COOPERATIVE MIMO PRECODERS FOR ENERGY-EFFICIENT TRANSMISSION IN WIRELESS SENSOR NETWORK

Ghadir Madi, Baptiste Vrigneau, Anne-Marie Poussard and Rodolphe Vauzelle

Poitiers University, XLIM-SIC Laboratory CNRS UMR 6172
Téléport 2, Bd Marie et Pierre Curie, BP 30179 86962 Futuroscope Cedex (France)
email: madi, vrigneau, poussard, vauzelle@sic.univ-poitiers.fr

ABSTRACT

*Energy-efficient data transmission is one of the key factors for wireless sensor networks (WSN). By allowing sensor nodes in close proximity to cooperate in transmission, and by introducing a powerful data gathering node (DGN) equipped with an antenna array to collect data, a virtual multiple input multiple output (MIMO) channel can be formed. In a such system, recent advances in MIMO technologies can be applied. In this paper, two precoders (*max-$d_{\min}$ *and P-OSM) for closed-loop MIMO systems are considered. Energy-efficient cooperative schemes are proposed for these precoders based on a quantification of the feedback information. The results show that these MIMO precoders-based cooperative schemes can provide a significant energy efficiency compared to a space-time block codes-based cooperative schemes, even after using additional steps required in transmission.*

1. INTRODUCTION

Recent hardware advancements in wireless sensor networks (WSN) allow more signal processing functionality to be integrated into a single sensor chip. A wide range of applications are envisioned for WSN in various fields including healthcare, military applications, environmental monitoring, industrial control and other fields of public interest.

A WSN consists of a large number of low-cost, low-power distributed sensor nodes which are usually battery operated. In many applications, their replacement can be expensive and/or difficult, which makes energy efficiency the most critical issue in system design. Multiple-input-multiple-output (MIMO) is one of the techniques that has a considerable importance in wireless systems during recent years and is also a potential candidate for energy efficient design in WSN due to its diversity and bit error rate (BER) improvements. However, a drawback of MIMO techniques is that they require complex transceiver circuitry and large amount of signal processing power resulting in large power consumptions at the circuit level. Moreover, physical implementation of multiple antennas at a small-size sensor node may not be feasible. The solution came in the form of cooperative MIMO [1, 2] where the multiple inputs and outputs are formed via cooperation. The concept has been proposed to achieve MIMO capability in a network single antenna nodes. Many cooperative MIMO systems based on space-time block codes (STBC) are recently studied [1, 2, 3, 4, 5, 6]. Results show that this cooperative MIMO system may lead to better energy efficiency compared to the traditional single-input single-output (SISO) approach even after taking into account the additional circuit power, communications, and training overheads.

In this paper, we still consider a cooperative MIMO system to optimize the energy efficiency in the WSN. Our goal is to exploit more the performance of MIMO systems by using recent MIMO techniques like the two MIMO max-$d_{\min}$ [7] et P-OSM precoders [8]. These precoders improve the BER and increase the spectral efficiency of the system. In a typical WSN, the communication is mainly between low-power distributed nodes and a high-end data gathering node (DGN) that is less energy constrained [2]. Since most of the required processing in these precoders is on the receiver side, a virtual MIMO scheme based precoders can improve energy efficiency at distributed nodes by transferring most of the computational burden to the DGN. STBC only require the channel state information (CSI) at the receiver but precoders require the knowledge of the CSI at the transmitter. The precoder exploits the CSI to improve the performance of a wireless system by optimizing a pertinent criteria. After estimating the channel at the receiver, the CSI must be sent to the transmitter via a feedback channel. In WSN, the approach of feedback channel has already been considered in several contexts [6, 9, 10]. However, it is not clear in our case if max-$d_{\min}$ et P-OSM precoders lead to more energy savings because of added consumption due to the feedback channel. Therefore, this paper evaluates the energy and delay efficiencies of precoders-based virtual MIMO system. To do so, we propose and analyse different schemes of cooperative transmission for the two precoders. A finite-rate limited feedback channel is considered with a quantification of the CSI applied to the precoders.

This paper is organized as follows. In Section 2, we present a brief overview of max-$d_{\min}$ et P-OSM precoders with limited feedback channel. Section 3 presents the basic energy consumption model for MIMO cooperative in WSN and explains how the precoders can improve the performance. The proposed schemes for the two precoders are illustrated in Section 4, where the expressions for the total energy consumption are also derived. Numerical results for the proposed schemes and the traditional STBC-based scheme are given in Section 5. Finally, Section 6 concludes the paper.

