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On the role of receiving beamforming in transmitter cooperative communications

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1. Introduction

Multiple Input – Multiple Output (MIMO) communications have challenged the research community with promising capacity increases with respect to the standard single-antenna systems (Telatar 1999; Foschini 1996). Most of the original work was motivated by the point-to-point link trying to provide structures achieving the theoretical capacity predicted by the logdet formula. Probably, the most well studied strategy is BLAST with many variants sharing in common the space-time layered structure.

More recently, there has been much interest in MIMO systems where a multi-antenna node transmits to multiple terminals, or where multiple nodes transmit to a single multi-antenna terminal. The former case is known as the broadcast channel (BC) while the latter is known as the multiple access channel (MAC).

Available literature shows many different approaches dealing with this topic. One of the most representative works are (Viswanath & Tse, 2003; Jindal et al, 2004) where theoretical analysis is provided through the duality principle between the downlink and the uplink case. The main point is that the achievable rate region of the BC is equivalent to the rate region of its dual MAC with a sum power constraint. This duality allows the characterization of the BC rate region to be performed in the dual MAC context where well-known optimization algorithms can be used. This achievable rate region will be considered as an upper bound for all the suboptimal approaches.

Our approach presented here is based on (Caire & Shamai, 2003) where a suboptimal precoder of a DPC structure is proposed using the QR decomposition of the channel matrix. However, this technique was discussed for the case of single-antenna terminals. We have extended this procedure where there could be several antennas at the receiver. Our contribution optimizes the receive beamforming strategy for any terminal assuming that its channel is known but that no other terminal's channel is known. On the other hand, the transmitter has full knowledge of every channel. We proposed a suboptimal precoder using a combination of DPC and zero-forcing criteria whose performance in terms of mutual information is close to the optimum case but with reduced complexity (Zazo & Huang 2006).

On the other hand, 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* (Scaglione et al, 2006; Stankovic et al, 2006). This point is quite important because it connects this new topic with the more mature field of MIMO communications using a *real antenna array*. Connecting with our previous points, 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 (Cover and Thomas, 1991) that can provide asymptotic performances in Wireless Sensor Networks (WSN) 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 second part.

The notion of cooperative communication has been formulated in several recent works (Jindal 2004 and references therein) and reviewed as an equivalent (degraded) BC or MAC channel. 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 a forwarding process (this is the relay principle, although other approaches may be considered) and also the channel themselves and c) the information is shared at both sides. Reference (Ng et al, 2006) presents a very suitable model for this link addressing penalizations in terms of required power and bandwidth to achieve the cooperation benefits establishing a trade off between them.

Our second contribution follows the idea in (Ng et al, 2006), although in our case a more general situation is considered including the effect of fading channels instead of just a phase shifting. Moreover we modelled the effect of interference coming from the adjacent clusters. In this case, where there is no intercluster coordination, performances degrades for whatever intracluster cooperation may be proposed. This effect may be modeled as an extra Gaussian noise following the Central Limit Theorem. Our reasoning is based on the idea of waking up an extra set of sensors in the cluster (N_b new degrees of freedom for each active node) that interchange the received signal within the group to create a beamforming pointing towards the transmitter (Ochiai et al, 2005; Mudumbai et al, 2007; Barton et al, 2007). Assuming that clusters are spatially separated, interference in minimized. Most of these ideas are presented in (Zazo et al, 2008). This second approach modifies the design of the first one because now instead of throughput maximization, the goal is interference minimization. Assuming that interference fading channels are known, beamformers maximize throughput constrained to belong to the null subspace of the interference. Performance compared to standard cases is clearly improved.

2. MIMO COMMUNICATIONS

2.1 System model

We consider a MIMO broadcast channel where a base station with N_t antennas transmits to N_u users, each with N_r receive antennas. We will further assume that we have the same number of transmit antennas as the number of users. Figure 1 shows the corresponding block diagram of the system, where $\mathbf{T}$ is the linear precoder (or transmit beamformer) (size N_txN_u), $\mathbf{H}_k$ represents the kth user's flat MIMO channel (size N_rxN_t), $\mathbf{r}_k$ represents the kth user's linear receiver (or receive beamformer) (size N_rx1), and $\mathbf{n}_k$ is the AWGN at receiver k.

The dirty paper coding block jointly encodes users so that the interference among users is reduced or eliminated at the output of their decoders.
All the schemes that we are going to describe in the paper are based on the following view: determine ($\mathbf{T}$, $\mathbf{r}_1$, $\mathbf{r}_2$, …, $\mathbf{r}_{Nu}$) to optimize the performance, either in terms of maximizing the sum rate or maximizing a common SINR achievable by all users. In order to make a fair comparison, all schemes in the simulation results will be measured under a common figure of merit, the sum rate. The specific description of some of these contributions will be described in a forthcoming section, after describing our approach.

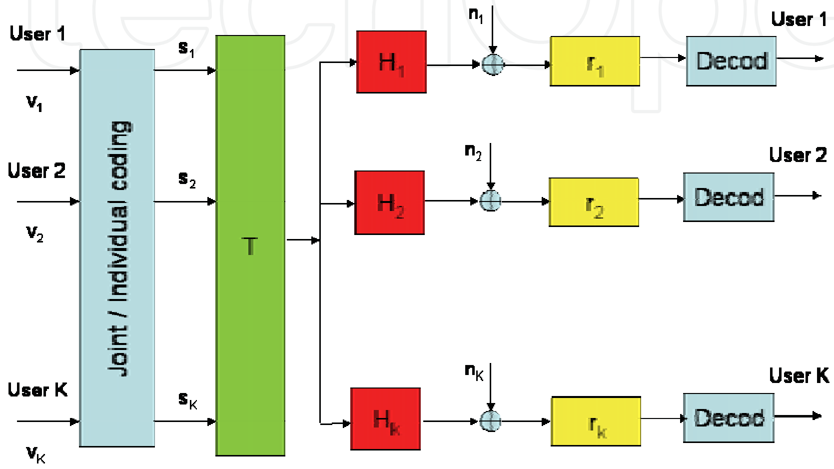

Fig. 1. Block diagram

2.2 Our proposal: ZF-DPC with receive beamforming

Our proposal intends to mix the concept of DPC with its simpler Zero Forcing (ZF) implementation with some beamforming design that provides an acceptable loss of performance. The received signal stacking all the users in a single column-vector becomes,

$$\mathbf{y} = \mathbf{R}^H \mathbf{H}\mathbf{T}\mathbf{s} + \mathbf{R}^H \mathbf{n} \tag{1}$$

where $\mathbf{R}$ is a diagonal block matrix collecting individual array processing at every receiver, and $\mathbf{0}$ vectors mean that the receivers do not cooperate

$$\mathbf{R} = diag\{\mathbf{r}_1 \quad \mathbf{r}_2 \quad \cdots \quad \mathbf{r}_{N_u}\} = \begin{bmatrix} \mathbf{r}_1 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{r}_2 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{r}_{N_u} \end{bmatrix} \tag{2}$$

