Energy Analysis of MIMO Techniques in Wireless Sensor Networks

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***Abstract*— Energy efficiency of MIMO techniques in wireless sensor networks is analyzed. Assuming a cooperative sensor network, the energy consumption of MIMO-based wireless sensor networks is compared with conventional SISO sensor networks. The dependence of energy efficiency on coherence time of the fading process and communications distance is considered. Our results show the applicability of MIMO techniques in such sensor networks with judicious system design.**

I. Introduction

Energy-constrained wireless sensor networks have gained considerable research attention in recent years. In such sensor networks, battery-operated sensors are expected to work for months, or even years, without replacement or renewing its energy rendering energy optimization a critical issue in system design.

In traditional wireless systems the main power consumption is due to the actual transmissions power. However, this may not be the case in a wireless sensor network. In fact, in some cases it is the circuit energy needed for receiver and transmitter processing that is dominant. Thus, usual energy optimization techniques that minimize the required transmission energy may not be effective in wireless sensor networks.

Multiple-input-multiple-output (MIMO), or multiple antenna communication is one of the techniques that has gain considerable importance in wireless systems during recent years. These include various space-time coding schemes [1]–[3], layered space-time architectures [4] and of course well-developed smart antenna techniques [5]. 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. This fact has so far precluded the application of MIMO techniques to wireless sensor networks consisting of battery-operated sensor nodes.

A closer look at energy comparisons of MIMO and SISO techniques in wireless sensor networks was taken recently in [6]. There the applicability of cooperative MIMO techniques to wireless sensor networks were considered based on total energy consumption. The energy evaluations in [6] showed that in some cases cooperative MIMO-based sensor networks may in fact result in better energy optimization.

In this paper we refine the results presented in [6] taking into account the training overhead required in MIMO systems. Although these were ignored in [6], a rigorous energy optimization needs to take into account the energy spent on training since this is crucial for the proper operation of MIMO-based techniques. In a fading channel, depending on the coherence time, the system will need to send periodic training symbols. The number of required training symbols may at least be equal to the number of transmitter antennas [7] thereby resulting in large training overheads for MIMO systems. We provide analytical methods for computing the energy in MIMO-based sensor networks taking into account these overheads.

This presentation is organized as follows: In Section II we present the assumed MIMO system model for sensor networks and the analysis of energy consumption. We will closely follow the model developed in [6], but introduce overhead terms associated with MIMO training requirements and also provide exact analytical expressions. In Section III we investigate the energy efficiency of fixed-rate MIMO systems compared to that of SISO systems. In Section IV we consider variable-rate M-ary quadrature amplitude modulation (M-QAM) MIMO systems for wireless sensor networks. We evaluate the energy efficiency of such systems with optimized transmission rates. Next, in Section V we evaluate the energy efficiency of virtual MIMO-based cooperative wireless sensor networks. Finally, we conclude in Section VI giving some final remarks.

II. Signal Model and the System Description

We consider a narrow-band, flat fading, communication link connecting two wireless sensor nodes, which can in general be MIMO, multiple-input-single-output (MISO), single-input-multiple-output (SIMO) or SISO. As assumed in [6], we will omit the energy consumption in baseband signal processing blocks and will assume uncoded communication in order to keep the analysis simple. The transmitter and receiver are equipped with N_T and N_R antennas, respectively.

As discussed in [6], [8]–[10], the total power consumption along the signal path can be divided into two main components: the power consumption of all the power amplifiers P_{PA} and the power consumption of all other circuit blocks P_C. Assuming that the power consumed by the power amplifiers is linearly dependent on the transmit power P_{out}, the total power consumption of the power amplifiers can be approximated as [6], [8]

$$P_{PA} = (1+\alpha)\, P_{out} \quad (1)$$

where $\alpha = \xi/\eta - 1$ with η being the drain efficiency of the RF power amplifier and ξ being the peak-to-average ratio (PAR) that depends on the modulation scheme and the constellation size. Throughout this paper we assume M-QAM systems, so that [9]

