowing the application of the technique with minimal to no modifications in the hardware of existing WSNs. This complexity is transfered to the software responsible for managing the communication involving a large number of nodes. One of the most critical aspects of successful MIMO communications is the proper synchronization between the nodes involved.

In this paper, we analyze the behavior of a simple synchronization mechanism for WSNs employing cooperative MIMO. The efficiency of the proposed methods is studied by means of simulations. The remainder of this paper is divided into six sections. In section 2 the principles of MIMO communication are presented. Traditional equalization methods are introduced and their performances are compared with standard SISO communications. In section 3 the cooperative MIMO transmission technique for WSNs is briefly presented. In section 4 two algorithms for synchronizing Cooperative MIMO clusters are presented. In section 5 simulation results are shown and discussed. Conclusions are drawn in section 6.

2 MIMO Communications

MIMO communications consist of the use of multiple antennas for data transmission and reception. The use of multiple antennas to achieve benefits in various aspects of communication such as a lower bit error ratio (BER) or increased throughput.

This work focuses on MIMO techniques to achieve spatial multiplexing. Spatial multiplexing is used to transmit parallel bit streams simultaneously over the same frequency. MIMO also results in the array gain phenomenon, which is the increase of effective received power, due to multiple copies of the signal being received on different antennas.

Consider a sequence of symbols

$$\boldsymbol{s} = [s_1,s_2,...,s_N], \tag{1}$$

that needs to be transmitted over a wireless channel. The channel is assumed to be flat fading, which means that channel impulse response is constant over the frequency domain, also equivalent to considering the transmitted signal to be narrow-band. The impulse response between antennas is assumed to be uncorrelated and constant over a transmission period.

A technique called V-BLAST [16] which is employed for MIMO communications in this work, is of particular interest. In a normal transmission at each time slot a single symbol would be transmitted over the channel while, in the case of V-BLAST transmission, the symbols are grouped into multiple parallel streams. In the case shown in Figure 1, groups of size Q , and transmitted over the same time slot.

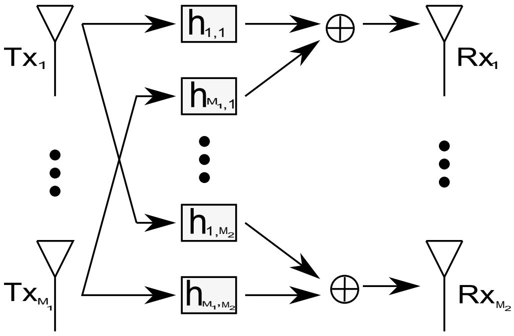

Fig. 1. Example of a Q by Q MIMO system

The received signal at a given receiving antenna x_i at a given time slot can be modeled as

$$x_i = \sum_{k=1}^{Q} h_{k,i} \cdot s_k + n_i, \tag{2}$$

where $h_{k,i}$ represents the complex impulse response of channel between transmit antenna k and receive antenna i and s_k is the symbol transmitted by the k-th antenna. n_i is the noise present at the i-th receiving antenna during sampling. Equation 2 can be rewritten in matrix form as

$$x_i = [h_{1,i}, h_{2,i}, ..., h_{Q,i}] \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_Q \end{bmatrix} + n_i. \tag{3}$$

Equivalently a matrix representation for the signals received at all receiving antennas can be written as

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_Q \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{2,1} & \cdots & h_{Q,1} \\ h_{1,2} & h_{2,2} & \cdots & h_{Q,2} \\ \vdots & \vdots & \cdots & \vdots \\ h_{1,Q} & h_{2,Q} & \cdots & h_{Q,Q} \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_Q \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_Q \end{bmatrix}, \tag{4}$$

$$\Updownarrow$$

$$\boldsymbol{x} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}, \tag{5}$$

The first step necessary in order to estimate the transmitted symbols is to estimate the channel matrix $\boldsymbol{H}$. An estimate $\hat{\boldsymbol{H}}$ can be obtained by transmitting a set of pilot symbols vectors $\boldsymbol{P} = [\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_U] \in \mathbb{C}^{Q\times U}$ where $\boldsymbol{p_i} \in \mathbb{C}^{Q\times 1}$ and $U > Q$

$$\hat{\boldsymbol{H}} = \boldsymbol{X}\boldsymbol{P}^{\dagger}, \tag{6}$$

here $\boldsymbol{P}^{\dagger} = \boldsymbol{P}^{\mathrm{H}}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}})^{-1}$ is known as the right pseudo inverse of matrix $\boldsymbol{P}$ and the operator $^{\mathrm{H}}$ denotes the conjugate transposition. For a more detailed discussion on trade offs and optimal pilot symbol selection for MIMO channel estimation the reader may refer to [17, 18].

