Distributed CS-CDMA Cooperative Wireless Sensor Networks

Rodrigo Pereira David, César S. Medina and Raimundo Sampaio-Neto

***Abstract*—In this paper, cooperation in CS-CDMA wireless sensor networks (WSN) is considered in order to improve the quality of the estimates of the sensor messages used by the fusion center to generate the final decision. In the proposed cooperative wireless sensor networks each node forwards its own decisions and relays the message of a neighbor sensor deploying the detect-and-forward cooperation. Simulations have shown that with cooperative distributed detection and exploitation of spatial diversity, better detection error performance is achieved and the number of sensor can be reduced. The performance gain is however more significant in flat fading environment, since in multipath environment the non-cooperative CS-CDMA WSN already exploits efficiently the multipath diversity.**

Keywords— Wireless Sensor Networks, Detect-and-Forward, cooperation, CS-CDMA transmission

I. INTRODUCTION

In a typical distributed detection scenario, the information of interest is collected locally by a large number of low-cost sensors. Each sensor then delivers a summary of its own observation to a remote fusion center where the received data is processed using a pre-determined fusion rule, to decide on one of the possible hypothesis [1-6]. The reliability of the sensor decisions as observed in the fusion center depends of both the quality of the sensor observation and the quality of the transmission channel between the sensor and the fusion center, measured in terms of signal-to-noise ratio (SNR). Distributed detection with relay nodes has been investigated in [7-8]. In this scheme, relay nodes are deployed in the wireless sensor network to forward the sensor node data, and thus enhance the transmission performance. In those works, orthogonal and flat fading transmission channels are assumed. However, the premise of orthogonal channels is hard to achieve in applications involving dense, low-power, distributed wireless sensor networks where it is likely that all nodes share common available bandwidth. In such cases, a multiple access scheme as CDMA may allow all low-power nodes to access the channel simultaneously and go to an energy saving mode, thus preserving sensor batteries. Some works in non-cooperative CDMA based wireless sensor networks (WSN) were published in [9-10] under the assumption of flat fading channels. Nevertheless, frequency selective channels would be more natural for the CDMA transmission system used in the proposed WSN.

In the presence of frequency selective channels the performance of the CDMA systems may degrade substantially due to strong multiple access interference (MAI) which results from the loss of orthogonality between the spreading codes used by the sensors. A chip spread code division multiplex access (CS-CDMA) technique [11] was proposed in [12] as the access method for use in a wireless sensor networks in the presence of frequency selective channels. This technique has the property of avoiding MAI in frequency selective channels, thus keeping the premise of orthogonality between sensors transmission. The optimal Bayesian fusion rule for this scheme was derived as well as a less complex suboptimum receiver, which first estimates the decisions transmitted by the sensors and makes the final decision through the majority rule.

In this paper a cooperative CS-CDMA wireless sensor network is studied in environments with multipath and flat channels in order to explore the natural tradeoffs between the increasing of sensor/relay nodes complexity and global detection error performance. In the scheme proposed here each sensor node forwards its own data and relays the data of a neighbor node applying detect-and-forward (DEF) cooperation [13].

The remainder of the paper is organized as follows: Section II presents the system model. In Section III the cooperative wireless sensor network model is discussed. Simulation results and performance evaluation of the proposed cooperative CS-CDMA WSN in different channel environments are presented in Section IV. Finally, conclusions are drawn in Section V.

Notation: Bold upper case characters represents matrix; bold lowercase denotes vectors. The operators $(.)^T, (.)^H$ denotes transpose and Hermitian respectively , the operator $\mathbb{E}[.]$ denotes the expected value and $Q(.)$ represents the Gaussian tail distribution.

II. SYSTEM MODEL

We consider a binary hypothesis testing problem in a wireless sensor network connected to a data fusion center in a distributed parallel architecture. Let H_0 and H_1, denote the null and alternative hypothesis with prior probabilities $\Pr(H_0) = p_0$ and $\Pr(H_1) = p_1$, respectively. In each observation period, sensors make independent decisions, u_k, based on its local observation, which under each hypothesis is assumed to be:

$$\begin{aligned} H_0:\ y_k &= -d + n_k \qquad k = 1,2,\dots,\mathrm{K} \\ H_1:\ y_k &= \ \ d + n_k \qquad k = 1,2,\dots,\mathrm{K} \end{aligned} \tag{1}$$

where K is the number of sensors, d is a known constant and n_k are mutually independent Gaussian random variables with zero mean and variance σ^2.

