COOPERATION IN WIRELESS SENSOR NETWORKS WITH INTRA AND INTERCLUSTER INTERFERENCE

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ABSTRACT

Virtual MIMO configuration, a common model for cooperation in sensor networks, trades off cooperation cost in front of MIMO gains. Most of proposed approaches rely mainly on the fact that cooperation at transmitter side alone seems to be much more powerful than receiver cooperation alone. The scenario that is analysed in this contribution includes the effect of interference of other clusters located closely that clearly degrades whatever cooperation type aforementioned. Under these circumstances, the use of additional sensors at receiver side helps creating a set of virtual beamformers, optimally designed to cancel the undesired signal. So, transmitter cooperation based on Dirty Paper Coding (DPC) strategies to minimize intra-cluster interference and virtual beamformers to minimize inter-cluster interference seems to be a very satisfactory combination.

1. INTRODUCTION[1]

Sensor networks and ad-hoc networks are receiving more and more attention from the research community in the recent years. There are several challenges from many points of view coming up from Information Theory limits, device efficiency (power saving) and network issues (routing). In particular, cooperative diversity is a novel technique where several nodes work together to form a *virtual antenna array* [1, 2]. This point is quite important because connects this new topic with more mature experience in MIMO communications in the *real antenna array*. Vector Gaussian, Broadcast, Multiple Access and Interference Channels (GC, BC, MAC, IC) are the standard models assumed for different degrees of cooperation in real MIMO links [3]. In Wireless Sensor Networks (WSN) the same asymptotic performance can be achieved if cooperation is not penalized. However, although these results are very valuable it is also important to review critically these conclusions considering more realistic models. This is the fundamental goal of this contribution.

The notion of cooperative communication has been formulated in several recent works [4 and references therein] and reviewed as an equivalent (degraded) BC or MAC channels. Basically, three following scenarios are considered depending on the available information: a) at the transmitter side a group of sensor are able to share the messages to be transmitted and also the set of channels, b) at the receiver side, nodes share their own received signals by forwarding processes (this is the relay principle, although other approaches may be considered) and also the channel coefficients, c) the information is shared at both sides. Reference [5] presents a very suitable model for these link addressing penalizations in terms of required power and bandwidth to achieve the cooperation benefits establishing a trade off between them.

This contribution follows the idea of [5], although in our case a more general situation is considered including the effect of fading channels instead of just a phase shifting. More indeed we have modeled the effect of interference coming from adjacent clusters. This effect may be modeled as an extra Gaussian noise following the Central Limit Theorem. In the case where there is not inter-cluster coordination, performance degrades for whatever intra-cluster cooperation that might be proposed. Our contribution is based on the idea of exploiting spatial diversity by setting an extra (N_b -1) number of sensors and waking up them to create a beamformer pointing towards the transmitter [6, 7, 8]. Assuming that clusters are spatially separated, interference is minimized. This strategy is an extension of our proposal analyzed in [9], where a suboptimum precoder based on Zero-Forcing DPC, combined with optimally designed beamformers at each multiantenna receiver, is shown to be performing very close to the optimum DPC approach. The present work modifies the design of the beamforming criteria by minimizing interference instead of maximizing throughput. For this purpose interference fading channels are supposed to be known at both transmitter and receiver sides.

The paper is organized as follows: In Sections 2 and 3 the system model is presented for the interference-free and interference scenario, respectively. The proposed solution is given in Section 4 while some simulations are presented in Section 5. Conclusions are given in Section 6. References are provided at the end of the paper.

2. INTERFERENCE FREE SCENARIO

The system model assumes that N simultaneously active (awake) sensors are split in N_c clusters, each one with N_s= N/N_c sensors (assumed integer). P is the total available power for inter and intra-cluster communications. Schematically, the sensors configuration and situation are shown in Figure 1. In this contribution, the emphasis is put on the joint Tx /Rx cooperation strategy because it is the most general configura-

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tion. In [5] states that Tx cooperation is the most suitable approach of cooperation to be used in the absence of inter-cluster interference. Nevertheless, assuming existence of the inter-cluster interference, some kind of Tx / Rx cooperation is recommended.