Once the channel matrix estimate $\hat{\boldsymbol{H}}$ has been obtained the receiver needs to equalize the received symbols in order to obtain an estimate of the transmitted symbols, various methods exist for performing this equalization, here the Zero Forcing, Minimum Mean Square Error (MMSE) and Maximum Likelihood (ML) methods are analyzed.

The Zero Forcing method consists of finding a matrix $\boldsymbol{W}$ that satisfies $\boldsymbol{W}\boldsymbol{H} = \boldsymbol{I}$, where $\boldsymbol{I}$ is an identity matrix. This matrix in given by

$$\boldsymbol{W} = (\hat{\boldsymbol{H}}^{\mathrm{H}}\hat{\boldsymbol{H}})^{-1}\hat{\boldsymbol{H}}^{\mathrm{H}}, \tag{7}$$

as Equation 7 shows, calculation $\boldsymbol{W}$ is equivalent to calculating the left pseudo inverse of $\hat{\boldsymbol{H}}$. An estimate of the transmitted symbols is given by

$$\hat{\boldsymbol{S}} = \boldsymbol{W}\boldsymbol{H}\boldsymbol{S} + \boldsymbol{W}\boldsymbol{N}, \tag{8}$$

Equation 8 shows that depending on the structure of $\boldsymbol{W}$ the received noise might be amplified at equalization, thus degrading the estimate of the transmitted signals.

MMSE equalization tries to solve to problem the of noise amplification by taking into account the noise when calculating the equalizer. MMSE tries to find a matrix $\boldsymbol{W}$ that minimizes the criterion

$$E\left\{[\boldsymbol{W}\boldsymbol{X}-\boldsymbol{S}][\boldsymbol{W}\boldsymbol{X}-\boldsymbol{S}]^{\mathrm{H}}\right\}, \tag{9}$$

where $\boldsymbol{W}$ is obtained by

$$\boldsymbol{W}=(\hat{\boldsymbol{H}}^{\mathrm{H}}\hat{\boldsymbol{H}}+\mathrm{N}_0\boldsymbol{I})^{-1}\hat{\boldsymbol{H}}^{\mathrm{H}}, \tag{10}$$

where N_0 is the power of the received noise. Notice that in the absence of noise Equation 10 reduces to 7.

Finally, ML equalization tries to find a matrix $\hat{\boldsymbol{S}}$ that minimizes the criterion

$$Err=\left|\boldsymbol{X}-\hat{\boldsymbol{H}}\hat{\boldsymbol{S}}\right|^2, \tag{11}$$

this is done numerically by testing all possible combinations of $\hat{\boldsymbol{S}}$ and deciding on the one which leads to the minimum Err. Computationally efficient alternatives exist for the ML method such as spherical decoding.

Figure 2 shows a comparison between standard SISO systems and a 2 × 2 MIMO configuration using the equalization methods discussed previously. The ML equalization method is clearly the most efficient in terms of minimizing the bit error rate (BER) of the received bit stream, thus it is the method of choice for the remainder of this work.

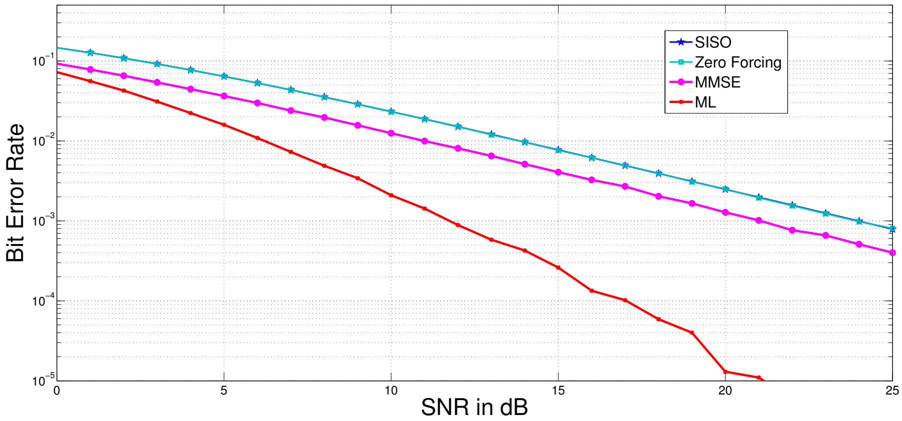

Fig. 2. Performance comparison between standard SISO systems and 2 × 2 MIMO systems using Zero Forcing, MMSE and ML equalization