$\mathbf{H}$ is the channel matrix ($N_u N_r$ x N_t), that can be expressed as the stacking of the per user matrices $\mathbf{H}_i$ (N_r x N_t):

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{H}_2 \\ \vdots \\ \mathbf{H}_{N_u} \end{bmatrix} \tag{3}$$

For the case of single-antenna receivers, the optimum precoding matrix **T** is obtained using the duality principle (Visvanath,& Tse, 2003). This strategy is also remarked in (Jindal, 2004) where a tight suboptimal design is proposed where **T** is the unitary matrix associated to the QR-decomposition of the channel matrix **H**. In this contribution we are going to follow this suboptimal design where the determination of **T** is straightforward for the transmitter if it knows all the channels and also the beamforming processing to be done at receivers,

$$\mathbf{H}_{eq} = \mathbf{R}^H \mathbf{H} = \mathbf{LQ} \tag{4}$$

where **L** is the upper triangular matrix and **Q** is the orthogonal matrix associated with the QR decomposition of matrix $\mathbf{H}_{eq}$. According to this idea, in our scenario we force $\mathbf{T} = \mathbf{Q}^H$. Therefore, the optimization procedure in this case is based on the design of the beamformers constrained to $\mathbf{r}_i = f(\mathbf{H}_i)$ remarking that its own channel is the only available information at each receiver. Applying these ideas to equation (1), we reach an equivalent model as follows,

$$\mathbf{y} = \mathbf{R}^H \mathbf{HTs} + \mathbf{R}^H \mathbf{n} = \mathbf{LQTs} + \mathbf{R}^H \mathbf{n} = \mathbf{LQQ}^H \mathbf{s} + \mathbf{R}^H \mathbf{n} = \mathbf{Ls} + \mathbf{R}^H \mathbf{n} \tag{5}$$

Assuming that DPC is working properly (recall that due to the triangular structure of **L**, DPC is able to cancel all the interference, this is thus labelled as ZF-DPC), the instantaneous sum rate *R* is given by

$$R = \sum_{k=1}^{N_u} \log_2\left(1 + snr\left|l_k\right|^2\right) \tag{6}$$

where l_k are the diagonal elements of the triangular **L** matrix and *snr* is the common Signal to Noise Ratio. Therefore, the optimization problem can be expressed as:

Optimization criteria

Find **R** constrained to be block diagonal with $\mathbf{R}^H\mathbf{R}=\mathbf{I}$ and $\mathbf{r}_i = f(\mathbf{H}_i)$, that maximizes

$$R = \sum_{k=1}^{N_u} \log_2\left(1 + snr\left|l_k\right|^2\right) \tag{7}$$

where l_k are the diagonal elements of the triangular **L** associated to the QR decomposition of $\mathbf{H}_{eq} = \mathbf{R}^H \mathbf{H} = \mathbf{LQ}$. Let us remark that the previous relationship $\mathbf{R}^H\mathbf{R}=\mathbf{I}$ transforms equation (6) into the standard problem with spatially uncorrelated noise:

$$\mathbf{y} = \mathbf{Ls} + \mathbf{R}^H \mathbf{n} = \mathbf{Ls} + \mathbf{n} \tag{8}$$

Solution

The set of beamformers $\mathbf{r}_i$ that maximizes the rate in (6) for high SNR are the eigenvectors related to the maximum eigenvalue of matrix $\mathbf{H}_i^H \mathbf{H}_i$:

$$\mathbf{H}_i \mathbf{H}_i^H \mathbf{r}_i = \lambda_{\max} \mathbf{r}_i \tag{9}$$

Proof

For high SNR, the sum rate can be expressed as

$$R = \sum_{k=1}^{N_u} \log_2\left(1 + snr\left|l_k\right|^2\right) \approx \sum_{k=1}^{N_u} \log_2\left(snr\left|l_k\right|^2\right) = N_u \log_2 snr + \log_2\left(\prod_{k=1}^{N_u}\left|l_k\right|^2\right) \tag{10}$$

Therefore, we just need to maximize the last term that can be expressed as a determinant

$$\log_2\left(\prod_{k=1}^{N_u}\left|l_k\right|^2\right) = \log_2\left(\det \mathbf{L}\mathbf{L}^H\right) = \log_2\left(\det \mathbf{L}\mathbf{Q}\mathbf{Q}^H\mathbf{L}^H\right) = \log_2\left(\det \mathbf{H}_{eq}\mathbf{H}_{eq}^H\right) \tag{11}$$

As the logarithm function is a monotonic increasing function, the optimization criteria may be expressed as follows

$$J(\mathbf{R}) = \max_{\mathbf{R}}\left(\det \mathbf{R}^H\mathbf{H}^H\mathbf{H}\mathbf{R}\right) \tag{12}$$

$$\text{Constrained to } \mathbf{R} \text{ block diagonal, } \mathbf{R}^H\mathbf{R} = \mathbf{I},\ \mathbf{r}_i = f\left(\mathbf{H}_i\right)$$

Recall that **R** is constrained to be block diagonal because users perform linear combining separately from one another. This constraint limits the determinant to the main diagonal of the desired matrix. This point is critical because if we consider the whole matrix, crossed terms depending on two different terminals' beamformers appear. The constraint $\mathbf{r}_i = f\left(\mathbf{H}_i\right)$ imposes that the optimization criteria depend only on the main diagonal elements.