$$\xi = 3\frac{M-2\sqrt{M}+1}{M-1}. \quad (2)$$

The transmit power P_{out} in (1) can be calculated according to the link budget relationship [11]

$$P_{out} = \frac{(4\pi)^2\, d^{\kappa} M_l N_f}{G_t G_r \lambda^2}\bar{E}_b R_b \quad (3)$$

where d is the transmission distance, κ is the signal attenuation parameter, 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_f is the receiver noise figure, $\bar{E}_b$ is the average energy per bit required for a given bit-error-rate (BER) specification and R_b is the system bit rate. Note that the receiver noise figure N_f is given by $N_f = \frac{N_r}{N_o}$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_o is the single-sided thermal noise PSD at the room temperature.

In the model used in [6], it is assumed that the frequency synthesizer (LO) is shared among all the antenna paths even in a MIMO system. Using the same assumption, we may estimate the total power consumption in all the circuit blocks as

$$\begin{aligned} P_c \approx{} & N_T\left(P_{DAC}+P_{mix}+P_{filt}\right)+2P_{synth} \\ & +N_R\left(P_{LNA}+P_{mix}+P_{IFA}+P_{filr}+P_{ADC}\right) \end{aligned} \quad (4)$$

where P_{DAC}, P_{mix}, P_{filt}, P_{synth}, P_{LNA}, P_{IFA}, P_{filr} and P_{ADC} are the power consumption values for the D/A converter (DAC), the mixer, the active filters at the transmitter side, the frequency synthesizer, the low noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the receiver side and the A/D converter (ADC), respectively. We estimate the power consumption values P_{DAC}, P_{ADC} and P_{IFA} based on the models developed in [10].

Total energy per bit for a fixed rate system can then be estimated using (1) and (4):

$$E_{bt} = \frac{P_{PA}+P_c}{R_b}. \quad (5)$$

The received discrete-time signal in a MIMO system can be written as

$$\mathbf{y}(i) = \mathbf{H}(i)\mathbf{x}(i)+\mathbf{n}(i)\ , \quad (6)$$

where $\mathbf{y}(i)$, $\mathbf{x}(i)$ and $\mathbf{n}(i)$ are the complex N_R-vector of received signals on the N_R receive antennas, the complex N_T-vector of transmitted signals on the N_T transmit antennas, and the complex N_R-vector of additive receiver noise, respectively, at symbol time i. The components of $\mathbf{n}(i)$ are independent, zero-mean, circularly symmetric complex Gaussian random variables with independent real and imaginary parts having equal variance $N_o/2$. The noise is assumed to be independent with respect to the time index.

The matrix $\mathbf{H}(i)$ in the model (6) is the $N_R \times N_T$ matrix of complex fading coefficients. The (n_R, n_T)-th element of the matrix $\mathbf{H}(i)$, denoted by $[\mathbf{H}(i)]_{n_R,n_T}$, represents the fading coefficient value at time i between the n_R-th receiver antenna and the n_T-th transmitter antenna which represents the further random attenuation of the signal on top of the square-law path loss implied in (1). We will assume a flat Rayleigh fading model in which each element $[\mathbf{H}(i)]_{n_R,n_T}$ is a zero-mean circularly symmetric complex Gaussian random variable with variance $\frac{1}{2}$ per dimension.