3 Cooperative MIMO

Wireless sensor networks are cooperative by nature, taking advantage of this behavior a cooperative MIMO approach can be implemented in order to minimize the energy spent with communication between nodes. As opposed to traditional MIMO systems, where a set of antenna is present at the transmitter and at the receiver, the cooperative MIMO utilizes a virtual MIMO approach, where the multiple antennas involved are present at different systems (different nodes). This avoids the increased hardware complexity involved, which is specially important in WSNs due to their limitations in term of size and hardware complexity. The additional complexity is transferred to the communication protocol. Figure 3 presents the steps involved in a cooperative MIMO communication.

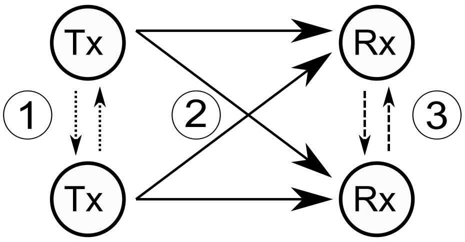

Fig. 3. Steps involved in a cooperative MIMO transmission

The first step represented by ① consists of synchronization and exchanging data that needs to be transmitted, if both sensors need to transmit data this exchange is not necessary, as each sensor can transmit its own data. Note that since WSNs usually operate at low data rates the synchronization does not need to be extremely precise as the symbol duration is usually long enough so that small or even moderate offset in transmission instants does not result in errors. The same can be said for the synchronization in the reception. Small offsets in the sampling instant in the reception will not interfere with the overall system performance. On ② both sensors transmit different symbols at the same time slot according to the BLAST architecture discussed above. Space time block codes (STBCs) such as [19][20] can be chosen according to the necessary or expected behavior of the network. Finally on ③ the receiving sensors sample and quantify the received symbols and exchange the quantified data so that the originally transmitted symbols can be extracted. If the data is destined to only one sensor of the receiving cluster this exchange becomes uni directional. Another option is to exchange only a portion of the received information so that every sensor is responsible for part of the decoding, alleviating the computational burden of a single node.

4 Cooperative MIMO synchronization

The problem of network wide synchronization in WSNs has been extensively studied [21–24]. Algorithms have been proposed in order to keep a common clock across the entire network. Most solutions suggest keeping a relationship between clocks across the network instead of trying to forcefully synchronizing clocks across all nodes. For networks relying on GPS synchronization it has been shown that very precise synchronization can be achieved, with variations being kept as small as 200 ns [25]. However, relying on GPS receivers results in increased energy demand and in a WSN that is no longer self contained. Broadcast synchronization schemes capable of achieving 1 μs of accuracy have been proposed [26].

For networks operating at a 256 kbps rate and using BPSK modulation the resulting symbol duration is approximately 4 μs, a synchronization error of 1 μs represents 25 % of the symbol duration. MIMO communications demand precise synchronization in order to achieve proper decoding, it is clear that another mean of synchronizing transmitting nodes and receiving nodes is necessary.

A simple method of synchronization is to over sample a received tonal wave and compare it with a reference wave kept internally. This can be done by using a sliding matched filter to digitally find the delay, in samples, that results in maximum correlation with the received wave. Since the networks are assumed to already be synchronized with a maximum error of 1 μs the range of comparison is reduced.

The first proposed method consists in scheduling a tonal transmission between a pair or tonal broadcast to a group of nodes, the sampling on the receiving nodes will start at the scheduled time, and the clock error can be compensated. To avoid problems created by sampling with a difference of more than a period of the tonal wave the time length of the tonal transmission needs to be known to the receiving nodes, this way, if a signal with less than the expected length is received the receiver can compensate by starting sampling earlier or later, and adjust its internal clock accordingly. Figure 4 presents the proposed mechanism. The sampling synchronization error d can be compensated prior to applying the sliding correlator achieve precise synchronization.

