Energy Efficient Transmission in MIMO Wireless Sensor Networks with Antenna Selection

Glauber Brante, Marcos Tomio Kakitani, Richard Demo Souza, and Luc Vandendorpe

Abstract— **In this paper, we compare the energy efficiency of different multiple antenna (MIMO) techniques in wireless sensor networks. The considered energy consumption model takes into account the radio frequency (RF) circuitry, the efficiency of the power amplifier, and the transmission rate. Since the energy consumption of the additional RF chains required by each antenna becomes relevant at short transmission ranges, we show that antenna selection is a strong candidate for energy efficient communication as it uses a single RF chain. Based on this observation, we focus on transmit antenna selection (TAS) and switch and stay combining (SSC) at the receiver. In addition, we also show that cooperative single antenna (SISO) schemes may be more energy efficient than non-cooperative multiple antenna methods for very short ranges or low spectral efficiencies.**

Keywords— **Energy efficiency, wireless sensor networks, multiple antennas.**

I. Introduction

Wireless sensor networks (WSNs) usually operate with battery-powered devices, whose recharge or replacement is undesired or even impossible, so that energy efficiency is of paramount importance in the system design. This issue becomes even more evident if we compare the large computational gains reached in the last decades with the small improvement in the capacity of the batteries. Recent studies show an increase of 1 million times in terms of throughput and 40 million times in computational capacity since 1957, while only 3.5% of gain per year in the nominal battery capacity has been reached in the last two decades [1], [2], highlighting the necessity of designing energy efficient communication techniques.

One alternative to improve the energy efficiency of wireless systems is the use of multiple antenna (MIMO) techniques. Due to spatial diversity gains, MIMO systems can considerably improve the signal-to-noise ratio (SNR) if compared to single antenna (SISO) systems [3]. Thus, for the same performance requirement, MIMO may demand less transmit power than SISO. However, despite the benefits in terms of transmit power, increasing the number of antennas also implies in multiple radio frequency (RF) chains, which increases the energy consumption. Therefore, the reduction of the transmit power is followed by an increase of the circuitry energy consumption, what may compromise the energy efficiency. A representative example is given in [4], where it is shown that with more realistic power consumption models the advantage of MIMO techniques over SISO transmission is not always evident for short-range communications. However, in [4] the authors consider only the of use of the Alamouti space-time codes as MIMO technique.

In order to circumvent this issue, we address some diversity combining techniques that reduce the number of required RF chains. At the receiver, we exploit antenna selection by using switch-and-stay combining (SSC) instead of maximal ratio combining (MRC) [3]. Such technique allows only one antenna to remain active at the receiver, and achieves the same diversity as MRC, with a small penalty to the outage performance [3]. At the transmitter side, transmit antenna selection (TAS) may be an alternative to reduce the RF circuitry consumption [5]. In TAS the receiver must inform the transmitter, by means of a feedback channel, of which transmit antenna has the best condition. Under the outage probability viewpoint, antenna selection is a sub-optimal strategy, nevertheless, this fact is compensated by a lower circuitry energy consumption.

In this paper we compare the energy efficiency of SISO and MIMO transmission schemes in a point-to-point link between WSN nodes. At the transmitter, we focus on the use of space-time (ST) codes, TAS, and beamforming via a singular value decomposition (SVD) technique. At the receiver, either MRC or SSC are employed. Our results show that, although SVD presents the best performance in terms of required transmit power, the combination of TAS and SSC is the most energy efficient option when the circuitry consumption of the antennas is accounted. In addition, since cooperative communications emerged as an alternative to achieve spatial diversity even with single-antenna devices [6], we also compare the energy efficiency of the MIMO schemes with a SISO single-relay cooperative scheme employing decode-and-forward (DF). Our results show that, when a feedback channel is available, cooperative SISO can be more energy efficient than non-cooperative MIMO for short-range communications and for relatively low data rates.