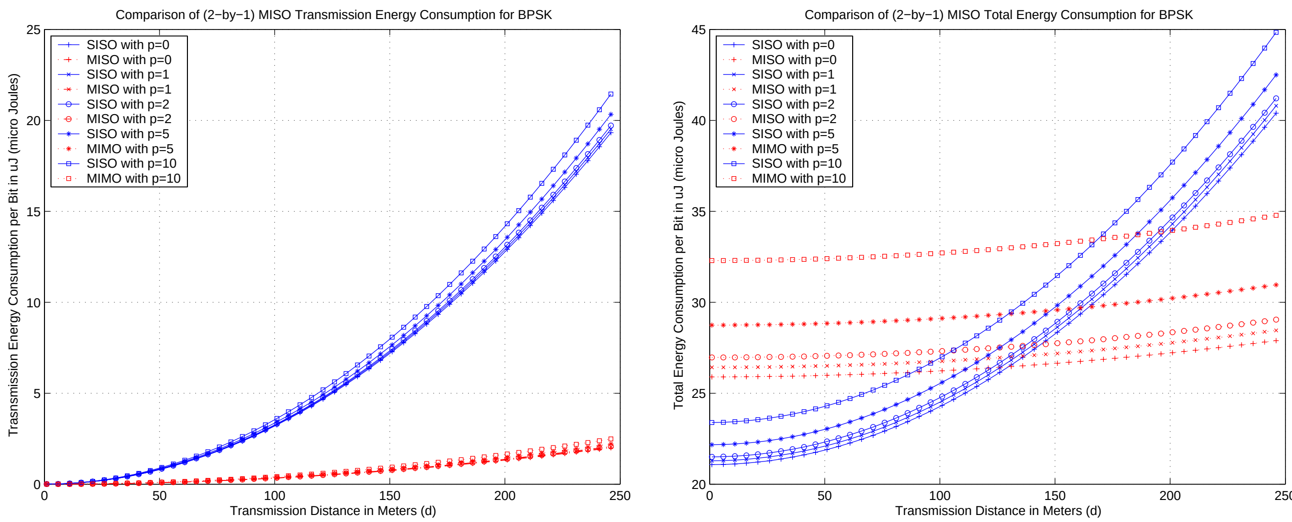
The MIMO technique that we consider in this paper is the simple Alamouti scheme for a 2×1 MISO system or space-time block codes that provide its generalization to more antennas. According to the Alamouti scheme, if two consecutive input symbols to the space-time block encoder are denoted by $b(j)$ and $b(j+1)$ then $\mathbf{x}(i) = [b(j),\ b(j+1)]^T$ and $\mathbf{x}(i+1) = [-b^*(j+1),\ b^*(j)]^T$ where * denotes complex conjugation.

III. Energy Efficiency of Fixed Rate MIMO Systems

A. 2×1 BPSK MIMO System with Alamouti Scheme

The instantaneous received signal-to-noise ratio ($SNR_i^{(2\times 1)}$) of a 2×1 BPSK MIMO system with Alamouti scheme can be written as $SNR_i^{(2\times 1)} = \|\mathbf{H}(i)\|_F^2 \frac{\bar{E}_b}{2N_o}$ where $\|\mathbf{H}(i)\|_F$ is the Frobenius norm of the matrix $\mathbf{H}(i)$. Since $\|\mathbf{H}(i)\|_F^2$ is a random variable equal to the sum of the squares of $2N_T$ independent $\mathcal{N}\left(0,\frac{1}{2}\right)$ Gaussian random variables, the average BER of a MISO system based on the Alamouti scheme is given by

$$\begin{aligned} \bar{P}_b ={} & \frac{1}{2^{N_T}}\left(1-\frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^{N_T} \times \\ & \sum_{k=0}^{N_T-1}\frac{1}{2^k}\binom{N_T-1+k}{k}\left(1+\frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^{k}. \end{aligned} \quad (7)$$



(a) (b)

Fig. 1. Comparison of (2-by-1) MISO Vs. SISO Energy Consumption for BPSK. (a) Transmission Energy Consumption. (b) Total Energy Consumption.

In order to obtain the required average energy per bit $\bar{E}_b$ for a given BER requirement we numerically invert (7). For the 2×1 Alamouti scheme (7) simplifies to

$$\bar{P}_b = \frac{1}{4}\left(1 - \frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^2 \left(2 + \frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right). \quad (8)$$

Note that, in [6] simulation was used to estimate $\bar{E}_b$ as opposed to the exact analytical method we propose above.

In [6] comparison of MIMO and SISO systems was performed assuming that the receiver has perfect channel state information (CSI), which is critical for the proper operation of the Alamouti scheme, but ignoring the training overhead required for the channel estimation. However, this distorts the comparison results since MIMO system could require more training symbols compared to the SISO system thus resulting in extra energy consumption.