Let us consider first the scenario where no interference is present. For the notation, $\mathbf{h}_k$ (1xN_s), k =1..N_s represents the Rayleigh fading between all the N_s transmitters and the k-th receiver while $\mathbf{x}$ (1xN_s) is the transmitted vector.

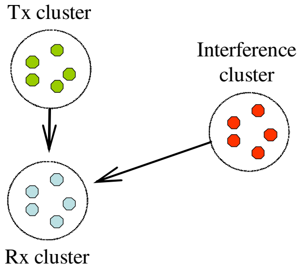

Figure 1. Schematic scenario

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$$y_k = \sqrt{P_{MIMO}}\,\mathbf{h}_k^H \mathbf{F}\mathbf{x} + n_k \tag{1}$$

where $n_k \sim \mathcal{N}_c(0,\sigma^2)$ and $\mathbf{F}$ is a general precoder power normalized. Following the spirit in [5], cooperation link is assumed just a Gaussian channel with gain G representing that intra-cluster nodes are $\sqrt{G}$ times closer than inter-cluster distance normalized to 1.

If we allow receivers to relay their own received signals through cooperation channel, each sensor may create its own virtual MIMO. For instance, if we consider receiving sensor 1, the virtual MIMO signal becomes

$$\mathbf{y}_1 = \begin{bmatrix} y_1 \\ \sqrt{GP_r}\, y_2 + n_{12} \\ \vdots \\ \sqrt{GP_r}\, y_{N_s} + n_{1N_s} \end{bmatrix}, \tag{2}$$

where $n_{kj} \sim \mathcal{N}_C(0, \sigma^2)$, $k \neq j$ and $n_{kk} = 0$. By normalization of the noise component at each element in order to have unit variance, we can easily get

$$\mathbf{y}_1 = \begin{bmatrix} \frac{1}{\sigma}\mathbf{h}_1^H \mathbf{F}\mathbf{x} + \tilde{n}_{11} \\ \sqrt{\frac{P_{MIMO}GP_r}{\sigma^2(1+P_rG)}}\mathbf{h}_2^H \mathbf{F}\mathbf{x} + \tilde{n}_{12} \\ \vdots \\ \sqrt{\frac{P_{MIMO}GP_r}{\sigma^2(1+P_rG)}}\mathbf{h}_{N_s}^H \mathbf{F}\mathbf{x} + \tilde{n}_{1N_s} \end{bmatrix} = \mathbf{H}_1\mathbf{F}\mathbf{x} + \tilde{\mathbf{n}}_1 \tag{3}$$

Now $\mathbf{H}_1$ collects all the effect related with the virtual MIMO creation and $\tilde{\mathbf{n}}_1$ is the equivalent white normalized Gaussian noise. It is remarkable that this situation becomes a standard MIMO problem but with non identical distributions of the matrix entries. Obviously, the choice of P_t and P_r will determine the achievable rate for the inter-cluster communication. We can choose a pair of values of P_t and P_r in order to maximize the sum capacity in a similar way as in [5]. However, due to space limitations, we skip out this point and assume that an appropriate selection on the powers is made.

Figure 2 shows the schematic equivalent view of the simplest case where 2 transmit sensors and 2 receiving sensor are allowed to cooperate. It is observed that the original interference channel is transformed into a BC channel with multiple receiving antennas. This is the reason of the performance improvement.

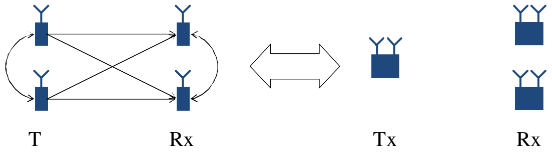

Figure 2. Left hand side. Original scenario. Right hand side, equivalent scenario with both Tx and Rx cooperation