The remainder of this paper is organized as follows. Section II presents the system model. Section III presents the minimal required transmit power for a given outage probability, and the corresponding energy efficiency, for three MIMO techniques: orthogonal ST codes, TAS, and SVD. The case of single antenna transmission is also included. Some numerical results for the total energy consumption for a given target outage probability and spectral efficiency are given in Section IV, while Section V concludes the paper.

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II. System Model

We consider a general wireless link between two nodes in a wireless sensor network, as illustrated in Figure 1. The source is equipped with n_t transmit antennas, where n_{t_e} denotes the number of active antennas, and the destination has n_r receive antennas, of which n_{r_e} are active. Then, the received signal can be represented in the following vector form

$$\mathbf{y} = \sqrt{\frac{\kappa P}{n_{t_e}}}\,\mathbf{H}\,\mathbf{x} + \mathbf{w}, \tag{1}$$

where P is the total transmit power, κ is the link budget relationship, $\mathbf{H}$ is the $n_{r_e} \times n_{t_e}$ matrix of quasi-static channel gains, which are independent and identically distributed (i.i.d.) assuming a zero-mean and unity-variance Rayleigh distribution, $\mathbf{x}$ is the $n_{t_e} \times 1$ unity energy transmitted symbol vector, and $\mathbf{w}$ is a $n_{r_e} \times 1$ vector of Gaussian noise, with variance $N_0/2$ per dimension, where N_0 is the unilateral thermal noise power spectral density.

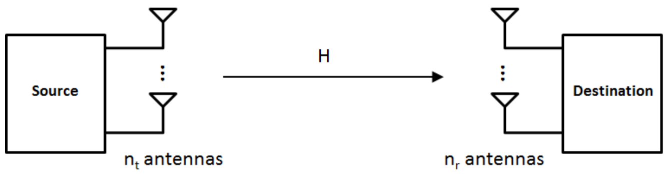

Fig. 1. System Model. The source is equipped with n_t transmit antennas, of which n_{t_e} are active, and the destination has n_r receive antennas, of which n_{r_e} are active.

The link budget relationship is assumed to be given by [4]

$$\kappa = \frac{G\lambda^2}{(4\pi)^2 d^{\nu} M_l N_f}, \tag{2}$$

where G is the total antenna gain, $\lambda = \frac{3e^8}{f_c}$ is the wavelength, f_c is the carrier frequency, d is the distance between the nodes, ν is the path loss exponent, M_l is the link margin, and N_f is the noise figure at the receiver.

The instantaneous SNR at the receiver is

$$\gamma = \|\mathbf{H}\|_F^2 \cdot \overline{\gamma}, \tag{3}$$

where

$$\|\mathbf{H}\|_F = \sqrt{\sum_{i=1}^{n_{r_e}} \sum_{j=1}^{n_{t_e}} |h_{ij}|^2} \tag{4}$$

is the Frobenius norm of $\mathbf{H}$, with $h_{ij} \in \mathbf{H}$ representing the channel gain between the selected j-th transmit antenna and i-th receive antenna, $\overline{\gamma} = \frac{\kappa P}{n_{t_e} N}$ is the average SNR, $N = N_0 \cdot B$ is the noise power, and B is the bandwidth. It is worth noting that γ is computed among all n_{t_e} and n_{r_e} antennas.

In terms of energy consumption, a significant amount of energy is spent by the RF circuitry while transmitting and receiving. We follow the same circuitry model introduced in [4], which represents the state of the art for current hardware for sensor technologies [7], so that each transmit antenna consumes $P_{\text{DAC}} + P_{\text{mix}} + P_{\text{fil}_{\text{tx}}}$, representing the power consumed along the signal path by the digital-to-analog converter, mixer, and transmit filters, respectively. In addition, the power consumed by the frequency synthesizer is denoted by P_{syn}, which is shared among all transmit antennas. Thus, the total RF circuitry consumption at the transmitter is

$$P_{\text{TX}}(n_{t_e}) = n_{t_e}\left(P_{\text{DAC}} + P_{\text{mix}} + P_{\text{fil}_{\text{tx}}}\right) + P_{\text{syn}}. \tag{5}$$

