

Energy-Efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks

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Abstract—We consider radio applications in sensor networks, where the nodes operate on batteries so that energy consumption must be minimized, while satisfying given throughput and delay requirements. In this context, we analyze the best modulation and transmission strategy to minimize the total energy consumption required to send a given number of bits. The total energy consumption includes both the transmission energy and the circuit energy consumption. We first consider multi-input–multi-output (MIMO) systems based on Alamouti diversity schemes, which have good spectral efficiency but also more circuitry that consumes energy. We then extend our energy-efficiency analysis of MIMO systems to individual single-antenna nodes that cooperate to form multiple-antenna transmitters or receivers. By transmitting and/or receiving information jointly, we show that tremendous energy saving is possible for transmission distances larger than a given threshold, even when we take into account the local energy cost necessary for joint information transmission and reception. We also show that over some distance ranges, cooperative MIMO transmission and reception can simultaneously achieve both energy savings and delay reduction.

Index Terms—Cooperative multi-input–multi-output (MIMO), energy efficiency, MIMO, sensor network.

I. INTRODUCTION

RECENT hardware advances allow more signal processing functionality to be integrated into a single chip. It is believed that soon it will be possible to integrate an radio frequency (RF) transceiver, A/D and D/A converters, baseband processors, and other application interfaces into one device that is as small as a piece of grain and can be used as a fully functional wireless sensor node. Such wireless nodes typically operate with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must operate without battery replacement for many years. Consequently, minimizing the energy consumption is a very important design consideration and energy-efficient transmission schemes must be used for the data transfer in sensor networks.

Multiantenna systems have been studied intensively in recent years due to their potential to dramatically increase the channel capacity in fading channels [1]. It has been shown

[1] that multi-input–multi-output (MIMO) systems can support higher data rates under the same transmit power budget and bit-error-rate performance requirements as a single-input single-output (SISO) system. An alternative view is that for the same throughput requirement, MIMO systems require less transmission energy than SISO systems. However, direct application of multiantenna techniques to sensor networks is impractical due to the limited physical size of a sensor node which typically can only support a single antenna. Fortunately, if we allow individual single-antenna nodes to cooperate on information transmission and/or reception, a cooperative MIMO system can be constructed such that energy-efficient MIMO schemes can be deployed.

Energy-efficient communication techniques typically focus on minimizing the transmission energy only, which is reasonable in long-range applications where the transmission energy is dominant in the total energy consumption. However, in short-range applications such as sensor networks where the circuit energy consumption is comparable to or even dominates the transmission energy, different approaches need to be taken to minimize the total energy consumption. Here, the circuit energy consumption includes the energy consumed by all the circuit blocks along the signal path: analog to digital converter (ADC), digital to analog converter (DAC), frequency synthesizer, mixer, lower noise amplifier (LNA), power amplifier, and baseband DSP. Some joint energy-minimizing techniques have been proposed for SISO systems in [2]–[6], where multimode operation with optimized system parameters is investigated. This problem becomes more significant in MIMO systems since the circuit complexity of MIMO structures is much higher than that of SISO structures and it is not clear whether MIMO systems are more energy-efficient than SISO systems due to the high circuit complexity associated with the MIMO structure.

In this paper, we first model the energy consumption of simple MIMO systems and compare the value with that of reference SISO systems under the same throughput and bit-error rate (BER) requirement. The energy efficiency is compared over different transmission distances. We assume that Alamouti diversity codes are used for the MIMO systems. For the rest of this paper, unless otherwise stated, all the statements about MIMO systems are referring to the ones coded with Alamouti diversity codes. We first consider binary phase-shift keying (BPSK)-based systems, where we show SISO systems may be more energy-efficient than MIMO systems when transmission distance is short. We then show that if we allow the constellation size to be optimally chosen, the energy efficiency of MIMO systems can be dramatically increased. For the data transfer in sensor networks, we show that if we allow the cooperation

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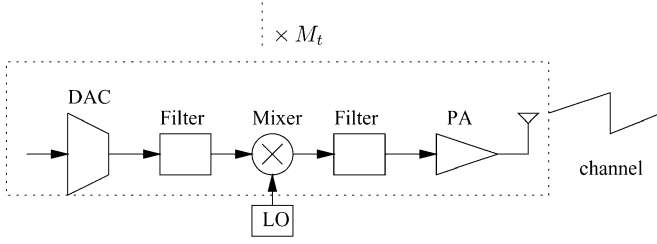


Fig. 1. Transmitter circuit blocks (analog).