3. SCENARIO WITH INTERCLUSTER INTERFERENCE

The model presented in this section permits to quantify the new situation where other cluster is also transmitting therefore interfering in transmission. We will only consider the case of one interfering cluster. Extension to several clusters is straightforward and will reinforce the Gaussian hypothesis for the interference that we will claim. Interfering signal at sensor k will be

$$i_k = \sqrt{\alpha P_{MIMO}}\,\mathbf{m}_k^H \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} \tag{4}$$

where $\mathbf{m}_k$ is the flat fading channel from interfering cluster to the reference sensor, $\mathbf{F}_{\text{int}}$ is the precoding (power normalized) performed at that cluster and $\mathbf{x}_{int}$ is the transmitted sequence. The factor $\sqrt{\alpha} > 0$ means the extra loss in front of the desired link and models the fact that interfering cluster may be further away. Mean interference power clearly becomes:

$$P_{\text{int}} = \alpha P_{MIMO}\,\mathbf{m}_k^H \mathbf{F}_{\text{int}} \mathbf{F}_{\text{int}}^H \mathbf{m}_k = \alpha P_{MIMO} \tag{5}$$

By applying the Central Limit Theorem to the interference, we can approximate it as additional Gaussian noise. The equivalent effect of interference makes effective noise to be increased from:

$$\sigma_{eff}^2 = \sigma^2 + \alpha P_{MIMO} \tag{6}$$

Figure 3 shows performance degradation in a 4x4 system in terms of the sum rate for different values of the effective noise variance, σ_{eff}^2.

The result of the simulation states that independently of the cooperation strategy, wireless ad hoc networks needs some kind of coordination between neighbouring clusters in terms of multiple access strategy to avoid this important performance degradation.

In order to provide a feasible solution to this problem, we recall that in fact in a cluster are usually located many sensors additional to the already mentioned N_s that use to be sleeping until some event wakes them. The idea that we propose is to awake a set of sensors N_b -1 per every N_s sensors so involving N_bN_s sensors where in each group of N_b sensors, the N_b-1 sensors play the role as dumb antennas in an irregular bidimensional beamforming. Hence we exploit SDMA (Space Division Multiple Access) principles. Although this is a well know topic in the literature, we have to claim that decentralized beamforming adds some new features that must be looked at carefully. In fact we are dealing with irregular spatial distributed beamformers where preliminary results point out a significant array gain. It is also important to remark that the main drawback of this approach is that synchronization must be quite accurate [6, 7, 8].

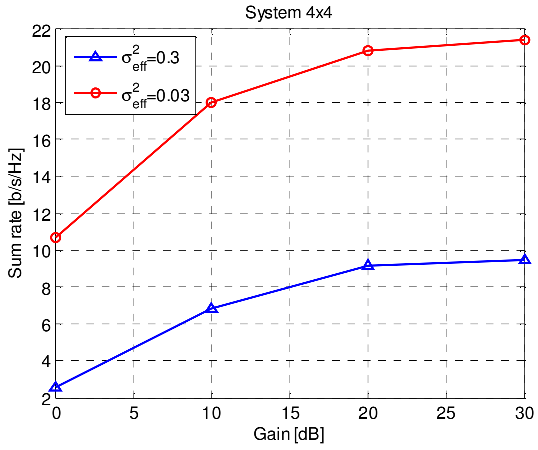

Figure 3. Performance degradation due to interference

The use of dummy sensors and the equivalent MIMO system are shown in Figure 4. The 2x2 system with 3 dummy sensors per each receive sensor is depicted. It can be seen that the equivalent system becomes a MIMO system with single transmitter with N_t=2 antennas, and N_s=2 receivers with N_b=4 antennas.

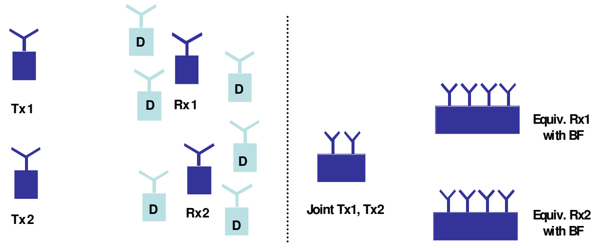

Figure 4. Left: 2x2 system with 3 dummy sensors per receive sensor. Right: Equivalent MIMO system

The key issue now is how to design beamfoming to improve performance. It is important to remark that dummy nodes only retransmit the received signal and that beamforming is only performed at the principal node. Our proposal follows a double purpose: on one hand, eliminate intercluster interference, on the other maximize intra-cluster throughput. In order to provide a reasonable model for this situation, we recall a suboptimum approach to the DPC optimization criteria known as Zero-Forcing DPC (ZF-DPC) [10].