Similarly, each receive antenna consumes $P_{\text{LNA}} + P_{\text{mix}} + P_{\text{IFA}} + P_{\text{fil}_{\text{rx}}} + P_{\text{ADC}}$, representing the power consumed by the low noise amplifier, mixer, intermediate frequency amplifier, receive filters, and analog-to-digital converter, respectively. Since the frequency synthesizer is also shared among all receive antennas, as it is the case with the transmit antennas, the total consumption at the receiver is

$$P_{\text{RX}}(n_{r_e}) = n_{r_e}\left(P_{\text{LNA}} + P_{\text{mix}} + P_{\text{IFA}} + P_{\text{fil}_{\text{rx}}} + P_{\text{ADC}}\right) + P_{\text{syn}}. \tag{6}$$

Moreover, the power consumption of a practical power amplifier is actually higher than the required transmit power P, due to the amplifier efficiency. In typical class B power amplifiers, the power consumption is given by $(1+\alpha)P$, where $\alpha = \left(\frac{\xi}{\eta} - 1\right)$, $\xi = 3\left(\frac{\sqrt{M}-1}{\sqrt{M}+1}\right)$ is the peak-to-average ratio (PAR) for an M-QAM modulation and η is the amplifier drain efficiency [4].

Let us remark that we consider narrowband single-carrier transceivers, which are typically used in sensor nodes, so that the power consumed by baseband processing is very small when compared to the circuitry power consumption. If broadband multi-carrier transceivers were used, then the consumption of baseband processing should be considered [8].

III. Transmission Schemes

We consider three MIMO communication strategies: i) orthogonal ST codes; ii) TAS; and iii) SVD. Moreover, for comparison purposes, we also include the SISO transmission. We characterize the methods in terms of their outage probabilities, which was shown to predict well the frame error rate of good practical codes with relative short block lengths [9], [10].

A. SISO

We first assume a SISO communication scheme, so that $n_t = n_r = 1$ antenna. The mutual information between the two nodes is given by [3]

$$I = B\log_2(1+\gamma), \tag{7}$$

and an outage event occurs when $I < R$, where $R = \Delta \cdot B$ is the data rate in bits/s, and Δ is the spectral efficiency, given in bits/s/Hz. Then, the outage probability can be expressed as $\Pr\{I < R\}$, which in the case of Rayleigh fading is

$$\mathcal{O}_{\text{SISO}} = 1 - \exp\left(-\frac{N\beta}{\kappa P}\right), \tag{8}$$

where $\beta = 2^{\Delta} - 1$.

Then, the required transmit power can be obtained by establishing a target outage probability $\mathcal{O}^{\star}$, such that $\mathcal{O}_{\text{SISO}} \leq$

$\mathcal{O}^\star$. Therefore, the minimal transmit power is achieved by replacing $\mathcal{O}_{\text{SISO}}$ by $\mathcal{O}^\star$ in (8), which yields

$$P^\star_{\text{SISO}} = -\frac{N\beta}{\kappa \ln(1-\mathcal{O}^\star)}. \tag{9}$$

Finally, we define the energy efficiency in terms of total energy consumption per bit as

$$E_{\text{SISO}} = \frac{(1+\alpha)P^\star_{\text{SISO}} + P_{\text{TX}}(1) + P_{\text{RX}}(1)}{R}. \tag{10}$$

B. Space-Time Codes

Now consider a transmitter with n_t antennas employing orthogonal ST coding, and that the receiver applies either MRC among all its n_r antennas, or applies SSC selecting a single antenna to receive.