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Each sensor processes its noisy observation y_k independently to generate the local decision $u_k \in \{0,1\}$ which is the output of a likelihood ratio threshold test (LRT). Assuming a binary phase keying (BPSK) system (for simplicity), the binary local decisions are mapped to symbols $b_k \in \{-1,+1\}$ and then transmitted using a CS-CDMA transmission system. In the CS-CDMA scheme [11], all the N chips of a code sequence $\mathbf{c}_k = [c_{k,0} \ldots c_{k,\mathrm{N}-1}]^T$, with $c_{k,j} \in \left\{\pm\frac{1}{\sqrt{N}}\right\}$, $\|\mathbf{c}_k\|^2 = 1$, are multiplied by the same data symbol vector $\mathbf{b}_k$ of length P.

The block transmitted by sensor k in the j-th transmission interval, $j = 0,1,..,\mathrm{N}-1$, is given by $\mathbf{b}_k c_{k,j}$. The components of $\mathbf{b}_k c_{k,j}$ are serially transmitted through a multipath channel. The discrete equivalent channel linking sensor k to the receiver (the fusion center or relay node) is modeled as a FIR filter $\mathbf{h}_k$ of length L whose coefficients are the samples of the equivalent low-pass impulse response channel taken at a rate $1/\mathrm{T_o}$, where $\mathrm{T_o}$ is the duration associated to the components of the block $\mathbf{b}_k c_{k,j}$:

$$\mathbf{h}_k = [h_{k,0} \ldots h_{k,\mathrm{L}-1}]^T. \quad (2)$$

In order to avoid inter-block interference in the received signal, we propose here that the vector $\mathbf{b}_k$ be formed by the sensor k message b_k concatenated with $\mathrm{L}-1$ zeros (admitting knowledge of the channel length) therefore $\mathbf{b}_k = [b_k \; \mathbf{0}_{\mathrm{L}-1}]^T$.

Assuming perfect symbol synchronism the composite signal to be processed at the receiver, is given by [12]:

$$\mathbf{r}(j) = \sum_{k=1}^{K} b_k \mathbf{h}_k c_{k,j} + \mathbf{n}_w(j), j = 0,1,\ldots,\mathrm{N}-1 \quad (3)$$

where $\mathbf{n}_w(j)$ is the receiver white noise vector with zero mean and covariance matrix $\mathbb{E}[\mathbf{n}_w(j)\mathbf{n}_w(j)^H] = \sigma_w^2 \mathbf{I}_\mathrm{L}$ where $\mathbf{I}_\mathrm{L}$ denotes the identity matrix L x L.

By collecting N consecutive received signals the L x N matrix, $\mathbf{R} = [\mathbf{r}(0) \ldots \mathbf{r}(\mathrm{N}-1)]$ is formed and can be written as:

$$\mathbf{R} = \textstyle\sum_{k=1}^{K} b_k \mathbf{h}_k \mathbf{c}_k^T + \mathbf{N}. \quad (4)$$

where $\mathbf{N} = [\mathbf{n}_w(0) \ldots \mathbf{n}_w(\mathrm{N}-1)]$

Assuming that the CS-CDMA system uses orthogonal spreading codes, then the signal transmitted by sensor k can be obtained as:

$$\tilde{\mathbf{r}}_k = \mathbf{R}\mathbf{c}_k = b_k \mathbf{h}_k + \mathbf{n}_k \qquad k = 1,2,\ldots,\mathrm{K} \quad (5)$$

where the noise vector $\mathbf{n}_k = \mathbf{N}\mathbf{c}_k$ is complex Gaussian with zero mean and covariance matrix $\mathbb{E}[\mathbf{n}_k \mathbf{n}_k{}^H] = \sigma_w^2 \mathbf{I}_\mathrm{L} = \sigma_w^2 \mathbf{I}_\mathrm{L}$.

Therefore the use of the CS-CDMA scheme presented here, allows the ideal decoupling of the k sensors messages at the fusion center, despite the propagation through frequency selective multipath channels.