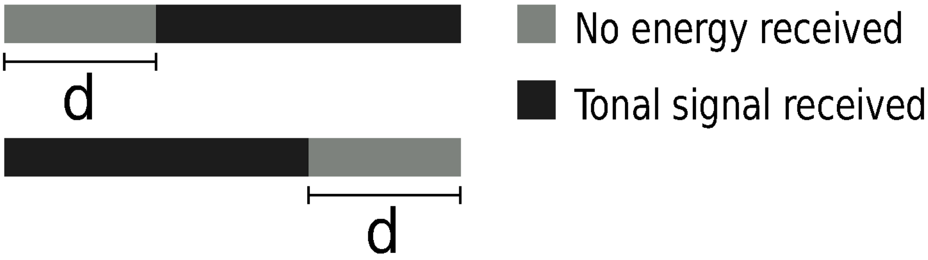

Fig. 4. Illustration of a sampling synchronization error

Once sampling is synchronized a finner synchronization can be done by applying a matched filter, the maximum theoretical error in the absence of noise is this case is equivalent to the sampling interval employed by the receiver. Figure 5 depicts how the sliding correlator is applied in order to achieve total synchronization.

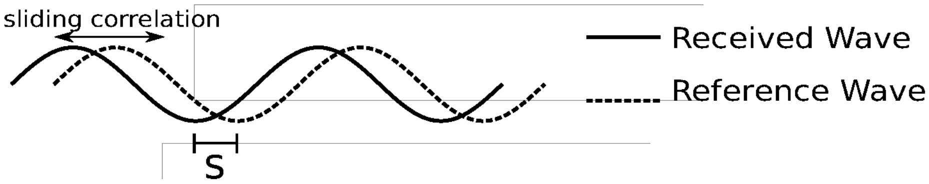

Fig. 5. Illustration of sliding correlation synchronization

It is important to notice that this synchronization does not take into account the propagation time of the transmitted wave, this correction can be done by measuring the approximate distance between a pair of sensors. This can be done, for example, by means of the RSSI. Another alternative is to employ DOA techniques such as MUSIC [27] or ESPRIT [28] to map relative sensor positions in the network.

Finally Figure 6 presents the steps involved in achieving complete synchronization between a pair of nodes.

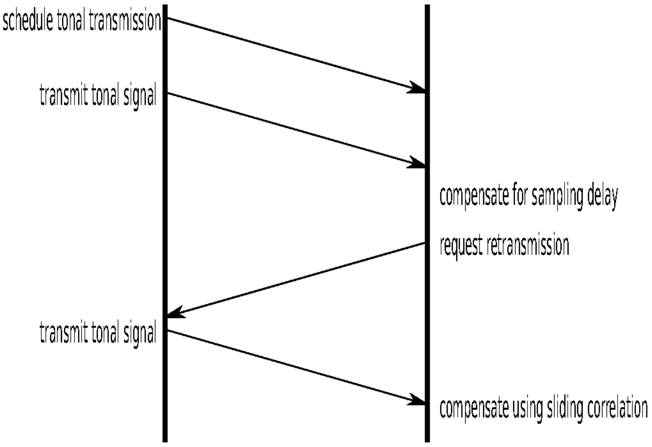

Fig. 6. Steps necessary for synchronization

A second and more robust method is to apply subspace methods used for parameters estimation in order to estimate the delay of the received wave with regard to the reference wave. This technique was first proposed in the context of achieving precise synchronization for GPS receivers [29] and its usage can be extended to the problem at hand. The time MUSIC consists of substituting the common antenna array configuration know in direction of arrival (DOA) estimation problems for a correlator bank configuration. The received signal is correlated to a set of forward and backward delayed replicas and a delay spectrum can be obtained similar to the spatial spectrum obtained in the original MUSIC.

The correlator bank transforms the input according to

$$\boldsymbol{x} = \boldsymbol{Y}, \tag{12}$$

where $\boldsymbol{x}$ is a vector containing the received signal and $\boldsymbol{Y}$ is a matrix with its rows containing the cross correlation between the received signal and its respective correlator. With $\boldsymbol{Y}$ an estimate of the covariance of the received signal trough the bank can be obtained by

$$R_{\boldsymbol{YY}} = \mathrm{E}\{\boldsymbol{Y} \times \boldsymbol{Y}^{\mathrm{H}}\}, \tag{13}$$

where E is the expectation operator. The covariance matrix can be decomposed using the eigendecomposition, yielding