1) MRC Applied at the Receiver: The outage probability of orthogonal ST coding with MRC being applied at the receiver, under Rayleigh fading, is already known and can be obtained from [11] as

$$\mathcal{O}_{\text{ST+MRC}} = 1 - \exp\left(-\frac{n_t N\beta}{\kappa P}\right) \sum_{m=0}^{n_t n_r - 1} \frac{1}{m!}\left(\frac{n_t N\beta}{\kappa P}\right)^m. \tag{11}$$

Similarly to SISO, the minimal transmit power $P^\star_{\text{ST+MRC}}$ can be found from (11) by establishing a target outage probability $\mathcal{O}^\star$, such that $\mathcal{O}_{\text{ST+MRC}} \leq \mathcal{O}^\star$. Nevertheless, the solution must be particularized for every number of transmit and receive antennas n_t and n_r, and, since the procedure is straightforward, we skip the formulation for brevity. Then, the total consumed energy per bit of ST is

$$E_{\text{ST+MRC}} = \frac{(1+\alpha)P^\star_{\text{ST+MRC}} + P_{\text{TX}}(n_t) + P_{\text{RX}}(n_r)}{R}. \tag{12}$$

2) SSC Applied at the Receiver: With SSC, rather than continually searching for the diversity path with the best quality, *e.g.*, as with selection combining (SC), the receiver selects one antenna ($n_{r_e} = 1$) until its received SNR drops below a predefined threshold γ_T. When this happens, the receiver switches to (and stays with) another antenna.

The advantage of SSC over SC is that the circuitry consumption at the receiver is $P_{\text{RX}}(1)$ in SSC, therefore it is not a function of n_r, while it increases to $P_{\text{RX}}(n_r)$ in SC. Therefore, SSC allows the receiver to consume less power than SC. Moreover, it was also shown in [3] that when γ_T is optimized, the performance of SSC is the same as SC. The outage probability of ST+SSC can be found from [5] as

$$\mathcal{O}_{\text{ST+SSC}} = \left[1 - \exp\left(-\frac{n_t N\beta}{\kappa P}\right) \sum_{m=0}^{n_t - 1} \frac{1}{m!}\left(\frac{n_t N\beta}{\kappa P}\right)^m\right]^{n_r}, \tag{13}$$

and the minimal transmit power $P^\star_{\text{ST+SSC}}$ can be found w.r.t. a target outage probability $\mathcal{O}^\star$. Then, the total consumed energy per bit is

$$E_{\text{ST+SSC}} = \frac{(1+\alpha)P^\star_{\text{ST+SSC}} + P_{\text{TX}}(n_t) + P_{\text{RX}}(1)}{R}. \tag{14}$$

C. Transmit Antenna Selection

Since in the MIMO schemes in general the energy consumption grows with n_t, TAS may be of particular interest as it reduces the number of required RF chains and therefore decreases the fixed energy consumption. Given our focus on reducing the energy consumption, we assume that a single antenna $n_{t_e} = 1$ is active among all n_t available antennas at the transmitter.

1) MRC Applied at the Receiver: With TAS, the receiver must inform the transmitter which antenna to use based on the instantaneous SNR. At the receiver, the signals received by all n_r antennas are combined, as for instance using MRC. Assuming an error-free feedback, the outage probability in this case can be found from [5] as

$$\mathcal{O}_{\text{TAS+MRC}} = \left[1 - \exp\left(-\frac{N\beta}{\kappa P}\right) \sum_{m=0}^{n_r - 1} \frac{1}{m!}\left(\frac{N\beta}{\kappa P}\right)^m\right]^{n_t}, \tag{15}$$

and the total consumed energy per bit becomes

$$E_{\text{TAS+MRC}} = \frac{(1+\alpha)P^\star_{\text{TAS+MRC}} + P_{\text{TX}}(1) + P_{\text{RX}}(n_r)}{R}. \tag{16}$$