2. PRESENTATION OF THE PRECODERS

We assume that the CSI is available at both transmit and receive side of a MIMO system with n_t transmit and n_r receive antennas over which $b \leq \min(n_t, n_r)$ independent data streams are achieved.

2.1 The max-$d_{\min}$ precoder

A MIMO system with linear precoder is given by

$$\mathbf{y} = \mathbf{GHFx} + \mathbf{Gn} = \mathbf{G}_d\mathbf{H}_v\mathbf{F}_d\mathbf{x} + \mathbf{G}_d\mathbf{n}_v \tag{1}$$

where $\mathbf{y}$ is the $b \times 1$ received vector, $\mathbf{x}$ is the $b \times 1$ symbols vector of the constellation C, $\mathbf{n}$ is an $n_r \times 1$ additive noise vector, $\mathbf{H}$ is the $n_r \times n_t$ Rayleigh fading channel matrix, $\mathbf{F}$ and $\mathbf{G}$ are the precoder and decoder matrices, respectively. The CSI permits the precoder to diagonalize the channel, where $\mathbf{H}_v = \mathbf{G}_v\mathbf{H}\mathbf{F}_v = \mathrm{diag}(\sigma_1, \ldots, \sigma_b)$ is the virtual channel matrix of size $b \times b$, σ_i stands for every subchannel gain sorted by decreasing order, $\mathbf{n}_v = \mathbf{G}_v\mathbf{n}$ is the virtual noise. The unitary matrices $\mathbf{F}_v$ and $\mathbf{G}_v$ are based on the singular value decomposition (SVD) of $\mathbf{H}$. As only a maximum Likelihood detection (MLD) is considered, the decoder matrix $\mathbf{G}_d$ has no impact on the performance and is consequently assumed to be $\mathbf{G}_d = \mathbf{I}_b$ (identity matrix of size $b \times b$). The max-$d_{\min}$ maximizes the minimum Euclidean distance $d_{\min}$ between signal points at the receiver as

$$\mathbf{F}_d = \arg\max_{\mathbf{F}_d} \; d_{\min}(\mathbf{F}_d), \quad d_{\min}(\mathbf{F}_d) = \min_{\mathbf{e}\,\in\, C^b} \|\mathbf{H}_v\mathbf{F}_d\mathbf{e}\| \tag{2}$$

where $\mathbf{e} = (\mathbf{x}_k - \mathbf{x}_l)$, $(k \neq l)$. A very exploitable solution of (2) is given in [7] for two independent data streams, $b = 2$ and a 4-QAM. The solution for 16-QAM is also available in [11]. These

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solutions are SNR-independent and simply depend on the value of the channel angle γ defined as ($\gamma = \arctan \frac{\sigma_2}{\sigma_1}$).

2.2 The P-OSM precoder

In [12], an orthogonalized spatial multiplexing (OSM) scheme was proposed for closed-loop MIMO systems. This scheme achieves orthogonality between transmitted signals by applying a proper rotation to transmitted symbols. Furthermore, a precoding scheme was also proposed in [8] for the OSM system (P-OSM). This precoding scheme or P-OSM precoder maximizes the minimum Euclidean distance $d_{\min}$ like max-$d_{\min}$ precoder. The OSM transmits $b = 2$ independent data streams over $n_t = 2$ transmit antennas. If $n_t > 2$, the OSM must be associated with an antenna-selection method. In [12], a simple antenna selection method based on the minimum Euclidean distance is proposed where it was shown that the set of candidate vectors in computing the distance minimal can be reduced from 120 to 2 for 4-QAM modulation. The principle of OSM consist in precoding symbols as $\mathbf{s}(\mathbf{x}) = [\mathscr{R}_e[x_1] + j\mathscr{R}_e[x_2] \quad \mathscr{I}_m[x_1] + j\mathscr{I}_m[x_2]]^T$ associated to the single-parameter precoder $\mathbf{F}(\mathbf{x}, \theta_0) = \text{diag}\{1, \exp(j\theta_0)\}\mathbf{s}(\mathbf{x})$, where $\mathscr{R}_e[.]$ and $\mathscr{I}_m[.]$ stand for the real and imaginary part respectively, θ_0 is the rotation phase angle applied to the second antenna. The angle θ_0 is chosen in order to orthogonalize the received symbols, leading to a MLD simplification with a single symbol decision. Note that the MLD in max-$d_{\min}$ requires searching for a pair of symbols. With the above precoding, the system model in (1) can be written as