We now consider a suboptimum detect-and-fuse receiver presented in [12] which is implemented in two stages. The first one detects the transmitted symbols, while the second applies the fuse rule to make a global decision. In this work, the vector $\tilde{\mathbf{r}}_k$ in (5) is used as input to the first stage detector in order to estimate b_k and, since the use of the CS-CDMA scheme eliminates MAI, the problem becomes the detection of antipodal vectors in the presence of AWGN. The optimum maximum likelihood (ML) detector for the vector $\tilde{\mathbf{r}}_k$ is a filter matched to the channel vector $\mathbf{h}_k$ followed by a polarity detector:

$$\hat{b}_k = sign\{Re(\mathbf{h}_k{}^H \tilde{\mathbf{r}}_k)\}, k = 1,2,\ldots,\mathrm{K}. \quad (6)$$

Under the assumption that the sensors perform a ML detection (LRT against a unity threshold) for the Gaussian observations given in (1), then the conditional error probabilities $\Pr(\hat{b}_k = -1|H_1)$ and $\Pr(\hat{b}_k = 1|H_0)$ resulting from (6) become identical. In this case it can be shown [2, 4] that the receiver makes the global decision u_0 according to the following optimum fusion rule:

$$u_0 = \begin{cases} 1; & \hat{b}_1 + \cdots + \hat{b}_k \geq \eta \\ 0; & otherwise \end{cases} \quad (7)$$

where $\hat{b}_k$ is the estimate of the sensor k transmitted symbol b_k and the threshold η depends on the *a priori* probabilities p_0 and p_1. For equal *a priori* probabilities the threshold η is zero and then the optimum fusion rule given by (7) reduces to the majority rule [4].

III. COOPERATIVE WIRELESS SENSOR NETWORK

In order to improve the reliability of the final decision u_0 for a fixed number of N sensors, the quality of the sensor message estimate, $\hat{b}_k$, should be enhanced. For this purpose, a cooperative wireless sensor network is presented to exploit spatial diversity and thus providing robustness to channel effects.

In the cooperative WSN proposed here each node works as both sensor and relay as indicated in Fig. 1.

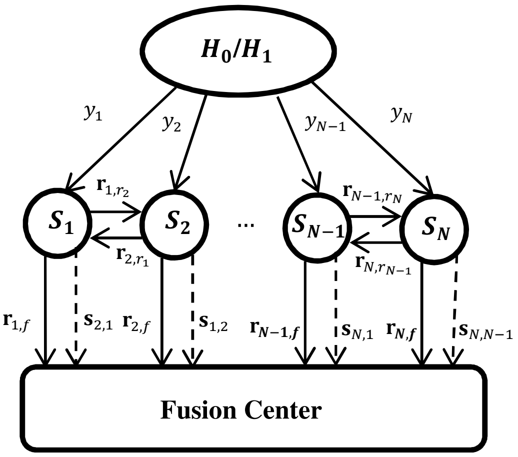

Fig 1. Schematic Diagram for Cooperative Wireless Sensor Network

According to Fig. 1, the WSN comprises a fusion center and a set of distributed homogeneous sensors formed by cooperative nodes, each of which is paired to a corresponding neighbor node. The DEF relaying signal transmissions are separated using TDMA or FDMA. Here we implement the TDMA where the cooperative transmissions occur in two disjoint slots of time. The cooperative strategy is divided in two phases.

In Phase I, each sensor working as both sensor and relay, transmits its CS-CDMA messages directly to the fusion center and to its correspondent paired node. Figs. 2 and 3 details the Phase I signal transmission to the fusion center and to the sensor relay nodes, respectively.