$$R_{\boldsymbol{YY}} = \boldsymbol{\Sigma \Lambda \Sigma^{-1}}. \tag{14}$$

By removing the eigenvector related to the strongest eigenvalue an estimate of the noise subspace $\boldsymbol{Q}_n$ can be obtained. Finally a delay spectrum can be obtained by

$$P(d) = \frac{\boldsymbol{a}(d) \times \boldsymbol{a}(d)^{\mathrm{H}}}{\boldsymbol{a}(d)^{\mathrm{H}} \times \boldsymbol{Q}_n \times \boldsymbol{Q}_n^{\mathrm{H}} \times \boldsymbol{a}(d)},$$

where $\boldsymbol{a}(d)$ is the cross correlation between a signal that would be received with a given delay d and the bank of correlators.

5 Simulation Results and Discussion

In order to verify the precision of the synchronization possible with the proposed first method numerical simulations were performed. The first result that needs to be analyzed is the behavior of the proposed method in the presence of noise. Figure 7 depicts the synchronization precision achieved in seconds in relation to different levels of white Gaussian noise. The transmitted signal has a frequency of 2.4 GHz, 5000 samples are used for the sliding correlator and the tonal wave is sampled at twice the Nyquist rate.

It is possible to notice that even for low SNR scenarios the proposed method is capable of achieving synchronization in the order of 10^{-8} seconds, two order of magnitude superior to what is currently achievable in network synchronization methods [21–24].

Another important factor that needs to be analyzed is the performance of the proposed method for different numbers of samples. For this simulation the

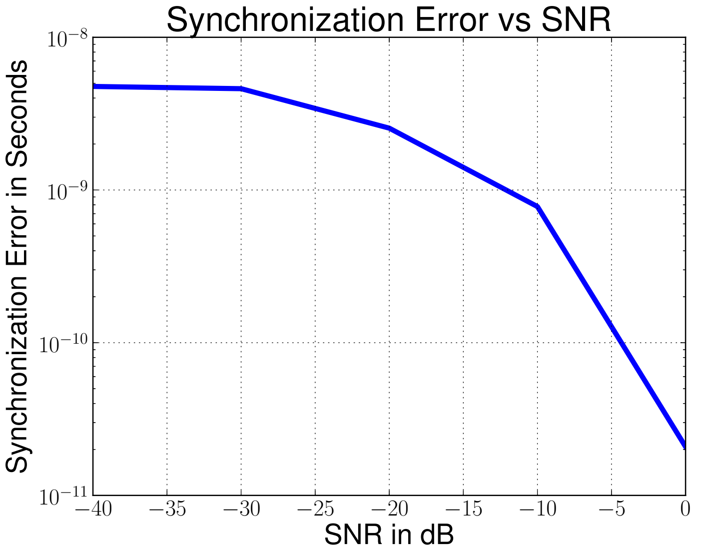

Fig. 7. Results for synchronization error in seconds versus SNR

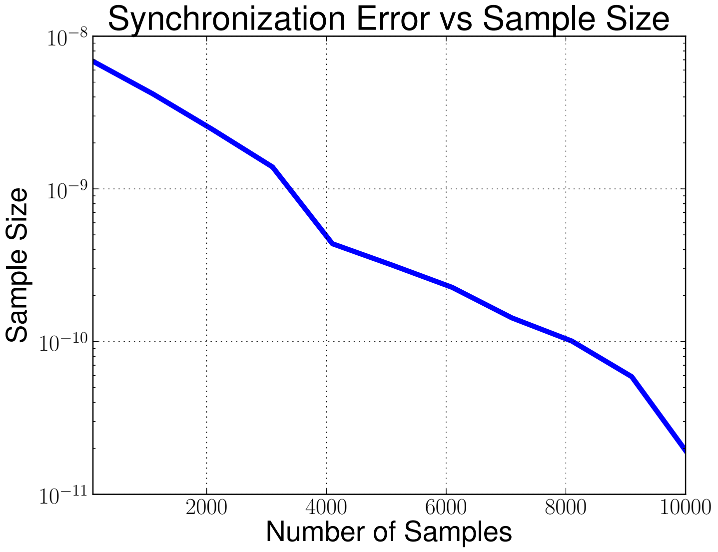

Fig. 8. Results for synchronization error in seconds versus sample size

SNR is kept fixed at -15 dB and the sampling rate is twice the Nyquist rate. Sample size ranges from 100 to 10000.