Therefore, the original constrained optimization must be expressed as follows:

$$J(R) = \max_{\mathbf{R}}\left(\det\left(diag\left(\mathbf{R}^H\mathbf{H}^H\mathbf{H}\mathbf{R}\right)\right)\right) = \max_{\mathbf{r}_i} \prod_{i=1}^{N_u} \mathbf{r}_i^H\mathbf{H}_i\mathbf{H}_i^H\mathbf{r}_i \tag{13}$$

$$\text{Constrained to } \mathbf{r}_i^H\mathbf{r}_i = 1, \forall i \in \left(1, N_u\right)$$

The solution to this problem is very well known as the set of eigenvectors associated with the maximum eigenvalues of the corresponding matrices, as proposed in equation (9).

It is very important to remark that this approach is non-iterative and that receivers just need to estimate their own channels. The main disadvantage could be the implementation of DPC which is currently unknown and could be very complex. In this sense, we propose to substitute the DPC structure by a vectorized Tomlinson-Harashima precoder as described in (Peel et al, 2005; Hochwald et al, 2005). However, the performance of this structure is out of the scope of this contribution. The results that we are going to show will assume perfect DPC behaviour and must be considered as an upper bound of more realistic implementations.

2.3 Some representative existing approaches

In this section we will include a brief description of some of the most representative approaches dealing with our scenario in order to address their merits, show their limitations in terms or performance or complexity and make a fair comparison among them.

In (Wong et al, 2002) several suboptimal approaches for communicating on the BC are suggested. One of them is the design of the precoder according to the SVD decomposition, applying MMSE beamformers at receivers to cope with residual interference. The main advantage of this scheme is its simplicity, though we have to remark that received covariance matrices must be estimated or fed back. Another proposal in (Wong et al, 2002), known as The Maximum Transmit SINR, maximizes an upper bound of the SINR.

JADE (Joint Approximated Diagonalization of Eigen-structures) refers to a well-known result coming from blind source separation (Cardoso and Soulumiac, 1996). This approach establishes that for a set of complex Hermitian matrices associated to the MIMO transmission, it is possible to find a unitary matrix that minimizes MAI. If the matrices do not have a common eigenstructure, the algorithm provides a kind of 'average eigenstructure'. Unfortunately, performance depends very much on the specific structure of the involved channels.

Reference (Pan et al, 2004) proposes another approach known as Orthogonal Space Division Multiplex (OSDM). This scheme is a zero-forcing strategy where optimization is performed iteratively through a recursive procedure between the transmitters and receivers. The main disadvantage of this scheme is that it requires multiple iterations of communication between both ends before reaching the desired solution. However, performance improves considerably in comparison to other suboptimal schemes.

SVD-MMSE

As we have already mentioned, the idea is quite straightforward: design the precoder according to the SVD decomposition (it is known to be optimal in the point to point link) and apply MMSE beamformers at receivers to cope with residual ISI. Assuming that

$$\mathbf{H}_k = \mathbf{U}_k \mathbf{\Sigma}_k \mathbf{V}_k^H \tag{14}$$

Precoder $\mathbf{t}_k$ for the k-user is chosen as $\mathbf{t}_k = \mathbf{V}_k(1)$ where $\mathbf{V}_k(1)$ refers to the column of $\mathbf{V}_k$ associated to the maximum singular value. The MMSE receiver for an arbitrary user k is therefore

$$\mathbf{r}_k = \left(\mathbf{H}_k \mathbf{T}\mathbf{T}^H \mathbf{H}_k^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{H}_k \mathbf{t}_k \tag{15}$$

where σ^2 means the noise variance and obviously $\mathbf{T}\mathbf{T}^H \neq \mathbf{I}$ because different columns are related to independent SVDs. The main advantage of this scheme is its simplicity although we have to remark that received covariance matrices must be estimated or matrix **T** should be broadcasted.

JADE-MMSE

This approach establishes that for a set of N_u complex Hermitian matrices $\mathbf{H}_k^H \mathbf{H}_k$ it is possible to find a unitary matrix **U** that minimizes

$$\sum_{k=1}^{N_u} off\left(\mathbf{U}\mathbf{H}_k^H \mathbf{H}_k \mathbf{U}^H\right) \text{ where } off(\mathbf{A}) = \sum_{1\le k\neq l\le N_t} |a_{kl}|^2 \tag{16}$$

If the matrices do not have a common eigenstructure, the algorithm provides a kind of 'average eigenstructure'. It is clear that the purpose of this strategy is to minimize the MAI although unfortunately, performance depends very much on the specific structure of involved channels.

According to our scenario, we select **T=U** for precoder and MMSE for receive beamformers,

$$\mathbf{r}_k = \left(\mathbf{H}_k \mathbf{H}_k^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{H}_k \mathbf{t}_k \tag{17}$$

This approach is quite similar to the former one, but now the autocovariance matrices at the receivers do not need to be estimated, although the selected precoder **t**$_k$'s still have to be transmitted to the corresponding users.

Maximum Transmit SINR (MTxSINR)

This algorithm has been proposed in (Pan et al, 2004) intending to maximize an upper bound of the SINR. Starting form the expression of SINR at user k,

$$SINR_k = \frac{E\left\{\left|\mathbf{r}_k^H \mathbf{H}_k \mathbf{t}_k\right|^2\right\}}{E\left\{\left|\mathbf{r}_k^H \mathbf{H}_k \mathbf{T}_k \mathbf{T}_k^H \mathbf{H}_k^H \mathbf{r}_k\right|^2\right\} + \sigma^2} \tag{18}$$

they found that assuming Gaussian entries, the channel capacity may be upper bounded by

$$C = \sum_{k=1}^{N_u} \log_2\left(1 + SINR_k\right) > \log_2\left(\prod_{k=1}^{N_u} SINR_k\right) \tag{19}$$

They found a quite interesting upper bound for

$$\prod_{k=1}^{N_u} SINR_k \geq \rho \prod_{k=1}^{N_u} \frac{\mathbf{t}_k^H \mathbf{H}_k^H \mathbf{H}_k \mathbf{t}_k}{\mathbf{t}_k^H \left(\sum_{m \neq k} \mathbf{H}_m^H \mathbf{H}_m + \sigma^2 \mathbf{I}\right) \mathbf{t}_k} \tag{20}$$

where ρ is a real constant.