The results in [7] suggest that in general we need the number of training symbols greater than or equal to the number of transmit antennas if both training and data symbols were to use the same transmit energy. However, the required number of training bits is a function of the operating SNR and thus could be much higher than this minimum required value. In order to incorporate this extra energy term, suppose that the block size is equal to F symbols and in each block we include pN_T training symbols where we assume that p symbols are used to train each transmitter and receiver antenna pair. The effective bit rate of the system is then given by

$$R_b^{eff} = \frac{F - pN_T}{F} R_b. \quad (9)$$

Replacing R_b in (5) with R_b^{eff} we get the modified energy consumption values for the 2×1 MISO system.

If the fading coherence time is T_c, then the maximum block size can be about $\lfloor T_c R_s \rfloor$ symbols where R_s is the symbol rate. We may obtain a best case energy consumption value by setting $F = \lfloor T_c R_s \rfloor$. The fading coherence time can be estimated via the relationship $T_c = \frac{3}{4 f_m \sqrt{\pi}}$ where the maximum Doppler shift f_m is given by $f_m = \frac{v}{\lambda}$ with v being the velocity [12].

Reference BPSK SISO System with Alamouti Scheme: The instantaneous received SNR in a reference single antenna (SISO), BPSK communications system is given by $SNR_i^{SISO} = |H(i)|^2 \frac{\bar{E}_b}{N_o}$. Thus, the average BER of a SISO system in Rayleigh fading is $\bar{P}_b = \frac{1}{2}\left(1 - \frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/N_o}}}\right)$. By inverting this we can obtain the average energy per bit $\bar{E}_b$ for a given BER requirement

$$\bar{E}_b = \frac{N_o}{\frac{1}{\left(1-2\bar{P}_b\right)^2} - 1}. \quad (10)$$

The effective bit rate for a SISO system can be obtained from (9) by setting $N_T = 1$.

Figure 1 shows the actual energy consumption values for a 2×1 MISO system and a SISO system for different lengths of training symbols. Note that in all simulations we have assumed $B = 10$ kHz, $f_c = 2.5$ GHz, $P_{mix} = 30.3$ mW, $P_{filt} = 2.5$ mW, $P_{filr} = 2.5$ mW, $P_{LNA} = 20$ mW, $P_{synth} = 50$ mW, $M_l = 40$ dB, $N_f = 10$ dB, $G_t G_r = 5$ dBi and $\eta = 0.35$. Also, in all simulations we have set $\kappa = 2$ unless noted otherwise. Figure 1a compares the two systems based only on the transmission energy consumption. In terms of this compariosn, the MISO system always outperforms the corresponding SISO system. However, in an energy-constrained wireless sensor network it is the total energy consumption per bit E_{bt} that should be the performance criterion. In Fig. 1b we show this total energy consumption comparison for different number of training symbols per block. From Fig. 1b we see that up to a certain transmission distance the SISO system is in fact preferable over the MISO system based on Alamouti scheme in terms of total energy consumption per bit. In the (unrealistic) case that we assume we do not need any training symbols per block ($p = 0$), the MISO system will be better for transmission distances above $d = 130$ meters. However, as we include more and more training symbols we see that this critical distance at which the MISO system becomes preferable also increases. For example, if $p = 10$ training symbols were used per block, then according to Fig. 1b, d should be at least about 169 meters in order to justify the use of MISO with Alamouti scheme in a wireless sensor network.