2) SSC Applied at the Receiver: When the transmitter applies TAS and the receiver uses SSC, we can derive the outage probability based on the mutual information between the nodes, which in this case is

$$I = B\log_2\left(1 + \overline{\gamma}\max_{i,j}\left\{|h_{ij}|^2\right\}\right), \tag{17}$$

recalling that $h_{ij} \in \mathbf{H}$ represents the channel gain between the selected j-th transmit antenna and i-th receive antenna. Moreover, assuming i.i.d. h_{ij}'s with zero mean and unity variance, we can write the outage probability as

$$\begin{aligned} \mathcal{O}_{\text{TAS+SSC}} &= \Pr\left\{\max_{i,j}\left\{|h_{ij}|^2\right\} < \frac{N\beta}{\kappa P}\right\} \\ &= \prod_{i=1}^{n_r}\prod_{j=1}^{n_t} \Pr\left\{|h_{ij}|^2 < \frac{N\beta}{\kappa P}\right\} \\ &= \left[1 - \exp\left(-\frac{N\beta}{\kappa P}\right)\right]^{n_t n_r}. \end{aligned} \tag{18}$$

Finally, since only one antenna is active in each node, the consumed energy per bit is

$$E_{\text{TAS+SSC}} = \frac{(1+\alpha)P^\star_{\text{TAS+SSC}} + P_{\text{TX}}(1) + P_{\text{RX}}(1)}{R}. \tag{19}$$

D. Beamforming (SVD)

Now we assume beamforming via a SVD technique, which represents the best performance in terms of outage probability and the minimal required transmit power. As in the case of TAS, a feedback channel is also required for SVD. Assuming that all n_t and n_r antennas are employed, the mutual information in this case can be expressed as [12]

$$I = B\sum_{l=1}^{k} \log_2\left(1 + \overline{\gamma}\,\omega_l^2\right), \tag{20}$$

where ω_l^2's are the eigenvalues of the matrix $\mathbf{HH}^*$. Then, applying the Jensen's inequality [12] in (20), we can bound the mutual information by

$$I \leq kB\log_2\left(1+\overline{\gamma}\left(\frac{1}{k}\sum_{l=1}^{k}\omega_l^2\right)\right). \quad (21)$$

It is worth noting that k multiplies the right term of the inequality since $E[\log_2(1+x)] \leq \log_2(1+E[x])$ according to the Jensen's inequality, where $E[.]$ is the mathematical expectation. Moreover, since $\sum_{l=1}^{k}\omega_l^2 = \sum_{i,j}|h_{ij}|^2$, the outage probability becomes

$$\begin{aligned}\mathcal{O}_{\text{SVD}} &\geq \Pr\left\{\sum_{i=1}^{n_r}\sum_{j=1}^{n_t}|h_{ij}|^2 < \frac{n_t N\beta_k}{\kappa P}\right\} \\ &\geq 1-\exp\left(-\frac{n_t N\beta_k}{\kappa P}\right)\sum_{m=0}^{n_t n_r - 1}\frac{1}{m!}\left(\frac{n_t N\beta_k}{\kappa P}\right)^m,\end{aligned} \quad (22)$$

where $\beta_k = k(2^{\frac{\Delta}{k}}-1)$, and (22) also assumes i.i.d. h_{ij}'s, $\forall i,j$[1].

Finally, as all antennas are active, the energy consumption of the SVD scheme is

$$E_{\text{SVD}} = \frac{(1+\alpha)P_{\text{SVD}}^{\star} + P_{\text{TX}}(n_t) + P_{\text{RX}}(n_r)}{R}. \quad (23)$$

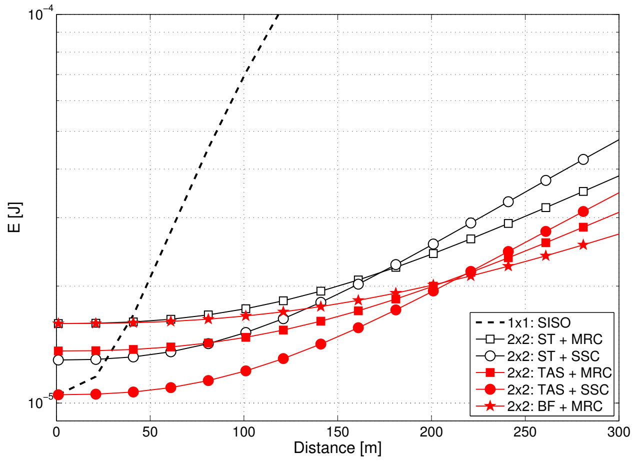

Fig. 2. Total energy consumption per bit for a target outage probability of $\mathcal{O}^\star = 10^{-2}$ at $\Delta = 2$ b/s/Hz.