Their procedure is based on the following steps to design the precoder. First find a set of matrices **W**$_k$ such that

$$\mathbf{W}_k^H \left(\sum_{m \neq k} \mathbf{H}_m^H \mathbf{H}_m + \sigma^2 \mathbf{I}\right) \mathbf{W}_k = \mathbf{I} \tag{21}$$

The solution of this problem is simple taking into account the eigendecomposition of the involved matrices

$$eig\left(\sum_{m \neq k} \mathbf{H}_m^H \mathbf{H}_m + \sigma^2 \mathbf{I}\right) = \mathbf{U}\mathbf{S}\mathbf{U}^H \tag{22}$$

The desired matrix **W**$_k$ is

$$\mathbf{W}_k = \mathbf{U}\mathbf{S}^{-1/2} \tag{23}$$

In a second step, they select

$$\mathbf{t}_k = \frac{\mathbf{W}_k \mathbf{v}_k}{\left(\mathbf{v}_k^H \mathbf{W}_k^H \mathbf{W}_k \mathbf{v}_k\right)^{1/2}} \tag{24}$$

where $\mathbf{v}_k$ is the eigenvector related to the maximum eigenvalue of $\mathbf{W}_k^H \mathbf{H}_k^H \mathbf{W}_k \mathbf{H}_k$. In fact, what they are doing is transforming the original problem into a standard Rayleigh quotient. At the receiver side, they apply an MMSE receiver with similar considerations regarding the estimation of the received autocovariance matrix or broadcasting the matrix **T**.

OSDM (Orthogonal Space Division Multiplex)
This scheme is a zero forcing strategy where the optimization is performed iteratively through a recursive procedure between the transmitter and receiver. Their proposal can be understood in two steps. In a first step, they intend to force

$$\mathbf{r}_k^H \mathbf{H}_k \mathbf{T}_k = \mathbf{0} \quad \forall k \tag{25}$$

This can be guaranteed iff

$$\mathbf{t}_m \in Null\left(\begin{bmatrix} \mathbf{r}_1^H \mathbf{H}_1 \\ \vdots \\ \mathbf{r}_{k-1}^H \mathbf{H}_{k-1} \\ \mathbf{r}_{k+1}^H \mathbf{H}_{k+1} \\ \vdots \\ \mathbf{r}_{N_u}^H \mathbf{H}_{N_u} \end{bmatrix}\right) \tag{26}$$

as there is no MAI, at the receiver side they apply the MRC criteria $\mathbf{r}_k = \mathbf{H}_k \mathbf{t}_k$. In practice, iteration is started choosing $\mathbf{r}_k = 1 \quad \forall k$ and after several iterations the scheme converges to the desired solution. The main disadvantage of this scheme is that it requires multiple iterative communications between both ends before reaching the desired solution. However, the performance improves considerably in comparison with previous suboptimal schemes.

2.4 Analytical results and simulations

We have calculated through simulations the sum rate for all the methods described in the previous section. Figure 2 shows the performance of these methods for three users (and three transmit antennas) and two antennas per terminal. It is important to remark that we have not included multiuser diversity in this analysis.

It can be observed that JADE and SVD perform quite badly because in fact they are not able to reduce the MAI effect. As they were defined for point to point communications, this performance is expected. Maximum transmit SINR (labelled as MTx SINR) performs a little bit better but the most interesting behaviour is provided by the OSDM. It is remarkable that our proposal labelled by ZF-DPC + BF has similar performance. It is important to have in mind that OSDM is iterative between the receiver and transmitter which makes this contribution quite impractical. Obviously, DPC and optimum beamforming show the best performance. Our method is shown to be as good as optimum beamforming for high SNR. Equation (27) presents the sum rate for DPC where $\mathbf{S}_n$ is the noise covariance matrix and $\mathbf{Q}_k$ are the optimized covariance matrices of different users.

$$R_{DPC} = \log_2 \det \left| \mathbf{S}_n + \sum_{k=1}^{N_u} \mathbf{H}_k^H \mathbf{Q}_k \mathbf{H}_k \right| \tag{27}$$

On the other hand, the sum rate for the beamforming structure is given by equation (28)

$$R_{BF}=\sum_{k=1}^{N_u}R_k=\sum_{k=1}^{N_u}\log_2\frac{\det\left|\mathbf{S}_n+\sum_{j=1}^{N_u}\mathbf{H}_k^H\mathbf{Q}_j\mathbf{H}_k\right|}{\det\left|\mathbf{S}_n+\sum_{j=1,j\neq k}^{N_u}\mathbf{H}_k^H\mathbf{Q}_j\mathbf{H}_k\right|} \tag{28}$$

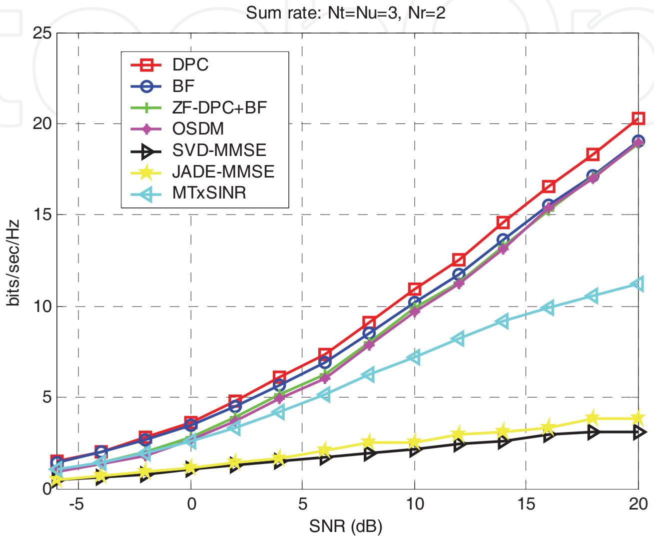

Fig. 2. Comparison of some existing algorithms for multiuser multiantennas schemes

Figure 3 shows for 6 transmit antennas, 6 users and a different number of receive antennas the ratio of our suboptimal proposal compared to the optimal DPC. The performance is similar for the different number of antennas and is close to the optimal for low and high signal to noise ratios (SNR). For high SNR, a saturated behaviour is observed stating that there will be a gap between both the approaches, as is seen in Figure 2. Unfortunately, for the most realistic interval of SNR between 0 and 10 dB, the ratio decreases, but it is always above 85 %. Clearly the loss of performance increases with the number of antennas, but in most mobile applications with 2 antennas at the terminals, the behaviour will reach more than 90%.