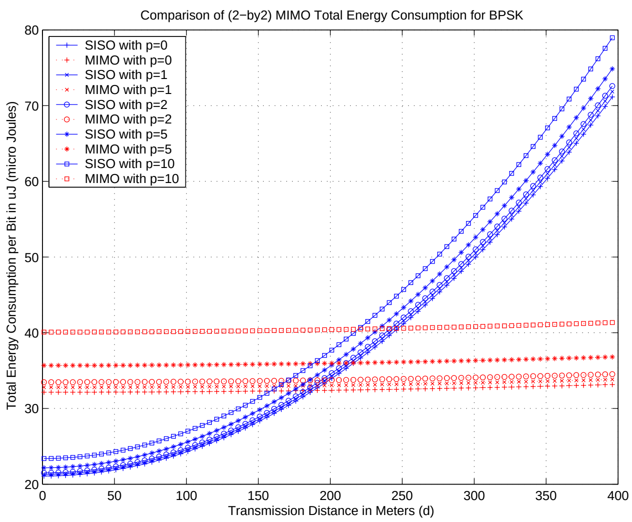


Fig. 2. Comparison of (2-by-2) MIMO Vs. SISO Total Energy Consumption for BPSK.

B. 2×2 BPSK MIMO System with Alamouti Scheme

The instantaneous received signal-to-noise ratio of a 2×2 BPSK MIMO system with Alamouti scheme is given by $SNR_i^{(2\times2)} = \|\mathbf{H}(i)\|_F^2 \frac{\bar{E}_b}{2N_o}$ where $Z = \|\mathbf{H}(i)\|_F^2$ has the pdf $p_Z(z) = \frac{z^{N_T N_R - 1}}{(N_T N_R - 1)!} e^{-z}$. As a result, the average BER is again given by (7) with N_T replaced by $N_T N_R$, and we may obtain the required average energy per bit $\bar{E}_b$ for a given BER requirement by inverting the resulting expression. The effective bit rate in the presence of training is still given by (9).

Figure 2 shows the total energy consumption values for a 2×2 MIMO and a SISO system employing BPSK. Comparing Fig. 2 with Fig. 1b we may notice that the critical distance at which the MIMO system outperforms the SISO system has increased. As noted in [6], the reason for this is that although the 2×2 MIMO system offers additional receiver diversity

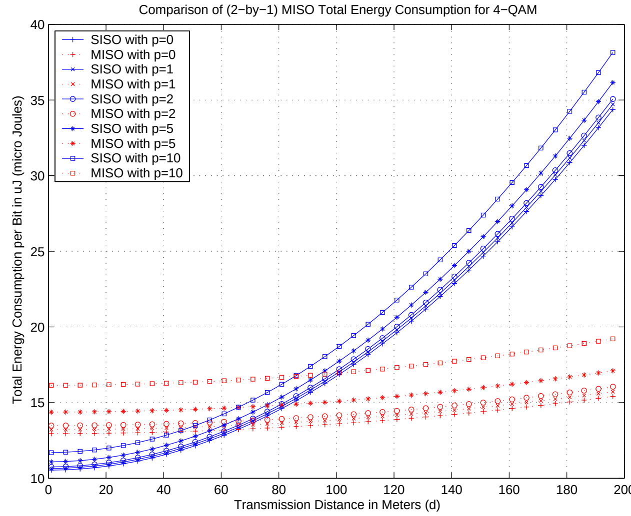


Fig. 3. Comparison of (2-by-1) MISO Vs. SISO Total Energy Consumption for 4-QAM.

over the MISO system, it also consumes more circuit energy according to (4). For example, the critical distances where the MIMO system is preferable over the SISO system has increased from 130 meters to 188 meters for $p = 0$ and from 169 meters to 220 meters for $p = 10$.

C. 2×1 QPSK MISO System with Alamouti Scheme

The distance at which the MIMO techniques outperform the corresponding SISO systems in a sensor network can be decreased by employing 4-QAM instead of BPSK. For a given channel matrix $\mathbf{H}$ the probability of bit error of a 4-QAM is given by $\mathbb{E}\left\{ Q\left(\sqrt{\|\mathbf{H}(i)\|_F^2 \frac{\bar{E}_b}{N_o}} \right) \right\}$ [11]. Hence, the average BER is again given by (8) which we can invert to obtain the required average energy per bit $\bar{E}_b$. However, for a fixed symbol rate $R_s = B$, the bit rate R_b and R_b^{eff} are changed since $R_b = bR_s$ where $b = \log_2(M)$ with $M = 4$. We may use the expressions derived in Section III-A earlier in order to compute the total energy consumption values after these modifications.