$$\mathbf{y} = \mathbf{HF}(\mathbf{x}, \theta_0) + \mathbf{n} = \mathbf{H}^{\theta_0}\mathbf{s}(\mathbf{x}) + \mathbf{n} \tag{3}$$

where $\mathbf{H}^{\theta_0}$ represents the channel matrix for $\mathbf{s}(\mathbf{x})$. In [8], the P-OSM precoder is given in a real-valued representation

$$\mathbf{y}_r = \mathbf{H}_r^{\theta_0}\mathbf{P}\mathbf{s}_r(\mathbf{x}) + \mathbf{n}_r = \mathbf{H}_r^{\theta_0}\begin{bmatrix} \mathbf{P}_1 & 0 \\ 0 & \mathbf{P}_2 \end{bmatrix}\mathbf{s}_r(\mathbf{x}) + \mathbf{n}_r \tag{4}$$

where $\mathbf{P}$ is 2×2 real precoding matrix decomposed into three ones:

$$\mathbf{P} = \begin{bmatrix} \mathbf{R}_{\theta 1} & 0 \\ 0 & \mathbf{R}_{\theta 1} \end{bmatrix}\begin{bmatrix} \mathbf{D} & 0 \\ 0 & \mathbf{D} \end{bmatrix}\begin{bmatrix} \mathbf{R}_{\theta 2} & 0 \\ 0 & \mathbf{R}_{\theta 2} \end{bmatrix}$$
$$\text{where } \mathbf{R}_{\theta i} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}, \mathbf{D} = \begin{bmatrix} p & 0 \\ 0 & \sqrt{2-p^2} \end{bmatrix} \tag{5}$$

The three parameters θ_1, θ_2 and p which maximize $d_{\min}$ are calculated in [8]. The angle θ_1 is directly calculated from $\mathbf{H}_r^{\theta_0}$ while θ_2 and p are chosen from tables depending on a threshold k.

2.3 Quantization of feedback information

The DGN uses its estimate of the channel matrix $\mathbf{H}$ to design the feedback needed by transmitters. In practical situations like WSN, this feedback should be as limited as possible for energy efficient purposes. Therefore, important issues are how to quantize feedback information needed at the transmitter and how much improvement in associated performance can be obtained as a function of the amount of feedback available.

2.3.1 *Precoder* max-$d_{\min}$

In the max-$d_{\min}$ precoder, the transmitter must know the unitary matrix $\mathbf{F}_v$ and the angle γ. For quantizing this matrix, we are based on the work on limited feedback unitary precoding of D.J. Love in [13]. The receiver chooses the optimal matrix from a finite codebook $\mathscr{F}_v = (F_{v1}, F_{v2}, \ldots, F_{vl})$, $l = 2^{n_1}$ known to both receiver and transmitter. The index of the chosen matrix is conveyed to the transmitter using n_1 bits of feedback. However, the max-$d_{\min}$ needs also the value of γ or the matrice $\mathbf{F}_d$ [14]. Thus, in order to limit the total number of bits, we have opted to directly design a codebook for the matrix $\mathbf{F} = \mathbf{F}_v\mathbf{F}_d$. This codebook is empirically designed from simulation with respect to the $\mathscr{F}_v$ codebook and the $(n_t \times n_r)$ Rayleigh MIMO channel. The matrice is choosen respecting the criterion of maximization of the minimum Euclidean distance.

2.3.2 *Precoder P-OSM*

The quantification is more simple since we only need to quantize the two angles θ_0 and θ_1. The total number of feedback bits conveyed to the transmitter is $(n_{\theta_0} + n_{\theta_1} + n_M + n_{AS})$, where n_{θ_0} and n_{θ_1} are the number of feedback bits for θ_0 and θ_1 respectively, n_M depends on the modulation ($n_M = 1$ for 4-QAM [8]) and $n_{AS} = \log_2(C_{n_t}^2)$ is additional feedback bits needed to select the antenna subset if $n_t > 2$.