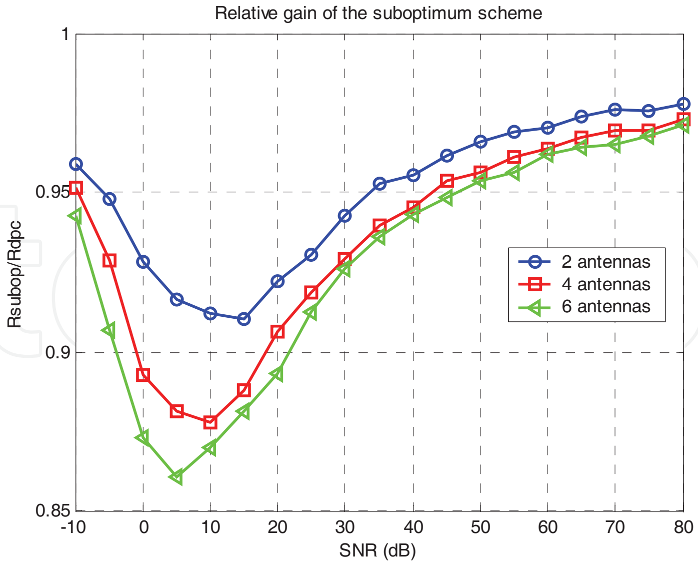

Fig.3. Relative gain of the suboptimal approach

3. Cooperative Communications in Wireless Sensor Networks

This section starts describing the new topic addressing two different scenarios, interference free and with interference to guide the reasoning to show how important is the role played by the beamforming in this second case.

3.1 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 assigned power to link N_s sensors between two clusters including the traffic link and also the transmitter and/or receiver cooperation. In the spirit of (Ng et al, 2006) but including fading effects, the 3 cooperative strategies already mentioned can be analysed. Schematically, the sensor configuration and situation are shown in figure 4.

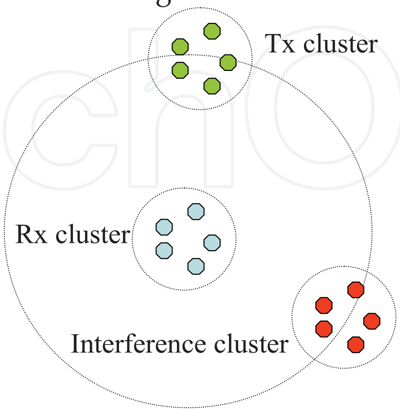

Fig. 4. Schematic scenario

In this contribution, the emphasis is put on the joint Tx /Rx cooperation strategy because it is the most general configuration, of which Tx or Rx cooperation are particular cases, and because it is the most suitable strategy for the analysed scenario. It will be showed that an important conclusion in (Ng et al, 2006) stating that Tx cooperation is the most feasible strategy where there is not intercluster interference is confirmed here. Nevertheless, assuming the existence of intercluster interference, some kind of Tx / Rx cooperation is recommended.

In order to simplify the notation, we assume that only the Tx and Rx clusters in Fig. 4 exist, where vectors $\mathbf{h}_k$ ($1xN_s$), $k \in (1, N_s)$ represents the Rayleigh fading between all the N_s transmitters and the k receiver. If we define P_t as the power consumed per sensor at the Tx part and similarly P_r at the Rx part to allow cooperation, clearly the available power for the intercluster link is $P_{MIMO}=P-N_sP_t-N_sP_r$. Denoting $\mathbf{x}$ ($1xN_s$) as the transmitted vector and y_k $k \in (1, N_s)$ the received signal at each sensor we have in the absence of interference:

$$y_k = \sqrt{P_{MIMO}}\mathbf{h}_k^H \mathbf{F}\mathbf{x} + n_k \tag{29}$$

where n_k is an AWGN noise signal with σ^2 power and $\mathbf{F}$ is a general precoder with normalized power. Following the spirit in (Ng et al, 2006) the cooperation link is assumed just a Gaussian channel with gain G representing that intracluster nodes are $\sqrt{G}$ times closer than intercluster distance normalized to 1. At the transmitter side, the achievable rate for cooperation is given by equation (30)

$$R_t = \log\left(1 + \frac{P_t G}{\sigma^2}\right) \tag{30}$$

If we allow the receivers to relay their own received signals in an equivalent channel also Gaussian with gain G, each sensor may create its own virtual MIMO. For instance, if we consider the receiving sensor 1, the virtual MIMO signal becomes after proper normalization:

$$\mathbf{y}_1 = \begin{bmatrix} y_1 \\ \sqrt{\dfrac{GP_r}{P_{MIMO}+\sigma^2}}y_2 + n_{12} \\ \vdots \\ \sqrt{\dfrac{GP_r}{P_{MIMO}+\sigma^2}}y_{N_s} + n_{1N_s} \end{bmatrix} \tag{31}$$

where new noise contributions appear due to the relaying process with powers defined in equation (32).

$$\sigma_{1k}^2 = \frac{\sigma^2\left(1+GP_r\right)}{P_{MIMO}+\sigma^2} \qquad k \in \left(2, N_s\right)$$
$$\sigma_{11}^2 = \sigma^2 \tag{32}$$

If we want to normalize the noise contribution to 1 in all the entries of the virtual MIMO receiver, easily we get

$$\mathbf{y}_1 = \begin{bmatrix} \frac{1}{\sigma}\mathbf{h}_1^H\mathbf{F}\mathbf{x} + \tilde{n}_1 \\ \sqrt{\frac{P_{MIMO}GP_r}{\sigma^2(1+P_rG)}}\mathbf{h}_2^H\mathbf{F}\mathbf{x} + \tilde{n}_2 \\ \vdots \\ \sqrt{\frac{P_{MIMO}GP_r}{\sigma^2(1+P_rG)}}\mathbf{h}_{N_s}^H\mathbf{F}\mathbf{x} + \tilde{n}_{N_s} \end{bmatrix} = \mathbf{H}_1\mathbf{F}\mathbf{x} + \tilde{\mathbf{n}} \tag{33}$$