Figure 3 compares the total energy consumption values for a 2×1 MISO and a SISO system employing QPSK. We may observe from Fig. 3 that for $p = 0$ training symbols, the distance at which the MISO system has better performance than a SISO system has reduced to 66 meters. However, as before the extra training symbols required for the channel estimation in the MISO system will increase this critical distance beyond 66 meters. For example, with $p = 10$ training symbols the minimum required transmission distance for the MISO system to outperform the SISO system is about 86 meters. However,this is still about half that of the corresponding BPSK system.

IV. Energy Efficiency of Variable Rate MIMO Systems

Results observed in Section III-C suggests that by optimizing the rate (constellation size) of the communications system over the transmissions distance we may be able to reduce the minimum transmission distance at which the MIMO outperforms SISO even further. Assuming an M-QAM system, this optimization results in the determination of the constellation size M for various values of d. In a cooperative sensor network such rate-optimized transmission is possible when each sensor *a priori* has knowledge on other sensor locations.

The bit error rate of an M-ary QAM MIMO system ($M = 2^b$) with a square constellation (i.e. b is even) is given by, for $b \geq 2$,

$$\bar{P}_b = \frac{4}{b}\left(1-\frac{1}{2^{b/2}}\right)\frac{1}{2^{N_T N_R}}\left(1-\frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^{N_T N_R} \sum_{k=0}^{N_T N_R-1}\frac{1}{2^k}\binom{N_T N_R-1+k}{k}\left(1+\frac{1}{\sqrt{1+\frac{1}{\bar{E}_b/2N_o}}}\right)^k \quad (11)$$

When $b \geq 2$ is odd, we will use (11) after dropping the term $\left(1-\frac{1}{2^{b/2}}\right)$ as an upper-bound for the BER (for $b=1$, the M-ary QAM reduces to the earlier BPSK system). By inverting (11) we obtain the required $\bar{E}_b$ for a specified BER value $\bar{P}_b$. Then, from (1) and (3) the total energy consumption per bit in the power amplifiers can be estimated as

$$E_{PA} = (1+\alpha)\frac{(4\pi)^2 d^\kappa M_l N_f}{G_t G_r \lambda^2}\bar{E}_b \frac{R_b}{R_b^{eff}} \quad (12)$$

where R_b^{eff} is given by (9). Note that, in (12) α depends on the constellation size M via (2). Since $R_b = bR_s$, for a given bandwidth B and a symbol rate $R_s = B$, the bit rate R_b also depends on the constellation size M (the ratio $\frac{R_b}{R_b^{eff}}$, however, is independent of M).

Suppose that we have a total of L data bits to transmit. Then, the total number of data symbols to be transmitted is L/b. Since in a block of F symbols pN_T number of symbols are allocated for channel estimation, the number of blocks to be sent are given by $\frac{L}{b(F-pN_T)}$. The total on-time T_{on} of the system in order to transmit this $\frac{L}{b(F-pN_T)}$ number of blocks (each with F symbols) at a symbol rate of R_s is then given by $T_{on} = \frac{L}{R_b^{eff}}$ where we have used (9). Then, the total power consumption per data bit in all the circuit blocks is given by $\frac{P_c T_{on}}{L} = \frac{P_c}{R_b^{eff}}$ with P_c given by (4). Hence, the total energy consumption per bit for an M-ary QAM MIMO system with $M = 2^b$ is

$$E_{ta} = \frac{1}{\mu}\left[\frac{3}{\eta}\frac{(4\pi)^2 d^\kappa M_l N_f}{G_t G_r \lambda^2}\frac{\left(M-2\sqrt{M}+1\right)}{M-1}\bar{E}_b + \frac{P_c}{bR_s}\right]. \quad (13)$$

where we have defined $\mu = \frac{R_b^{eff}}{R_b} = \frac{F-pN_T}{F}$. Note that μ specifies the energy penalty incurred due to extra symbols needed for channel estimation. In a variable rate system we employ the constellation size M that minimizes E_{ta} in (13) for each transmission distance d.