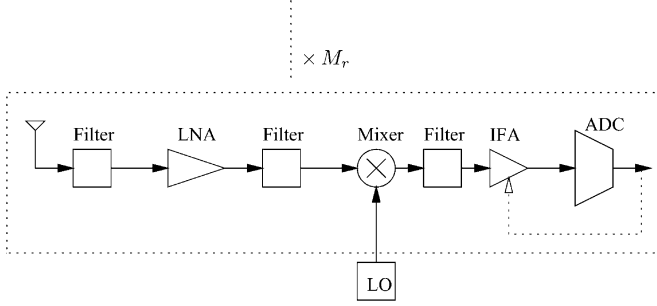


Fig. 2. Receiver circuit blocks (analog).

among sensors for information transmission and/or reception, we can reduce energy consumption, as well as transmission delay over some distance ranges.

The remainder of this paper is organized as follows. In Section II, the model for MIMO systems including energy consumption analysis is introduced. In Section III, we use multiple sensors to construct cooperative MIMO systems and compare their energy efficiency and delay with that of node-to-node transmission schemes. Section IV summarizes our conclusions.

II. ENERGY EFFICIENCY OF MIMO SYSTEMS

A. System Model

We consider a general communication link connecting two wireless nodes, which can be MIMO, multiple-input-single-output (MISO), single-input-multiple-output (SIMO), or SISO. In order to consider the total energy consumption, all signal processing blocks at the transmitter and the receiver need to be included in the model. However, in order to keep the model from being over-complicated at this stage, baseband signal processing blocks (e.g., source coding, pulse-shaping, and digital modulation) are intentionally omitted. We also assume that the system is uncoded. Hence, no error correction code (ECC) blocks are included. The methodology used here can be extended to include those blocks in future research work. The resulting signal paths on the transmitter and receiver sides are shown in Figs. 1 and 2, respectively, where M_t and M_r are the numbers of transmitter and receiver antennas, respectively, and we assume that the frequency synthesizer (LO) is shared among all the antenna paths. For the SISO case, we have $M_t = M_r = 1$.

Similar to the SISO case discussed in [4]–[6], the total average 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 . The first term P_{PA} is dependent on

the transmit power P_{out} , which can be calculated according to the link budget relationship [7]. Specifically, when the channel only experiences a square-law path loss, we have

$$P_{out} = \bar{E}_b R_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \quad (1)$$

where $\bar{E}_b$ is the required energy per bit at the receiver for a given BER requirement, R_b is the bit rate, d is the transmission distance, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference, and N_f is the receiver noise figure defined as $N_f = (N_r/N_0)$ with $N_0 = -171$ dBm/Hz the single-sided thermal noise power spectral density (PSD) at room temperature and N_r is the PSD of the total effective noise at the receiver input.

The power consumption of the power amplifiers can be approximated as [4]

$$P_{PA} = (1 + \alpha) P_{out} \quad (2)$$

where $\alpha = (\xi/\eta) - 1$ with η the drain efficiency [9] of the RF power amplifier and ξ the peak-to-average ratio (PAR), which is dependent on the modulation scheme and the associated constellation size [6].

The second term P_c in the total power consumption is given by

$$P_c \approx M_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} + M_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filt} + P_{ADC}) \quad (3)$$

where P_{DAC} , P_{mix} , P_{LNA} , P_{IFA} , P_{filt} , P_{fllr} , P_{ADC} , and P_{syn} are the power consumption values for the DAC, the mixer, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the ADC, and the frequency synthesizer, respectively. To estimate the values of P_{DAC} , P_{ADC} and P_{IFA} , we use the model introduced in [6].