4. PROPOSED SOLUTION FOR THE INTERFERENCE SCENARIO

Taking into account the interference and the fact that additional dummy nodes are used to form a sub-cluster of N_b nodes, signal vector received at the main node of the k-th sub-cluster (with beamforming) is given by

$$\mathbf{y}_k = \mathbf{r}_k^H \left(\mathbf{H}_k \mathbf{F} \mathbf{x} + \mathbf{M}_k \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} + \tilde{\mathbf{n}}_k \right) \tag{7}$$

where $\mathbf{H}_k$ (N_bxN_s) and $\tilde{\mathbf{n}}_k$ (N_bx1) are the same as in Eq. (3) but particularized to the k-th sub-cluster, $\mathbf{M}_k$ (N_bxN_s) are the channel coefficients (with proper scaling) between interfering cluster and k-th sub-cluster and $\mathbf{r}_k$ (N_bxN_s), is the beamformer applied at the main node of k-th sub-cluster. It is important to say that we will force $N_b>N_s$ for rank reasons as we will see later when computing the beamformers. If we define the received vector as $\mathbf{y} = [\mathbf{y}_1^T, \ldots, \mathbf{y}_{Ns}^T]^T$ (N_sN_bx1), the total channel matrix as $\mathbf{H} = [\mathbf{H}_1^T, \ldots, \mathbf{H}_{N_s}^T]^T$ (N_sN_bxN_s) and the total interfering matrix $\mathbf{M} = [\mathbf{M}_1^T, \ldots, \mathbf{M}_{N_s}^T]^T$, we can put it altogether to form

$$\mathbf{y} = \mathbf{R}^H \mathbf{H} \mathbf{F} \mathbf{x} + \mathbf{R}^H \mathbf{M} \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} + \mathbf{R}^H \mathbf{n} \tag{8}$$

where $\mathbf{R} = \text{diag}\{\mathbf{r}_1\ \mathbf{r}_2 \ldots \mathbf{r}_{N_s}\}$ is a diagonal block matrix collecting individual array processing at every receiver and $\mathbf{n}$ is an (N_sN_bxN_b) vector collecting the noise samples. The diagonal structure of $\mathbf{R}$ means that receivers in different clusters do not cooperate.

The ZF-DPC strategy is shown in [10] where $\mathbf{F}$ is the unitary matrix associated to the QR-decomposition of the equivalent channel matrix $\mathbf{H}_{eq}$

$$\mathbf{H}_{eq} = \mathbf{R}^H \mathbf{H} = \mathbf{L} \mathbf{Q} \tag{9}$$

where $\mathbf{L}$ is the upper triangular matrix and $\mathbf{Q}$ is the orthogonal matrix associated with the QR decomposition of matrix $\mathbf{H}_{eq}$. According to this idea, in our case we force $\mathbf{F} = \mathbf{Q}^H$. Clearly the triangular structure of $\mathbf{L}$ allows the DPC strategy to achieve no intra-cluster interference, while the beamforming design guarantees no intercluster interference.
Our criterion assumes that interference channels are known at receiver beamformers location. The suboptimum procedure can be described in several key ideas:

a) Eliminate completely the inter-cluster interference. In order to guarantee this condition, every beamformer $\mathbf{r}_k$ must fulfill:

$$\mathbf{r}_k^H \mathbf{M}_k \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} = 0 \tag{10}$$

where $\mathbf{M}_k$ is the same as in (7).
Eq. (10) is quite simple under the rank condition already mentioned because $\mathbf{r}_k$ must belong to the null space of $\mathbf{M}_k$.

b) Recalling [9] it is proposed a suboptimum solution to this problem in the real multiantenna scenario without interference. We showed that beamformers maximizing throughput must be found from the following eigenanalysis.

$$\mathbf{H}_k \mathbf{H}_k^H \mathbf{r}_k = \lambda_{\max} \mathbf{r}_k \tag{11}$$

c) In order to fulfil both previous points, our solution is based on the decomposition of $\mathbf{H}_k$ into 2 orthogonal components, one of them expanding the null subspace of $\mathbf{M}_k$.