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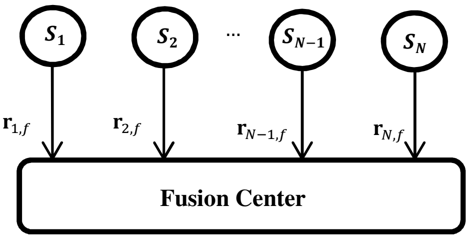

Fig 2. Diagram for Phase I transmission for the Fusion Center

The composed signal received at the fusion center in Phase I given by:

$$\mathbf{r}_{PhaseI}(j) = \sum_{k=1}^{K} \mathbf{r}_{k,f}(j) + \mathbf{n}_w, j = 0,1,\dots,\mathrm{N}-1 \qquad (8)$$

where $\mathbf{r}_{k,f}(j) = \sqrt{P_k} b_k \mathbf{h}_k c_{k,j}$ is the signal transmitted from each sensor to the fusion center with P_k being its average power. The fusion center collects N consecutive signals $\mathbf{r}_{PhaseI}(j)$ and the vector $\tilde{\mathbf{r}}_{k,f}$ corresponding to the sensor k transmission is obtained as in (5).

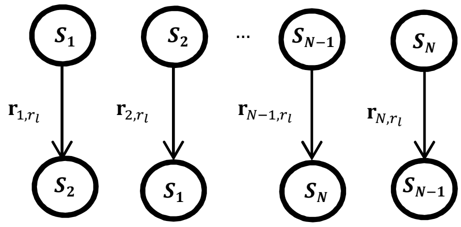

Fig 3. Diagram for Phase I transmission for a sensor relay

Similarly, the signal reaching the sensor relay l in Phase I is given by:

$$\mathbf{r}_{r_l}(j) = \sum_{k=1}^{K} r_{k,r_l}(j) + \mathbf{n}_{w,l}(j), j = 0,1,\dots,\mathrm{N}-1 \qquad (9)$$

where $\mathrm{r}_{k,r_l}(j) = \sqrt{P_k} b_k \mathbf{h}_{k,l} c_{k,j}$ is the signal transmitted from sensor k that reaches sensor relay l. The discrete equivalent channel $\mathbf{h}_{k,l}$ links sensor k to the sensor relay l and $\mathbf{n}_{w,l}(j)$ is the sensor relay white noise vector with zero mean and covariance matrix $\mathbb{E}\left[\mathbf{n}_{w,l}(j)\mathbf{n}_{w,l}(j)^{H}\right] = \sigma_l^2 \mathbf{I}_{\mathrm{L}}$.

After collecting N consecutive signals the matrix $\mathbf{R}_l$ is formed in the sensor relay l as (6):

$$\mathbf{R}_{r_l} = \sum_{k=1}^{K} \sqrt{P_k} b_k \mathbf{h}_{k,l} \mathbf{c}_k^T + \mathbf{N}_l \qquad (10)$$

where $\mathbf{N}_l = \left[\mathbf{n}_{w,l}(0) \dots \mathbf{n}_{w,l}(\mathrm{N}-1)\right]$. Similarly to the fusion center receiver, the desired vector $\tilde{\mathbf{r}}_{k,l}$ corresponding to the signal transmitted by sensor k to its paired sensor relay l is obtained as in (5) resulting in:

$$\tilde{\mathbf{r}}_{k,r_l} = \sqrt{P_k} b_k \mathbf{h}_{k,l} + \tilde{\mathbf{n}}_l \quad k = 1,2,\dots,\mathrm{K} \qquad (11)$$

where the noise vector $\tilde{\mathbf{n}}_l = \mathbf{N}_l \mathbf{c}_k$ is complex Gaussian with zero mean and covariance matrix $\mathbb{E}\left[\tilde{\mathbf{n}}_l \tilde{\mathbf{n}}_l^{H}\right] = \sigma_l^2 \mathbf{I}_{\mathrm{L}}$.

In Phase II, each sensor relay detects coherently the message from its paired sensor by a polarity detector:

$$\tilde{b}_k = sign\{Re(\mathbf{h}_{k,l}^{H} \tilde{\mathbf{r}}_{k,r_l})\}, k = 1,2,\dots,\mathrm{K} \qquad (12)$$

and encodes the estimate $\tilde{b}_k$ in a CS-CDMA scheme, as described in section II. The sensor relay then forwards the new CS-CDMA messages to the fusion center as depicted in Fig. 4. The composed signal received in the fusion center is given by:

$$\mathbf{r}_{PhaseII}(j) = \sum_{l=1}^{K} \mathbf{s}_{l,k}(j) + \mathbf{n}_w, j = 0,1,\dots,N-1 \qquad (13)$$

where $\mathbf{s}_{l,k}(j) = \sqrt{P_l} \tilde{b}_k \mathbf{h}_l c_{l,j}$ is the signal transmitted to the fusion center by the relay l paired to sensor k and P_l is the average power of the sensor relay transmission, $\mathbf{h}_l$ is discrete equivalent channel linking sensor l to the fusion center modeled by (2).