IV. Numerical Results

Following the definitions in [4], we assume a link margin of $M_l = 40$ dB, the noise figure is $N_f = 10$ dB, and the total antenna gain is $G = 5$ dBi. The carrier frequency is considered to be $f_c = 2.5$ GHz (which yields a wavelength of $\lambda = 12$ cm), and $N_0 = -174$ dBm/Hz. Moreover, we assume a bandwidth of $B = 10$ kHz and that the path loss exponent is $\nu = 2.5$. The power consumption of the circuits is summarized in Table I, also following [4]. Since we consider sensor nodes, we focus on the practical cases of one or two transmit/receive antennas.

[1]Note that, despite (22) being a bound, due to the Jensen's inequality in (21), our results are still valid since our goal is to show that TAS may be more energy efficient than SVD, even if the bound given by (22) is actually optimistic.

TABLE I

Circuitry Power Consumption

$\eta = 0.35$	$P_{\text{DAC}} = 15.4$ mW
$P_{\text{syn}} = 50$ mW	$P_{\text{LNA}} = 20$ mW
$P_{\text{mix}} = 30.0$ mW	$P_{\text{IFA}} = 3$ mW
$P_{\text{fil}_{\text{tx}}} = P_{\text{fil}_{\text{rx}}} = 2.5$ mW	$P_{\text{ADC}} = 6.7$ mW

Figure 2 shows the total energy consumption per bit of the considered MIMO schemes as a function of the distance between the nodes. The target outage probability is $\mathcal{O}^\star = 10^{-2}$ and the spectral efficiency is $\Delta = 2$ b/s/Hz. If we only consider the schemes without feedback (SISO, ST+MRC and ST+SSC), we can notice three distinct regions of interest. In long range communication, when $d > 170$ m, ST with MRC achieves the best performance in terms of energy consumption. When the distance between the nodes decreases, the use of SSC shows important energy savings. In this example, ST with SSC is the best strategy when $27 < d < 170$ m. Also very interestingly, when $d < 27$ m, SISO becomes the best strategy. If a feedback channel is available, the combination of TAS and SSC presents the best performance up to $d = 192$ m. For $d > 192$ m, SVD performs better due to its lower transmit power consumption.

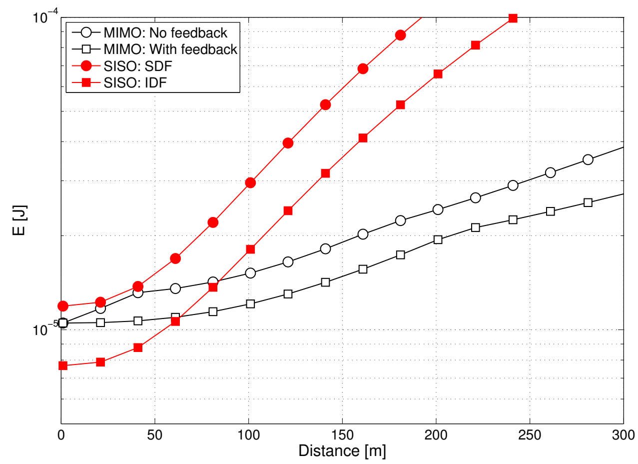

Fig. 3. Minimal energy consumed by the MIMO schemes and by the SISO cooperative DF schemes.

Figure 3 compares the minimal energy consumption that can be achieved with the MIMO schemes in the two different scenarios: with feedback, and without feedback from the receiver. In addition, the performance of a SISO cooperative Decode-and-Forward (DF) scheme is also included. We consider that cooperation is achieved through a single-relay that lies at the intermediate position between the source and the destination. In Selective DF (SDF), the relay forwards the information from the source to the destination whenever this information could be correctly decoded. Incremental DF (IDF), on the other hand, assumes a feedback from the destination such that a retransmission only takes place if necessary. Moreover, for a fair comparison, we assume that the nodes using DF transmit with twice the spectral efficiency as in the non-cooperative schemes, since cooperation requires two time slots to deliver each frame. A more detailed description of the energy efficiency of DF protocols is given in [13]. From the figure, it is interesting to notice that, for short range communications, cooperative SISO IDF outperforms the MIMO schemes. In this particular scenario, IDF presents the best performance when $d < 64$ m.