Figure 8 presents the synchronization results for different sample sizes. It is possible to notice that, as expected, increased sample sizes result in increased accuracy. However, this comes at the cost of more time and energy being spent to perform synchronization and at the cost of increased computational complexity, since correlation complexity increases with the increased number of samples.

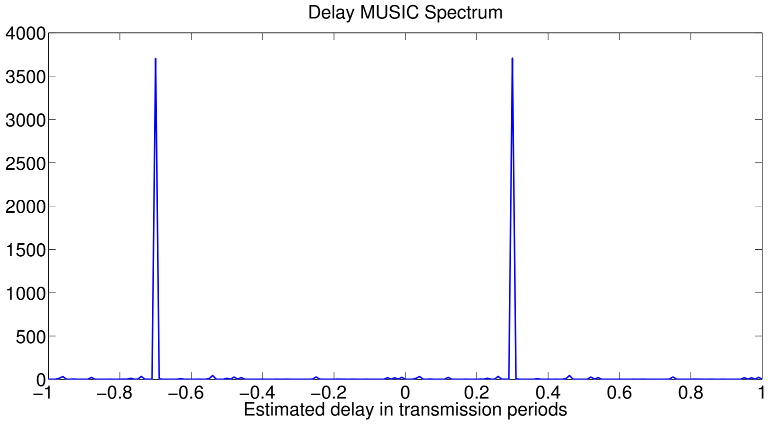

Fig. 9. Delay MUSIC spectrum

Figure 9 presents the spectrum obtained with the delay MUSIC technique. Notice that this technique is also unable to tell delays that are more than one transmission period apart, since their correlation is the same. Thus the proposed step of measuring the received energy is also necessary.

Figure 10 presents the delay estimation error for the delay MUSIC technique, notice that this technique is extremely robust to noise in the transmission, allowing very precise estimation even at an SNR greatly below the noise floor. This however, comes at the cost of increased computational complexity, since it is necessary to calculate the covariance matrix of the signal after the correlator bank and its eigendecomposition. Also, a search mechanism needs to be employed to find the peaks over the obtained delay spectrum.

Note that transmission rates in WSNs are usually very low, with 2000 kb/s being considered a very high rate, and only achievable at small distances between nodes under low SNR. Rates ranging between 80 kb/s - 250 kb/s are typical data rates for WSNs in operation today [30, 31]. High data rate systems usually employ modulations with large constellations, resulting in increased symbol duration. This allows the proposed techniques to be efficient in allowing communications for even such networks.

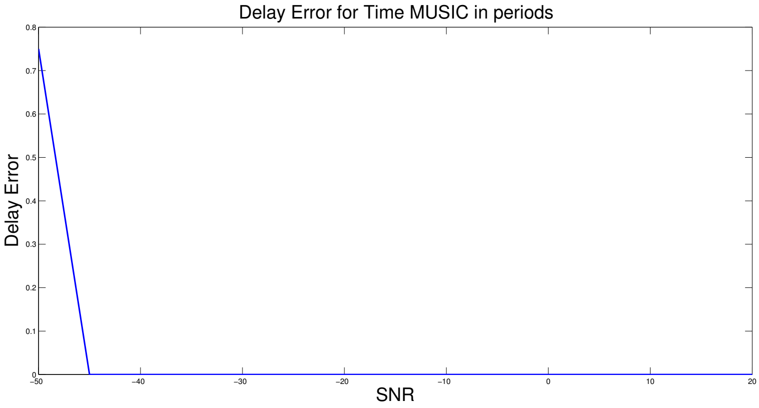

Fig. 10. Delay MUSIC mean error

6 Conclusion

This paper presents a initial approach for precise sensor synchronization in WSNs in order to employ Cooperative MIMO communications. Cooperative MIMO communications are capable of providing enhanced energy efficiency in WSNs by providing improved long range communications. However, since MIMO communications involve the decoding of multiple symbols transmitted at the same time slot, precise synchronization is required for proper decoding. Taking advantage of existing network synchronization protocols a method is proposed in order to achieve synchronization compatible with the transmission rate of WSNs in operation today. Simulation results corroborate that the proposed techniques are capable of such synchronization. Further study is planed in enhanced synchronization methods, employing reduced sample sizes or taking advantage of usual SISO traffic to avoid overhead specific to node synchronization.

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