Now $\mathbf{H}_1$ collects all the effects related to the virtual MIMO creation and $\tilde{\mathbf{n}}$ is the equivalent white normalized Gaussian noise. It is remarkable that this situation becomes a standard MIMO problem (as in equation (1)) but with non identical distributions of the matrix entries. Sum rate of this problem denoted as R_{Coop} using the dual BC-MAC decomposition is

$$R_{Coop} = \sum_{k=1}^{N_s} R_k \leq \log\det\left(\mathbf{I} + \sum_{k=1}^{N_s}\mathbf{H}_k^H\mathbf{Q}_k\mathbf{H}_k\right) \tag{34}$$

$$\text{Constrained to} \sum_{k=1}^{N_s} tr\mathbf{Q}_k \leq P_{MIMO}$$

where matrices $\mathbf{Q}_k$ represent the autocorrelation matrices in the dual MAC problem. As this optimization problem in fact depends on the choice of P_t and P_r, the solution may be expressed as follows:

$$R_{Sum} = \max_{P_t, P_r}\left(R_{Coop} = N_s \log\left(1 + \frac{P_tG}{\sigma^2}\right)\right) \tag{35}$$

that must be solved by exhaustive search in P_r and P_t. Fig. 5 shows the schematic equivalent view of the simplest case where 2 transmit sensors and 2 receiving sensors 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.

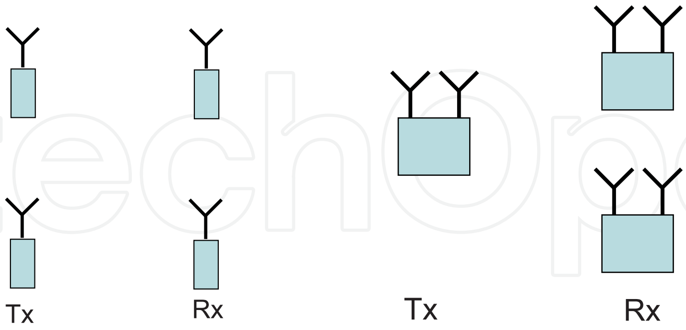

Fig. 5. Left hand side, original scenario. Right hand side, equivalent scenario with Tx /Rx cooperation

3.2 Scenario with intercluster interference

The model presented in this section permits us to quantify the new situation where another cluster is also transmitting and therefore causing interference to the aforementioned scenario in the previous section. Although only the case with one interfering cluster is modelled, the extension to several clusters is straightforward and will reinforce the Gaussian hypothesis for the interference that we will claim. The received signal i_1 at sensor 1 (our reference) in the original cluster coming from the interfering one is:

$$i_1 = \sqrt{\alpha P_{MIMO}}\,\mathbf{m}_1^H \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} \tag{36}$$

Where $\mathbf{m}_1$ is the flat fading channel from interfering cluster to the reference sensor, $\mathbf{F}_{\text{int}}$ (also assumed power normalized) is the precoding performed at that cluster and $\mathbf{x}_{int}$ is the transmitted sequence. $\sqrt{\alpha} \in (0,1)$ means the extra loss compared to the desired link to represent the fact that the interfering cluster may be further away (according to Figure 1, α=1). The mean interference power clearly becomes:

$$P_{\text{int}} = P_{MIMO}\,\alpha\,\mathbf{m}_1^H \mathbf{F}_{\text{int}} \mathbf{F}_{\text{int}}^H \mathbf{m}_1 = P_{MIMO}\,\alpha \tag{37}$$

Central Limit Theorem confirms the Gaussian hypothesis as a linear combination of i.i.d. random variables. So, the equivalent effect of interference makes effective noise to be increased from:

$$\sigma_{eff}^2 = \sigma^2 + P_{MIMO}\,\alpha \tag{38}$$

Clearly, the SNR becomes negative if we consider the circular distributions of sensors in figure 4 and in any case, the throughput degrades very significantly. Fig. 6 shows this performance degradation compared to the no interference case, in a 4x4 system (4 transmit sensors, 4 receive sensors). Recalling that the interference is modelled as an additional AWGN contribution, the sum rate of the system is depicted for different Gains G already described and for different values of the noise variance, σ_{eff}^2.

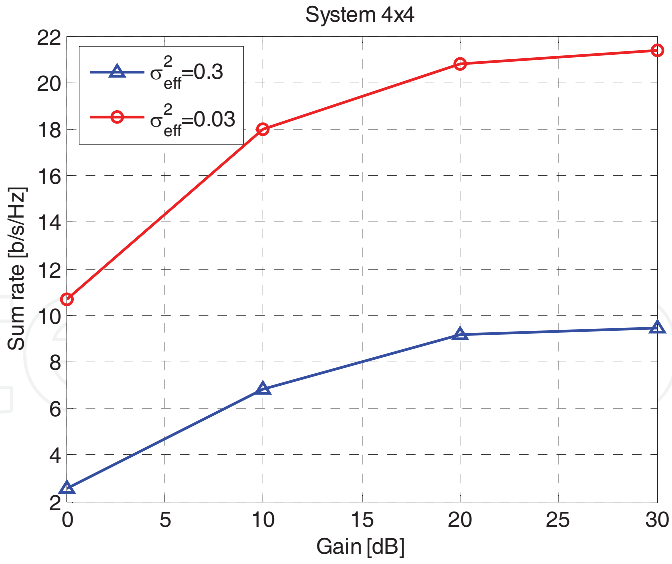

Fig. 6. Performance degradation due to interference

This previous result states that independently of the cooperation strategy, wireless ad hoc networks need some kind of coordination between neighbouring clusters in terms of multiple access strategy to avoid this large performance degradation.