3. COOPERATIVE AND ENERGY MODEL FOR WSN

3.1 Energy model

A typical scenario in WSN is that of a cluster of n_t data collection sensors connected over a wireless link with a high-end data gathering node (DGN) that acts as a lead sensor [2, 9]. The n_t sensors are typically subjected to strict energy constraints while DGN is not. Suppose that sensors have data to sent to the DGN and apply cooperative MIMO as follows. First, each of these sensors broadcasts their data to others in the cluster over a distance of d_m (we assume that sensors are close to each other). This step is known as the local communications at the transmitter side [1]. MIMO techniques are then used to send data simultaneously to the DGN over a distance d ($d \gg d_m$) as if each node were a distinct transmit antenna element in a centralized antenna array. This step is known as the long-haul MIMO communication. At the reception, the DGN can be of larger physical dimensions to accommodate multiple receiver antennas (n_r antennas). This allows realization of true MIMO capability with only the transmitter side local communications. In order to evaluate the power consumption, we consider the model developed in [1, 15]. The total power consumption of a RF system can be divided into two main components: the power consumption of all the power amplifiers P_{pa} and the power consumption of other circuit blocks P_c. The P_{pa} power can be approximated as ($P_{pa} = P_{out}\xi/\eta$), where ξ is the peak-to-average ratio (PAR), η is the drain efficiency of the RF power amplifier and P_{out} is the transmit power which can be calculated according to the link budget relationship. The P_{pa} power is then given by [1, 16]

$$P_{pa} = \frac{\xi}{\eta}P_{out} = \frac{\xi}{\eta}\left(\frac{E_b}{N_0}\right)\frac{(4\pi)^2 d^\alpha M_l N_r}{G_t G_r \lambda^2}R_b \tag{6}$$

where E_b/N_0 is the average energy per bit to the noise required for a given BER specification, R_b is the system bit rate, G_t and G_r are the transmitter and receiver antenna gains respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference, N_r is the power spectral density (PSD) of the total effective noise at the receiver input [1, 17], d is the transmission distance, α is the channel path loss exponent which could usually lie in the range $2-4$ for wireless communications channels. The P_c power can be estimated as $P_c \approx n_t P_c^{ClusterTx} + n_r P_c^{ClusterRx}$, where $P_c^{ClusterTx}$ and $P_c^{ClusterRx}$ are the circuit energy consumption of a single node during transmission and reception respectively. $P_c^{ClusterTx}$ typically includes that of the digital-to-analog converter, the mixer, the transmit filters, and the frequency synthesizer, while $P_c^{ClusterRx}$ typically includes that of the analog-to-digital converter, the mixer, the receive filters, the frequency synthesizer, the low noise amplifier, and the intermediate frequency amplifier [1]. Total energy per bit can then be estimated as

$$E_t = (P_{pa} + P_c)/R_b = E_{pa} + E_c \tag{7}$$

where E_{Pa} and E_c represent the transmission energy consumption ant the circuit energy consumption respectively. R_b can be replaced by $R_b^{eff} = R_b(F - pn_t)/F$ to take into account the energy spent on the training overhead required for the channel estimation needed for MIMO systems where the packet size is equal to F symbols and in each packet we include pn_t training symbols (p symbols are used to train each transmitter and receiver antenna pair) [2].

3.2 Benefits of precoders

The idea of applying the max-$d_{\min}$ and P-OSM precoders in WSN is to reduce the E_b/N_0 ratio while still ensuring the same target BER. In a WSN, any improvement on this front can be a significant gain since, in most situations, the transmission energy E_{pa} is the dominant power consumption term. On the other hand, these precoders also increase the bit rate R_b thanks to its spectral efficiency while still using the same modulation for the transmitted symbols and the same frequency band: $R_b = r\log_2(M)B$, where M is the constelletion size, B is the system bandwidth and r is the rate of the MIMO technique defined as the number of transmitted symbols over the number of symbol periods required. For example, the best rate of STBC is equal to 1 and is available for $n_t = 2$ (Alamouti's code) and when $n_t > 2$, STBC only exist for rates smaller than 1 ($3/4$ or $1/2$) [18]. This rate is increased to 2 for max-$d_{\min}$ and P-OSM precoders. Thanks to this spectral efficiency of precoders compared to STBC, it is possible to reduce the transmission time in WSN which leads to lower power consumption in circuits.