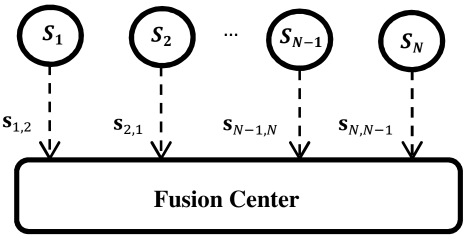

Fig 4. Diagram for Phase II transmission for the Fusion Center

It should be noted that the each sensor cooperative transmission satisfies a total average power constraint $P_T = P_k + P_l$.

Analogously to Phase I, after the fusion center collect N consecutive signals $\mathbf{r}_{PhaseII}(j)$, the vector $\tilde{\mathbf{s}}_{l,f}$ corresponding to sensor relay l transmission is obtained in the fusion center by (5).

Finally, the fusion center groups the received signals, $\tilde{\mathbf{r}}_{k,f}$, from the k sensor and the received signal $\tilde{\mathbf{s}}_{l,k}$ from its respective paired sensor relay to form a joint observation vector $\mathbf{x}_k = [\tilde{\mathbf{r}}_{k,f}{}^T \tilde{\mathbf{s}}_{l,k}{}^T]^T$ modeled by:

$$\mathbf{x}_k = \mathbf{H}\mathbf{b}_k + \mathbf{n}. \qquad (14)$$

where $\mathbf{H} = \begin{bmatrix} \sqrt{P_k}\mathbf{h}_k & 0 \\ 0 & \sqrt{P_l}\mathbf{h}_l \end{bmatrix}$, $\mathbf{b}_k = \begin{bmatrix} b_k \\ \tilde{b}_k \end{bmatrix}$ and $\mathbf{n} = \begin{bmatrix} \mathbf{n}_k \\ \mathbf{n}_l \end{bmatrix}$

The fusion center then employs a ML detection on the vector $\mathbf{x}_k$. The conditional probability density of $\mathbf{x}_k$, $p(\mathbf{x}_k | b_k, \mathbf{H})$ can be expressed as:

$$p(\mathbf{x}_k|b_k,\mathbf{H}) = p(\mathbf{x}_k|b_k,\mathbf{H},\tilde{b}_k = 1)\Pr(\tilde{b}_k = 1|b_k) + p(\mathbf{x}_k|b_k,\mathbf{H},\tilde{b}_k = -1)\Pr(\tilde{b}_k = -1|b_k). \qquad (15)$$

Using (15) and the received signal model in (14) the likelihood ratio-function $L(\mathbf{x}_k)$ can be derived as:

$$L(\mathbf{x}_k) = \frac{\sum_{\tilde{b}_k \in \{-1,+1\}} exp\left\{\frac{2}{\sigma_w^2} Re(\mathbf{x}_k^H \mathbf{H}\mathbf{b}_k^{+})\right\} \Pr(\tilde{b}_k | b_k = 1)}{\sum_{\tilde{b}_k \in \{-1,+1\}} exp\left\{\frac{2}{\sigma_w^2} Re(\mathbf{x}_k^H \mathbf{H}\mathbf{b}_k^{-})\right\} \Pr(\tilde{b}_k | b_k = -1)} \qquad (16)$$

where $\mathbf{b}_k^+ = \begin{bmatrix} 1 \\ \tilde{b}_k \end{bmatrix}$, $\mathbf{b}_k^- = \begin{bmatrix} -1 \\ \tilde{b}_k \end{bmatrix}$ and the conditional probability $\Pr(\tilde{b}_k | b_k = i)$ resulting from (11) and (12) are given by:

$$\Pr(\tilde{b}_k | b_k = i) = \begin{cases} P_e \, ; \tilde{b}_k \neq i \\ 1 - P_e ; \tilde{b}_k = i \end{cases} \tag{17}$$

where $P_e = Q\left(\frac{\|\mathbf{h}_{k,l}\|^2 P_k}{\sigma_l^2}\right)$.