A. 2×1 MIMO System with Alamouti Scheme

If we were to plot E_{ta} as a function of the constellation size b for various transmission distances d then we see that there is an optimal constellation size for each transmission distance for which the total energy per bit is minimized. Table-I shows the optimal constellation size b for each transmission distance d for both a SISO and a MISO system with 2×1 Alamouti scheme assuming $p = 0$.

TABLE I
Optimized M-QAM Constellation Sizes for 2×1 MIMO and SISO.

d (m)	1	5	10	20	40	80	100	150	200	250
b_{MISO}	15	11	9	8	6	5	4	3	3	3
b_{SISO}	13	9	7	5	4	2	2	2	1	1

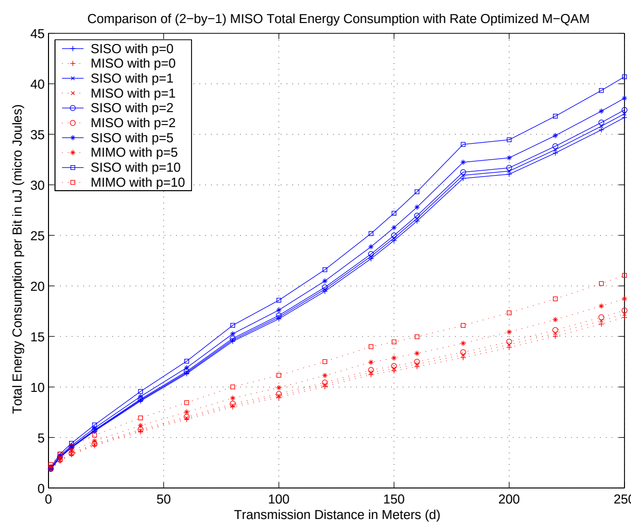


Fig. 4. Comparison of (2-by-1) MISO Vs. SISO Total Energy Consumption for Optimized M-QAM.

The total energy comparison of a 2×1 MISO system employing optimized variable rate M-QAM is given in Fig. 4. From Fig. 4 we observe that the use of optimized variable rate M-QAM considerably improves the performance of a MISO system compared to that of a SISO system. In fact, the critical distance at which the MISO system starts to outperform the corresponding SISO system in this case reduces to 1.1 meters and 4.8 meters for $p = 0$ and $p = 10$ training symbols per block, respectively.

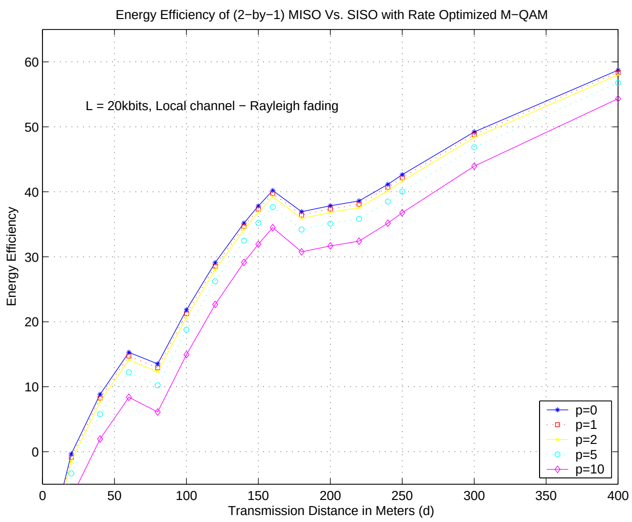


Fig. 5. Energy Efficiency of (2-by-1) MISO Vs. SISO with Rate Optimized M-QAM.