Figure 1 shows the BER of max-$d_{\min}$ and P-OSM precoders for a full and quantized CSI and of $3/4$-rate STBC. The channel is a 4×4 MIMO Rayleigh fading. The modulation of precoders is 4-QAM which gives a spectral efficiency of 4 $bits/s/Hz$ and modulation of STBC is 16-QAM and a spectral efficiency of 3 $bits/s/Hz$. A total of 7 feedback bits are considered: max-$d_{\min}$ with $n_1 = 7$ and P-OSM with $n_{\theta_0} = 2$, $n_{\theta_1} = 1$, $n_M = 1$, and $n_{AS} = 3$. Figure 1 shows that the quantization introduces a E_b/N_0 loss of 1.5 dB for max-$d_{\min}$ and 2 dB for P-OSM. For a target BER of 10^{-4}, E_b/N_0 are 2.5 dB, 5.1 dB and 6.8 dB for max-$d_{\min}$, P-OSM and STBC, respectively. Those results definitively indicate the benefit of precoders even with the limited feedback link.

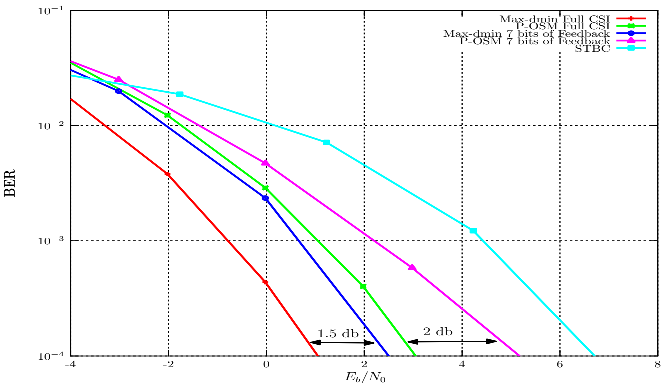


Figure 1: BER of the two precoders (full and quantized CSI) with $4bits/s/Hz$ and STBC with $3bits/s/Hz$

Moreover, the parameter ξ (PAR) depends on the modulation scheme and the constellation size [15, 19]. Throughout this paper we assume M-QAM systems, so that ($\xi = 3(M-2\sqrt{M}+1)/(M-1)$) [15] for STBC. This calculation is no longer accurate for the two precoders: each transmit signal becomes a composite signal due to processing caused by the precoders. Values of PAR for MIMO precoding system are not easily obtained analytically [20]. Thus, we resort numerical analysis to find these values. For a classical 4-QAM system, ξ is equal to 1. When precoding is used, results showed that the P-OSM is still ensuring this value while the max-$d_{\min}$ has a penalizing higher PAR ($\xi \approx 1.6$).

4. COOPERATIVE MIMO SCHEMES FOR max-$d_{\min}$ AND P-OSM PRECODERS

4.1 Precoder max-$d_{\min}$

In figure 2, we propose a cooperative transmission scheme for the max-$d_{\min}$. We assume that each sensor node has L bits to transmit to the DGN. In the local transmission, each node broadcasts their

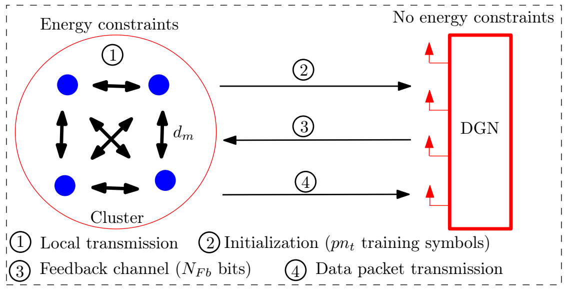


Figure 2: Cooperative scheme for max-$d_{\min}$ ($n_t \geq 2$) and P-OSM ($n_t = 2$)

data to the others in the cluster over a short distance d_m. Therefore, it may be realistic to assume that local transmissions are over an AWGN channel [21]. If the sensors are located in a dense scatterer environment, the short-range transmission may be modelled by a fading channel. Since the nodes in the cluster must know the CSI before starting the transmission of data packets, an initialization is firstly performed. This phase is based on STBC and permits to initialize the transmission by sending the pn_t training symbols for the channel estimation. Note that STBC only require the CSI at the receiver. This allows the DGN to estimate the channel and send the necessary feedback information to the cluster nodes via the limited feedback channel. After receiving the feedback information, the nodes can now send their data packets using precoding techniques to the DGN over a distance $d \gg d_m$. During data packet transmission, the training symbols are then inserted into each data packet and the estimation is able to track the channel variation. The total energy consumption for all bits of this cooperative MIMO-based scheme is