$$\mathbf{H}_k = \mathbf{H}_k^{\mathbf{M}_k} + \mathbf{H}_k^{\perp\mathbf{M}_k} \qquad (12)$$

Final solution modifies criteria given by (11) as

$$\mathbf{H}_k^{\perp\mathbf{M}_k}\mathbf{r}_k = \lambda_{\max}\mathbf{r}_k \qquad (13)$$

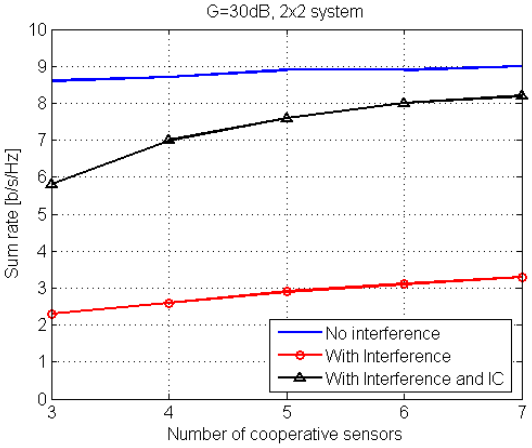

Figure 5. Effect of the number of dummy sensors

5. SIMULATION RESULTS

This section addresses some of the most remarkable results. The first scenario assumes that sensors are very closely spaced at both Tx and Rx (G=30dB). A low noise variance (σ^2=0.03) has been used in order to notice the degradation due to inter-cluster interference. Two transmit and two receive sensors (2x2) system is considered, with variable number of dummy sensors – from 2 to 6 (that is, 3 to 7 cooperative sensors). Simulation results are shown in Figure 5. The sum rate capacity is depicted depending on the number of dummy sensors for three different configurations: “Without interference”, “With interference” and “With interference and IC”. The first two approaches use beamforming given by Eq. (11) while the last one uses our proposed solution which cancels interference by using beamforming of Eq. (13).

These three scenarios enable the comparison of the proposed system in terms of the maximum sum rate when no intercluster interference is present and dummy sensors are used for throughput maximization. It is interesting to notice that increment of the number of dummy sensors does not lead to important capacity improvement in the scheme (With Interference) while our proposed solution (With interference and IC) approaches sum rate without interference as the number of dummy sensors increase.

Another analysis considers the effect of the gain *G*. The same, 2x2 system is considered again, with four dummy sensors per each active Rx sensor (2x2x5) and noise variance σ^2=0.03. The simulation results are depicted in Figure 7. Only gains above 10 dB are considered as cooperation is not recommendable at low gains [5]. It can be observed that the performance loss of the system with inter-cluster interference and IC with respect to the system without inter-cluster interference can be considered constant independent of the gain value. Nevertheless, it is interesting to notice that the performance gain is less pronounced with gain increment in the second system, with inter-cluster interference but without its cancellation, as the noise corresponding to the interference remains constant, independent of gain.

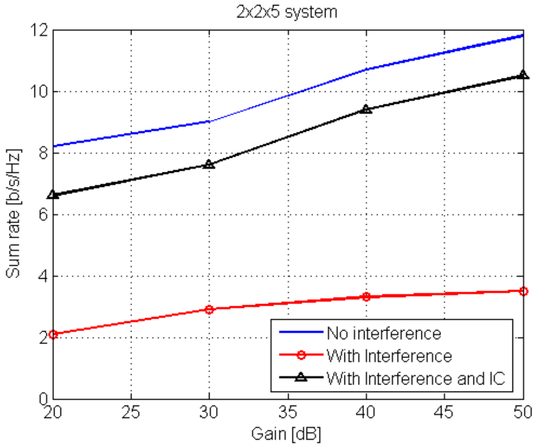

Figure 6. Effect of the gain in Tx and Rx sectors

6. CONCLUSIONS

This paper presents a new approach to the cooperation design in wireless sensor networks when both intra and inter-cluster interference are considered. The proposed solution is based on a combination of DPC principles for transmitter design to eliminate the intra-cluster interference while at receivers we have made use of dummy sensors to design a virtual beamformer that minimizes inter-cluster interference. This work also reinforces the idea that join Tx /Rx cooperation is the most suitable strategy for realistic scenarios with intra and inter-cluster interference.

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