The ML fusion center decision $\hat{b}_k$ on b_k is then:

$$L(\mathbf{x}_k) \underset{\hat{b}_k = -1}{\overset{\hat{b}_k = 1}{\gtrless}} 1. \tag{18}$$

Finally, the estimates $\hat{b}_k$ of the sensor messages, are used to make a global decision, u_0, applying the fusion rule given by (7).

IV. Numerical Results and Comparisons

In this section we present simulations results and evaluate the performance of the cooperative CS-CDMA WSN proposed. In the simulations the sensor k observation is given by (1) with d = 1 and equals hypothesis probabilities p_0 and p_1 are assumed. The sensor messages are mapped into BPSK symbols and then transmitted to the fusion center using the CS-CDMA scheme described in section II, with Hadamard codes of length N = 32. The channels $\mathbf{h}_k$ and $\mathbf{h}_l$ linking the local sensors/relay to the fusion center are mutually independent and modeled by a time invariant random FIR filter modeled here with L = 4 taps, with the coefficients of the local sensor k channel given by $h_{k,i} = q_l \alpha_{k,i}$, where $\alpha_{k,i}$, $i = 0,1,\ldots,\mathrm{L}-1$, are Gaussian complex mutually independent random variables, with zero mean and $\mathbb{E}\left[\left|\alpha_{k,i}\right|^2\right] = 1$. The values of $\alpha_{k,l}$ are randomly drawn and kept fixed throughout each simulation run. The coefficients q_i satisfies $\sum_{i=0}^{L-1} |q_i|^2 = 1$ with $q_0 = 0.8671$, $q_1 = 0.4346$, $q_2 = 0.2178$ and $q_3 = 0.1092$. The channel $\mathbf{h}_{k,l}$ linking sensor k to its paired relay l is modeled by a time invariant random FIR filter with L = 1 taps, with the coefficient $h_{k,l}$ being a Gaussian complex random variable. Each cooperative node uses half of its normalized total power P_T to transmit its own data and the other half to transmit the messages of its paired node, i.e, $P_k = P_l = 1/2$. The average SNR of the channel linking the nodes to the fusion center ($\mathrm{SNR}_w = b_k^2/\sigma_w^2$) is assumed to be 10 dB lower than that of the channel linking the paired nodes ($\mathrm{SNR}_l = b_k^2/\sigma_l^2$).The average local sensor is given by $\mathrm{SNR} = d^2/\sigma^2$. Full knowledge of the channels by the receivers is also assumed. Here we compare the performance of the cooperative CS-CDMA WSN and the non-cooperative CS-CDMA WSN, in which the sensors transmit the decisions with $P_T = 1$, i.e. no relay nodes are considered. The probability of error for both WSN as a function of the local sensors SNR is depicted in Fig. 5 for K = 7 sensors/relays and fixed average channel SNR_w of 6 dB. The results in this Fig. indicates that for low values of local sensor SNR there is little difference between the performances of cooperative WSN and non-cooperative WSN. In this region, the global performance of WSN are greatly influenced by the sensor decisions errors and the diversity gain arising from the cooperation has little influence. As the local SNR increases the channel errors become more pronounced and thus the performance of the cooperative WSN is better due its diversity gain which mitigates the channel effects more efficiently than the non-cooperative WSN.

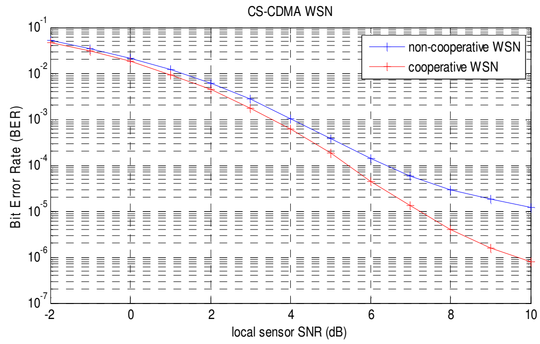

Fig 5. Bit error rate vs local sensor SNR for average multipath channel SNR_w = 6 dB and K=7 sensors