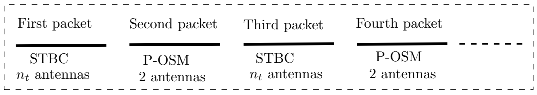
$$E_{CoopPrecoder} = E_{Loc} + E_{Init} + E_{Fb} + E_l \tag{8}$$

where E_{Loc}, E_{Init}, E_{Fb}, E_l are the energies required for local transmission, initialization phase, feedback channel, long-haul MIMO transmission, respectively. The energy E_{Loc} is equal to $N_p(P_{pa}+P_c)/R_b^{effLoc}$, where $P_c = P_c^{ClusterTx} + (n_r-1)P_c^{ClusterRx}$ (one transmitter and $n_r - 1$ receivers at each local sensor transmission), $N_p = n_t L$ is the total number of bits in all data packets and P_{pa} is calculated using (6) for SISO transmission over AWGN channel and a 16-QAM modulation. The energy E_{Init} is equal to $(N_{Ts}(P_{pa}+P_c)/R_b^{STBC})$, where $P_c = n_t P_c^{ClusterTx}$, N_{Ts} is the number of bits in the training symbols and P_{pa} is calculated using (6) for STBC MIMO transmission over $n_t \times n_r$ Rayleigh MIMO channel and 4-QAM. The energy $E_{Fb} = (N_{Fb} n_t P_c^{ClusterRx}/R_b)N_{packet}$, where the n_t nodes act as receivers, N_{Fb} is the number of bits in the feedback channel ($N_{Fb} = 7$ bits) and N_{packet} is the number of data packets to send (estimation for each packet). Finaly, we calculate the term E_l which represents the energy required for data packets transmission: $E_l = N_p(P_{pa}+P_c)/R_b^{effprecoder}$, where $P_c = n_t P_c^{ClusterTx}$ and P_{pa} is calculated using (6) for precoding MIMO transmission over $n_t \times n_r$ Rayleigh MIMO channel.

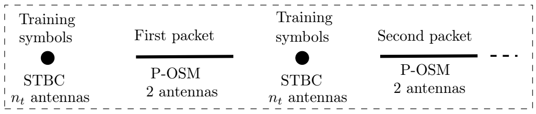
4.2 Precoder P-OSM

When $n_T = 2$, the scheme is the same as max-$d_{\min}$. However, when $n_t > 2$, the P-OSM must be alternated with STBC. Indeed, the P-OSM is associated with an antenna-selection method [12] which is performed at the DGN after estimating the $n_t \times n_r$ MIMO channel. In order to estimate the entire channel matrix, all antennas must transmit a signal. From this remark, we propose three configurations (figure 3):

- **Config.1**: in figure 3a, the nodes transmit their first packet using STBC which allows the DGN to estimate the $n_t \times n_r$ MIMO channel and sent the feedback information to the cluster. The



(a) Config.1 and Config.2



(b) Config.3

Figure 3: P-OSM schemes when $n_t > 2$

nodes then transmit their second packet using the P-OSM precoder over the two selected antennas among the available n_t antennas. Here, we use a 4-QAM for STBC codes which gives a spectral efficiency of $(r\log_2(M)|_{\text{STBC}} + r\log_2(M)|_{\text{P-OSM}})/2 = (3/4 \times 2 + 2 \times 2)/2 = 2.75\ bits/s/Hz$.

- **Config.2**: it is the same as Config.1 with a 16-QAM STBC. In this case, a spectral efficiency of 3.5 $bits/s/Hz$ is obtained. The total energy consumption for Config.1 and Config.2 is

$$E_{CoopPOSM1-2} = E_{Loc} + E_{Fb} + E_{l1} + E_{l2} \qquad (9)$$

where $E_{Fb} = N_{Fb}(n_t P_c^{ClusterRx}/R_b)N_{packet}/2$. E_{l1} is the energy during the STBC based transmission: $E_{l1} = ((P_{pa} + P_c)/R_b^{effSTBC})N_p/2$, where $P_c = n_t P_c^{ClusterTx}$. E_{l2} is the energy during the the P-OSM based transmission: $E_{l2} = ((P_{pa} + P_c)/R_b^{precoder})N_p/2$, where $P_c = 2P_c^{ClusterTx}$ because the P-OSM only uses 2 antennas. P_{pa} is always calculated using (6) for each case considered (STBC or P-OSM).