Finally, the total energy consumption per bit for a fixed-rate system can be obtained as

$$E_{bt} = (P_{PA} + P_c)/R_b. \quad (4)$$

For simplicity, we assume that Alamouti schemes are used to achieve diversity in the MIMO system. The Alamouti code with two transmit antennas, proposed in [8], uses two different symbols s_1 and s_2 that are transmitted simultaneously during the first symbol period from antennas 1 and 2, respectively, followed by signals $-s_2^*$ and s_1^* from antennas 1 and 2, respectively, during the next symbol period (where $\star$ denotes complex conjugate). The extension of the Alamouti code to more than two antennas is discussed in [1].

It has been shown [1] that for Rayleigh-fading channels MIMO systems based on Alamouti schemes can achieve lower average probability of error than SISO systems under the same transmit energy budget due to the diversity gain and possible array gain (when $M_r > 1$). In other words, under the same BER and throughput requirement, MIMO systems require less transmission energy than SISO systems. However, if we consider both the transmission energy and the circuit energy consumption, it is not clear which system is more energy-efficient,

TABLE I
SYSTEM PARAMETERS

$f_c = 2.5$ GHz	$\eta = 0.35$
$G_t G_r = 5$ dBi	$\sigma^2 = \frac{N_0}{2} = -174$ dBm/Hz
$B = 10$ KHz	$\beta = 1$
$P_{mix} = 30.3$ mW	$P_{syn} = 50.0$ mW
$\bar{P}_b = 10^{-3}$	$T_s = \frac{1}{B}$
$P_{filt} = P_{filr} = 2.5$ mW	$P_{LNA} = 20$ mW
$N_f = 10$ dB	$M_L = 40$ dB

since the MIMO system has much more energy-consuming circuitry. We analyze this energy-efficiency comparison in the next section.

B. Fixed-Rate System With BPSK Modulation

We assume a flat Rayleigh-fading channel, i.e., the channel gain between each transmitter antenna and each receiver antenna is a scalar. Therefore, the fading factors of the MIMO channel can be represented as a scalar matrix. In addition, the path loss is modeled as a power falloff proportional to the distance squared, as was shown in (1). In other words, on top of the square-law path loss, the signal is further attenuated by a scalar fading matrix $\mathbf{H}$, in which each entry is a zero-mean circulant symmetric complex Gaussian (ZMCSCG) random variable with unit variance [1]. The fading is assumed constant during the transmission of each Alamouti codeword. The related circuit and system parameters are defined in Table I, where the power consumption values of various circuit blocks are quoted from [9]–[12] as was also used in [4]–[6]. In the following two subsections, we focus on MISO and MIMO systems that use Alamouti schemes with BPSK modulation and compare their energy efficiency with that of a reference SISO system.

1) *Alamouti 2 × 1*: We consider a 2 × 1 MISO Alamouti scheme, where $\mathbf{H} = [h_1 h_2]$. The reference SISO system is treated as a special case of MISO systems with $\mathbf{H} = [h_1]$. As shown in [1], the instantaneous received SNR is given by

$$\gamma_b = \frac{\|\mathbf{H}\|_F^2 \bar{E}_b}{M_t N_0}, \quad M_t = 1, 2 \quad (5)$$

where the M_t in the denominator comes from the fact that the transmit power is equally split among transmitter antennas. The average BER is given by [1]

$$\bar{P}_b = \mathcal{E}_{\mathbf{H}}\{Q(\sqrt{2\gamma_b})\}. \quad (6)$$

According to the Chernoff bound [1] (in the high SNR regime)

$$\bar{P}_b \leq \left(\frac{\bar{E}_b}{M_t N_0} \right)^{-M_t} \quad (7)$$

we can derive an upper bound for the required energy per bit

$$\bar{E}_b \leq \frac{M_t N_0}{\bar{P}_b^{1/M_t}}. \quad (8)$$

By approximating the bound as an equality, we can calculate the total energy consumption (which is actually an upper bound)