In order to provide a feasible solution for 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 of dumb antennas in an irregular bidimensional beamforming. This way, instead of Rx cooperation in terms of a throughput increase following the BC approach showed in Fig. 4, we exploit the 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 spatially distributed beamformers (Ochiai et al, 2005;Mudumbai et al, 2007; Barton et al, 2007) 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. In particular, (Ochiai et al, 2005) analysed this case from the point of view of spatially random sampling and it shows the significant average gain (now beamforming performance becomes a random variable) and an acceptable average side lobes level.

The use of dummy sensors and the equivalent MIMO system are shown in Fig. 7 and Fig. 8. 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 a single transmitter with N_t=2 antennas, and N_s=2 receivers with N_b (4) antennas. The equivalent MIMO fading channels are given by equation (33).

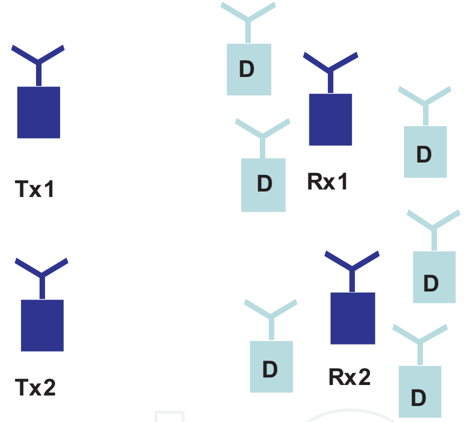

Fig. 7. 2x2 system with 3 dummy sensors per receive sensor

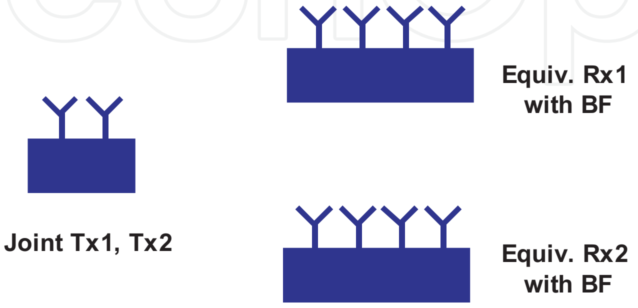

Fig. 8. Equivalent MIMO system of the 2x2 system with 3 dummy sensors per receive sensor

The key issue now is how to design the beamfoming to improve performance. Our proposal follows a double purpose: on the one hand, eliminate intercluster interference, and on the other maximize the intracluster throughput. In order to provide a reasonable model for this situation, we recall again the suboptimal approach described in section 1.

3.3 Proposed solution for the interference scenario

Fig.1 also shows the block diagram of the proposed scheme where $\mathbf{H}_\text{k}$ (N_b, N_s) represents the equivalent channel to the subcluster forming the beamforming. We will force $N_b>N_s$ for rank reasons as we will describe later. $\mathbf{r}_k$ represents again the beamforming to be designed.

In the interference-free scenario, the beamforming design would be the same as that described in section 2. However, current criteria assume that the interference channels are known at the receiver beamformers location. The suboptimal procedure can be described in several key ideas:

First point: eliminate completely the intercluster interference. In order to guarantee this condition, every beamformer must fulfil $\mathbf{r}_k$:

$$\mathbf{r}_k^H \mathbf{M}_k \mathbf{F}_{\text{int}} \mathbf{x}_{\text{int}} = 0 \tag{39}$$

where $\mathbf{M}_k$ is the channel (Ns, N_b) between the interfering cluster and the beamformer k.

Equation (39) is quite simple under the rank condition already mentioned because $\mathbf{r}_\text{k}$ must belong to the null space of $\mathbf{M}_\text{k}$.

Second point: recalling (9) a suboptimal solution to this problem is proposed in the real multiantenna scenario without interference. We showed that the beamformers maximizing throughput must be found from the following eigenanalysis (we show this again for convenience).

$$\mathbf{H}_k \mathbf{H}_k^H \mathbf{r}_k = \lambda_{\max} \mathbf{r}_k \tag{40}$$

Third point: 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 $\mathbf{M}_\text{k}$.

$$\mathbf{H}_k = \mathbf{H}_k^{\mathbf{M}_k} + \mathbf{H}_k^{\perp \mathbf{M}_k} \tag{41}$$

The final solution modifies the criteria given by (9) as

$$\mathbf{H}_k^{\perp \mathbf{M}_k} \left(\mathbf{H}_k^{\perp \mathbf{M}_k} \right)^H \mathbf{r}_k = \lambda_{\max} \mathbf{r}_k \tag{42}$$

3.4 Simulation Results

This section addresses some of the most remarkable results. The first scenario that is considered assumes a very closely spaced transmit sensor group, as well as the receive group, modelled with a high gain value (G=1000, that is, 30dB). The AWGN variance at the receive sensors is set to a very low value, in order to notice the degradation due to the intercluster interference and not to start with the scenario that is already close to saturation. Therefore, the noise variance is set to 0.03. A two transmit and two receive sensors (2x2) system is considered, with a variable number of dummy sensors – from 2 to 6 (that is, 3 to 7 cooperative sensors) and the simulation results are shown in Figure 9.

The sum rate capacity is depicted for the number of dummy sensors and for three configurations: a) system without intercluster interference and with beamforming according to equation (40), b) system with intercluster interference and beamforming according to equation (40) and finally, c) the proposed scheme, the system with intercluster interference and beamforming according to equation (42) that takes into account this interference and cancels it (Interference cancellation, IC). These schemes are denoted 'No interference', 'With Interference' and 'With Interference and IC', respectively.

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 in case a) to notice that incrementing the number of dummy sensors does not lead to a large capacity improvement. Moreover, the performance of this scheme is highly degraded when intercluster interference is included (case b)), and this is shown by the simulation results. It should be noted that above three or four dummy sensors, the sum rate improvement with increment of the number of dummy sensors is more pronounced in this case than in the former one. As the intercluster interference is modelled as an AWGN contribution, this shows that the throughput maximization with beamforming is more effective at lower SNR values. Finally, the third scheme (case c))is the ad hoc scheme for the analyzed configuration, with beamforming that takes into account the intercluster interference improving significantly the performance of the system, upper bounded by the sum rate of the system without intercluster interference. A smaller number of dummy sensors does not make sense for IC scheme as there are two transmitter sensors per interfering cluster, and at least two dummy sensors are needed to cancel the interference they cause.