- **Config.3**: Figure 3b shows the third configuration where the STBC is used to send only the pn_t training symbols, without data bits. In this case, a 4-QAM is used for STBC. This configuration gives a spectral efficiency of 4 $bits/s/Hz$ in real data transmission since data packets transmission is only done by using the P-OSM precoder. The total energy consumption for Config.3 is

$$E_{CoopPOSM-3} = E_{Loc} + N_{packet}E_{Init} + E_{Fb} + E_{l2} \qquad (10)$$

where E_{Init} and E_{Fb} are calculated as in the case of the max-$d_{\min}$ precoder. $E_{l2} = N_p(P_{pa} + P_c)/R_b^{precoder}$, where $P_c = 2P_c^{ClusterTx}$.

Finally, in contrast to these cooperative MIMO schemes, the total energy required in communicating the same amount of data by a cooperative MIMO based only on STBC is

$$E_{CoopSTBC} = E_{Loc} + N_p\left(\frac{P_{pa} + P_c}{R_b^{effSTBC}}\right), \quad P_c = n_t P_c^{ClusterTx} \qquad (11)$$

P_{pa} is calculated by using (6) for STBC MIMO transmission over $n_t \times n_r$ Rayleigh MIMO channel and M-QAM. The STBC-based cooperative scheme also needs the same $n_t p$ training symbols because the CSI is required at the receiver.

Note that: E_{Loc} is the same for all schemes, R_b^{eff} is only considered when a training symbols are inserted into data packets and energy consumptions at the DGN is dropped from our calculation because the DGN has no energy constraint. In comparing the performance of these cooperative systems, the delay efficiency is also important beside the energy consumption due to the extra communication steps needed. The transmission delay is defined as the total time required for transferring all the data bits from cluster nodes to the DGN.

5. NUMERICAL RESULTS

To evaluate the energy consumption, we use the same power consumption parameters that assumed in [1] (i.e., G_t, G_r, M_l, $P_c^{ClusterTx}$, $P_c^{ClusterRx}\ldots$). We have $n_t = 4$ sensor nodes and a DGN with $n_r = 4$ antennas. The calculated energy represents the energy consumed to transmit $L = 10^3$ bits with a target BER of 10^{-4} of each node to DGN over a distance d and Rayleigh channel. The E_b/N_0 values required for this BER are obtained from figure 1. The following values are taken for the other parameters: path loss exponent $\alpha = 3.5$, distance local $d_m = 10\ m$, number of feedback bits $N_{Fb} = 7$ bits and $p = 10$ training symbols. The target spectral efficiency is 4 $bits/s/Hz$ and the central frequency is 2.5GHz. We consider a perfect synchronization and channel estimation and a maximum likelihood detection is used in reception. Note that the parameters G_t, G_r, M_l, N_r, η, k, $P_c^{ClusterTx}$, $P_c^{ClusterRx}$ will apply equally to the various systems under consideration, so they are irrelevant when making relative comparison between systems.

5.1 Study of P-OSM configurations

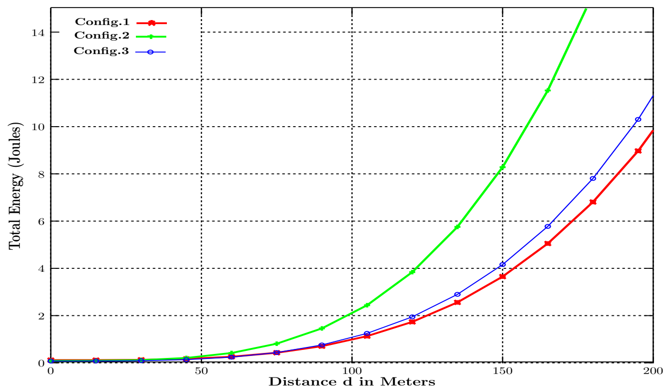


Figure 4: Energy consumption in the three P-OSM configurations, Target BER $= 10^{-4}$, Target spectral efficiency is 4 $bits/s/Hz$