Finally, we compare the energy consumption of the schemes that require a feedback channel, as a function of the spectral efficiency. In Figure 4, where $d = 50$ m, we can notice that IDF presents the best performance only for $\Delta < 2$ b/s/Hz. MIMO employing TAS and SSC performs better from $2 < \Delta < 5$ b/s/Hz, and SVD performs better for higher data rates. If we increase the distance between the nodes, with $d = 150$ m in Figure 5, the combination of TAS and SSC becomes the best option for low Δ, and SVD performs better for higher data rates, since the transmit power becomes more relevant at long transmission distances.

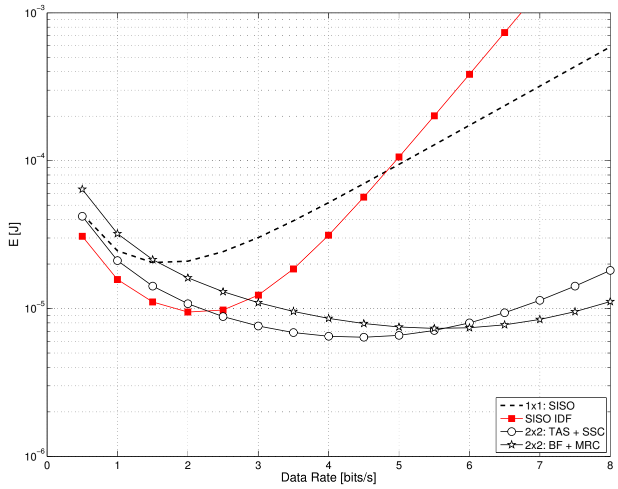

Fig. 4. Total energy consumption per bit for $\mathcal{O}^\star = 10^{-2}$ when $d = 50$ m.

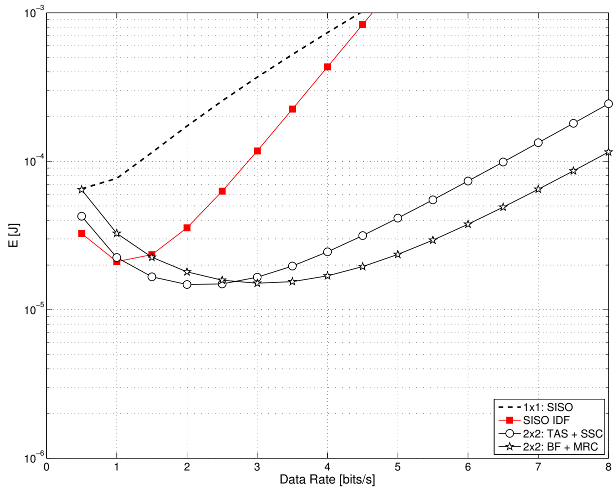

Fig. 5. Total energy consumption per bit for $\mathcal{O}^\star = 10^{-2}$ when $d = 150$ m.

V. Conclusion

We investigate the energy efficiency of different MIMO techniques in a general communication link between two nodes in a WSN, in which schemes such as ST coding, SVD, and TAS are compared. Our results show that TAS is a viable option to perform energy efficient transmission. The combination of TAS at the transmitter and SSC at the receiver, even though being a sub-optimal strategy in terms of outage probability, can be a very energy efficient solution due to the reduction of required RF chains and therefore of the fixed energy consumption. In addition, we show that cooperative SISO outperforms non-cooperative MIMO schemes only for very short-range and relatively low data rates. As a next step we plan to investigate the energy efficiency of cooperative MIMO techniques using TAS and SSC.

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