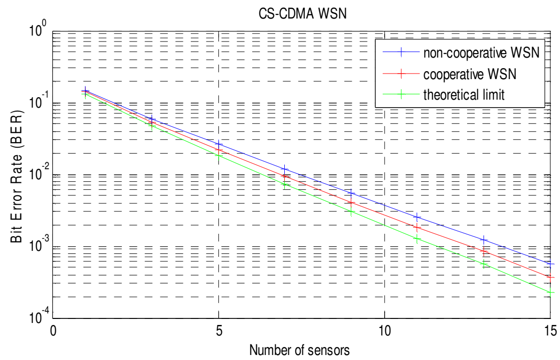

Fig 6. Bit error rate vs number of sensors for average multipath channel SNR_w = 6 dB and local SNR = 1dB

Fig. 6 depicts BER performance of the fusion center receiver for both WSN as a function of the number of sensors, K, for a fixed average channel SNR_w of 6 dB and a fixed local observation SNR of 1 dB for all sensors. The small gain in performance of the cooperative WSN is explained by the fact that the non-cooperative WSN already has a diversity gain arising from the receiver given in (6) which combines coherently the multipath components of the discrete channel $\mathbf{h}_k$. In fact the non-cooperative CS-CDMA WSN operates close to the theoretical limit of performance given by wireless environment without channel errors.

In order to evaluate the gain arising from cooperation only, in the next simulation we use a flat fading channel for both cooperative and non-cooperative WSN.

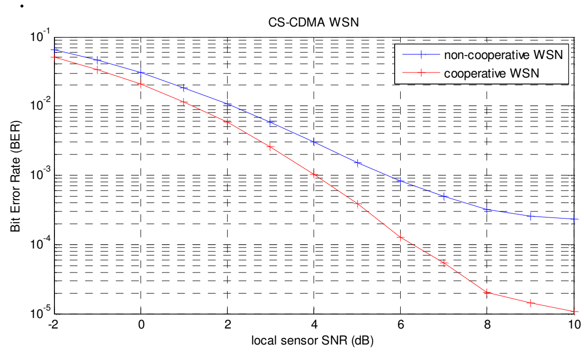

Fig 7. Bit error rate vs local sensor SNR for average flat channel SNR_w = 6 dB and K=7 sensors

As expect for medium to high SNR the difference in performances between the cooperative and non-cooperative

WSN is higher. In the flat channel case the non-cooperative receiver does not have any kind of diversity gain while the cooperative receiver explores the spatial diversity gain.

Fig. 8 depicts BER performance of the fusion center receivers as a function of the number K of nodes for fixed average flat channel SNR_w of 6 dB and a fixed local observation SNR of 1 dB for all sensors

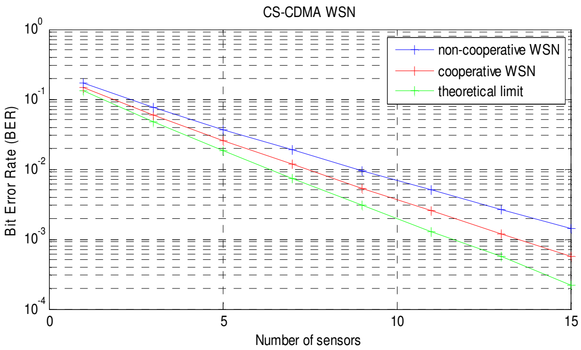

Fig 8. Bit error rate vs number of sensors for average flat channel SNR_w = 6 dB and local SNR = 1dB

Comparing the results in Figs. 6 and 8, we observe that the performance degradation of the non-cooperative WSN is higher than the degradation performance of the cooperative WSN. This is due, again, to the capability to explore spatial diversity in cooperative WSN.

V. CONCLUSION

A cooperative CS-CDMA wireless sensor network was proposed. In this network, each node is paired to a selected neighbor node to form a cooperative pair that forward its own data and relays the neighbor node data in a detect and forward cooperation scheme. It was shown through numerical examples that, as expected, cooperative WSN performs better that the non-cooperative counterpart. However the performance gain is more significant in flat fading environment. In multipath environments the non-cooperative CS-CDMA WSN already exploits efficiently the multipath diversity and the gain arising from the spatial diversity provided by cooperation does not result in substantial improvement in the overall performance. This indicates that the use of cooperative CS-CDMA schemes is more advantageous in environments with few multipath channel components.

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