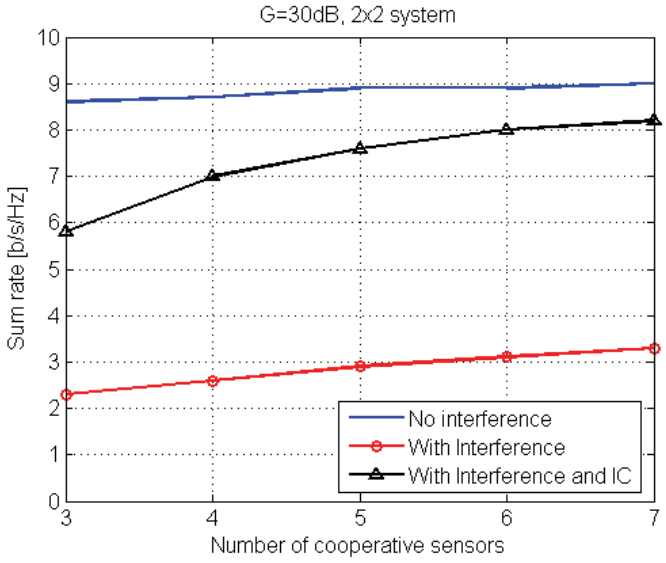

Fig. 9. Effect of the number of dummy sensors

Another aspect of the proposed scheme is its performance under a smaller gain between Tx and Rx groups. The same, 2x2 system is considered again, with four dummy sensors per each active Rx sensor (cooperative group of 5 sensors), and the same low noise variance (σ^2=0.03). The simulation results are depicted in Figure 10. This analysis is performed for gains greater than 100 (10dB), as cooperation is not recommendable at low gains (Ng et al, 2006). It can be observed that the performance loss of the system with intercluster interference and its cancellation with respect to the system without intercluster interference can be considered constant independent of the gain value.

Nevertheless, it is interesting to notice that the performance gain is less pronounced with the gain increment in the scenario with intercluster interference but without its cancellation, as the noise corresponding to the interference remains constant, independent of the gain.

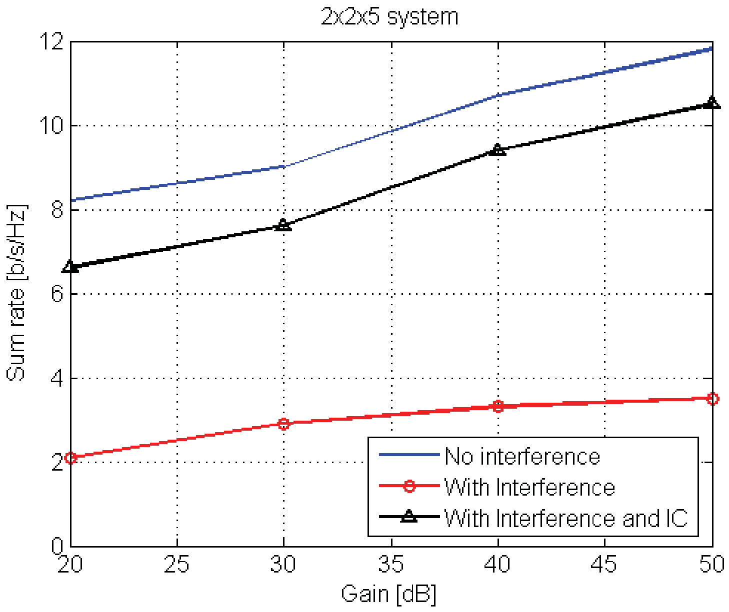

Fig. 10. Effect of the gain in Tx and Rx sectors

4. Conclusions

This chapter presents a new approach to the broadcast channel problem where the main motivation is to provide a suboptimal solution combining DPC with Zero Forcing precoder and optimal beamforming design. The receiver design just relies on the corresponding channel matrix (and not on the other users' channels) while the common precoder uses all the available information of all the involved users. No iterative process between the transmitter and receiver is needed in order to reach the solution of the optimization process. We have shown that this approach provides near-optimal performance in terms of the sum rate but with reduced complexity.

A second application deals with the cooperation design in wireless sensor networks with intra and intercluster interference. We have proposed a combination of DPC principles for the Tx design to eliminate the intracluster interference while at the receivers we have made use of dummy sensors to design a virtual beamformer that minimizes intercluster interference. The combination of both strategies outperforms existing approaches and reinforces the point that joint Tx /Rx cooperation is the most suitable strategy for realistic scenarios with intra and intercluster interference.

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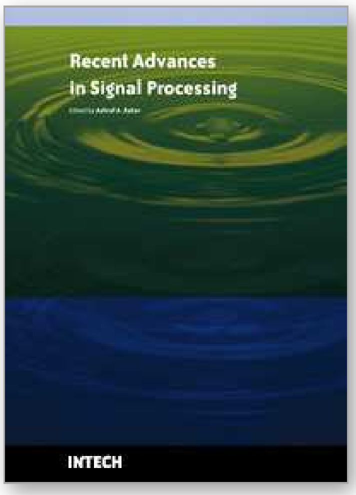

Recent Advances in Signal Processing
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The signal processing task is a very critical issue in the majority of new technological inventions and challenges in a variety of applications in both science and engineering fields. Classical signal processing techniques have largely worked with mathematical models that are linear, local, stationary, and Gaussian. They have always favored closed-form tractability over real-world accuracy. These constraints were imposed by the lack of powerful computing tools. During the last few decades, signal processing theories, developments, and applications have matured rapidly and now include tools from many areas of mathematics, computer science, physics, and engineering. This book is targeted primarily toward both students and researchers who want to be exposed to a wide variety of signal processing techniques and algorithms. It includes 27 chapters that can be categorized into five different areas depending on the application at hand. These five categories are ordered to address image processing, speech processing, communication systems, time-series analysis, and educational packages respectively. The book has the advantage of providing a collection of applications that are completely independent and self-contained; thus, the interested reader can choose any chapter and skip to another without losing continuity.

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