Figure 4 and Table 1a show respectively the total energy consumption as a function of the long-haul MIMO transmission distance d and the transmission delay in the three P-OSM configurations (Config. 1, 2, 3). Config.1 has the best energy consumption but with the higher delay (0.3 second) because of its low spectral efficiency (2.75 $bits/s/Hz$). Config.2 has a high energy consumption with a lower delay (0.23 second) because it uses a 16-QAM modulation for STBC which reduces the transmission time. On the contrary, Config.3 gives the best transmission delay (0.21 seconds) and a good energy consumption which is slightly higher than the energy consumption of Config.1. However, this small difference may be ignored thanks to the delay gain obtained. Config.3 is the only one that achieves a spectral efficiency of 4 $bits/s/Hz$ in data packets transmission where the P-OSM precoder is exploited. The STBC is only implicated for transmitting pn_t number of the training symbols which is much more smaller than the data symbols. Therefore, Config.3 will be considered in the rest of this paper.

5.2 Cooperative schemes: max-$d_{\min}$, P-OSM and STBC

In figure 5, we evaluate the total energy consumption for STBC, max-$d_{\min}$, and P-OSM (Config.3) cooperative schemes. Transmission energy consumption E_{pa} becomes the dominant power con-

	delay
Config.1	0.3
Config.2	0.23
Config.3	0.21

(a)

	delay
max-$d_{\min}$	0.21
P-OSM	0.21
STBC	0.25

(b)

Table 1: Transmission delay in second

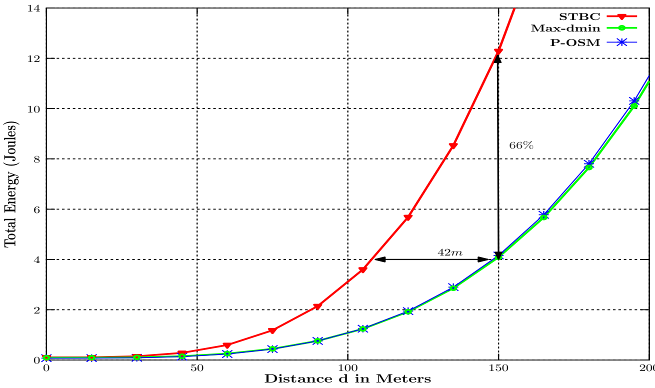


Figure 5: Energy consumption in max-$d_{\min}$, P-OSM and STBC cooperative schemes, Target BER $= 10^{-4}$, Target spectral efficiency is 4 $bits/s/Hz$

sumption term. Although the precoders max-$d_{\min}$ and P-OSM require several steps for transmission (initialization, Feedback...), their cooperative schemes outperform the STBC cooperative one in energy efficiency. For exemple, when $d = 150\ m$, the max-$d_{\min}$ and P-OSM cooperative schemes offer 66 % of energy savings compared to STBC based scheme. This is due to the E_b/N_0 improvements achieved by these precoders. Moreover, the quantification of precoders allows to reduce considerably the number of bits sent in feedback channel (7 bits) which reduces the energy consumption in this channel. On the other hand, the max-$d_{\min}$ precoder has an initialization phase energy consumption E_{Init} which is much more smaller than the E_l ou E_{l2} for P-OSM (cf (8) and (10)) because only $n_t p$ symbols are transmitted. However, the two precoders schemes seem to show a near performance while the max-$d_{\min}$ precoder archives a smaller E_b/N_0 than the P-OSM one. As mentioned before, the max-$d_{\min}$ precoder is penalized by a higher value of PAR (η) which increases the power consumption of amplifiers according to (6). From Table 1b, we see that these cooperative precoder-based schemes also lead to a slightly smaller transmission delay in spite of the additional steps mentioned before thanks to their heigher spatial multiplexing ability. Finally, we can slightly increase the feedback bits N_{Fb} to 8 or 10 bits and obtain more energy savings thanks to the improvement in E_b/N_0 values without a significant increasing of energy consumption in the feedback channel.

6. CONCLUSION

In this paper, we have investigated the energy efficiency of several efficient MIMO transmission techniques in cooperative wireless sensor networks. Assuming that the CSI is available at the transmitter, we have proposed and analyzed different cooperative schemes for the max-$d_{\min}$ and P-OSM MIMO precoders. In order to limit the complexity for a realistic realization, the feedback information is limited to 7 bits. Remember that STBC have been showed to save energy consumption compared to SISO transmission. Our results pointed that the cooperative precoders-based scheme can offer more substantial energy savings in WSN even with the additional steps required in transmission. Moreover, the channel is assumed static and future works will introduce mobility in order to see the impact on BER and therefore on energy consumption.

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