V. Energy Efficiency of Virtual MIMO-based Cooperative Wireless Sensor Networks

In Fig. 5 we have shown the energy efficiency of a cooperative sensor network of the form proposed in [10] employing a 2×1 virtual MISO system compared to that of a traditional SISO communications based wireless sensor network. In this type of virtual MIMO-based networks closely distributed sensors at transmitter and receiver side act as antenna elements of virtual multiple antenna arrays. The STBC is implemented distributively via local transmissions among these close sensors before the long-haul transmission. We refer the reader to [10] for details of the cooperative MIMO algorithm for a distributed wireless sensor network.

Figure 5 shows the effect of training overhead on the energy efficiency of 2×1 MISO in a cooperative wireless sensor network. From Fig. 5 we see that in order to justify the use of virtual MIMO communications in a wireless sensor network the long-haul transmission distance should be at least 21 meters with $p = 0$. However, in a more realistic scenario with $p = 10$, this distance is about 36 meters. This shows clearly that even when we consider the end-to-end sensor network, the effect of training overhead may not be negligible in a virtual MIMO-based system.

Figure 5 also shows the enormous energy savings a virtual MIMO-based system can offer in a well-designed wireless sensor network. For example, with $p = 0$ and $p = 10$, 2×1 MISO system offers 50% of energy saving compared to SISO-based system for $d = 309$ meters and 359 meters. Note that, in these example we have been conservative with $\kappa = 2$. In a typical wireless channel $2 < \kappa < 4.5$, and increase in κ will result in greater energy efficiencies with virtual MIMO-based sensor communications at shorter long-haul transmission distances.

VI. Conclusions

We have investigated the energy efficiency of virtual MIMO-based techniques in cooperative wireless sensor networks proposed in [6]. We have provided analytical methods to obtain these energy consumption values for both MIMO and SISO based sensor networks. Unlike [6], we have also taken into account the effect of increased training overhead required in MIMO systems in order to estimate the extra channel coefficient values. Our results show that even with these extra energy overhead requirements, virtual MIMO-based techniques can offer substantial energy savings in wireless sensor networks provided the system is designed judiciously. These include careful consideration of transmission distance requirements and rate optimization.

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References

[1] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journ. Select. Areas. Commun.*, vol. 16, no. 8, pp. 1451 – 1458, October 1998.
[2] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Trans. Inform. Theory*, vol. 45, no. 5, pp. 1456 – 1467, July 1999.
[3] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high rate wireless communication: Performance criterion and code construction,” *IEEE Trans. Inform. Theory*, vol. 44, no. 2, pp. 744 – 765, March 1998.
[4] G. J. Foschini, “Layered space-time architecture for wireless communication in a flat fading environment when using multi-element antennas,” *Bell Labs Tech. Journ.*, vol. 1, no. 2, pp. 41–59, 1996.
[5] A. J. Paulraj and C. B. Papadias, “Space-time processing for wireless communications,” *IEEE Sig. Proc. Mag.*, vol. 14, pp. 49 – 83, Nov. 1997.
[6] S. Cui, A. J. Goldsmith, and A. Bahai, “Energy-efficiency of mimo and cooperative mimo techniques in sensor networks,” *IEEE Journ. Select. Areas. Commun.*, 2003, submitted.
[7] B. Hassibi and B. M. Hochwald, “How much training is needed in multiple-antenna wireless links?” *IEEE Trans. Inform. Theory*, vol. 49, pp. 951 – 963, Apr. 2003.
[8] S. Cui, A. J. Goldsmith, and A. Bahai, “Modulation optimization under energy constraints,” in *Proc. IEEE Intl. Conf. Commun. (ICC 03)*, Alaska, USA, May 2003.
[9] ——, “Energy-constrained modulation optimization for coded systems,” in *Proc. IEEE Globecom Conf.*, San Francisco, CA, USA, December 2003.
[10] ——, “Energy constrained modulation optimization for both uncoded and coded systems,” *IEEE Trans. Commun.*, 2003, submitted.
[11] J. G. Proakis, *Digital Communications*. New York: McGraw-Hill, 2001.
[12] T. S. Rappaport, *Wireless Communications Principles and Practices*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2002.