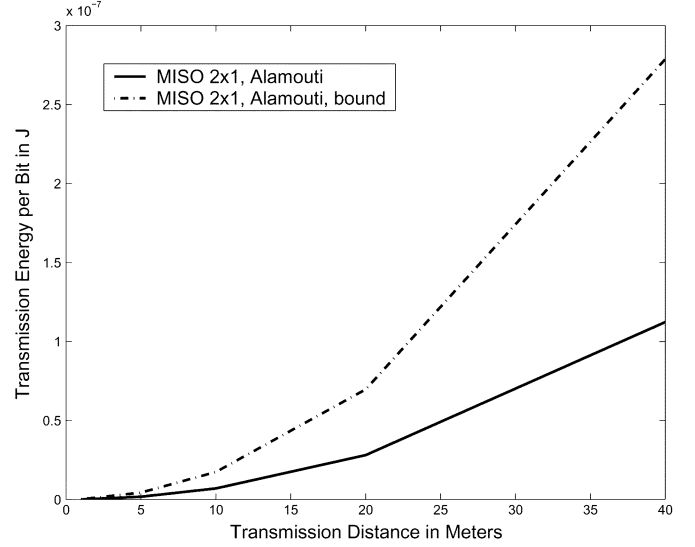


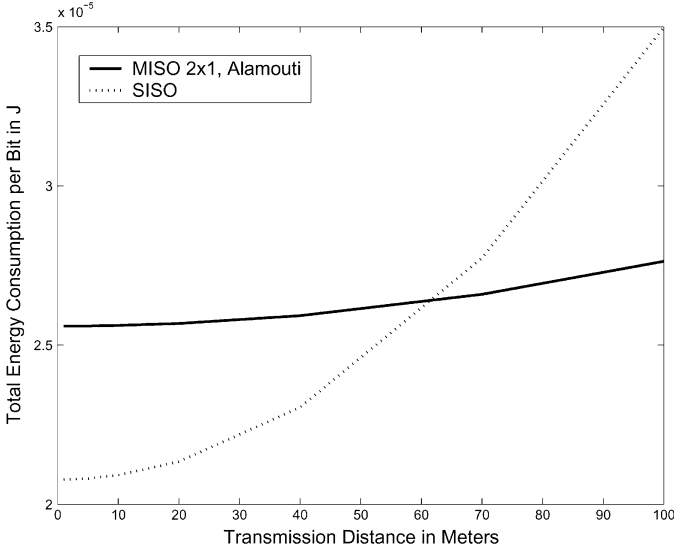
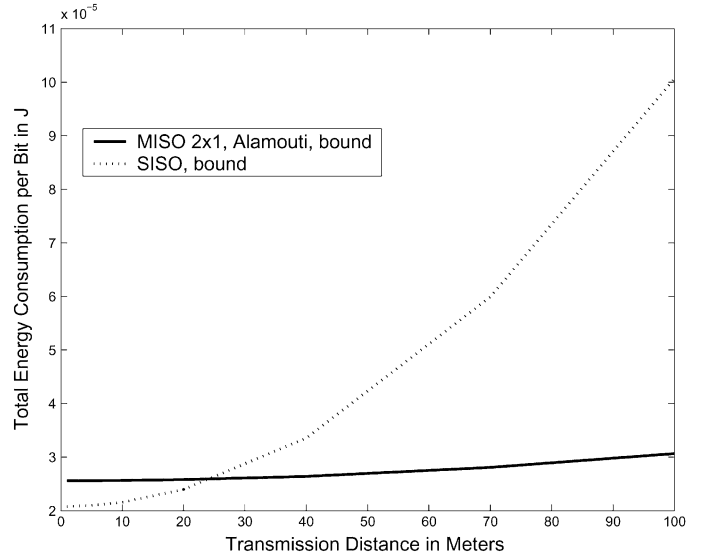
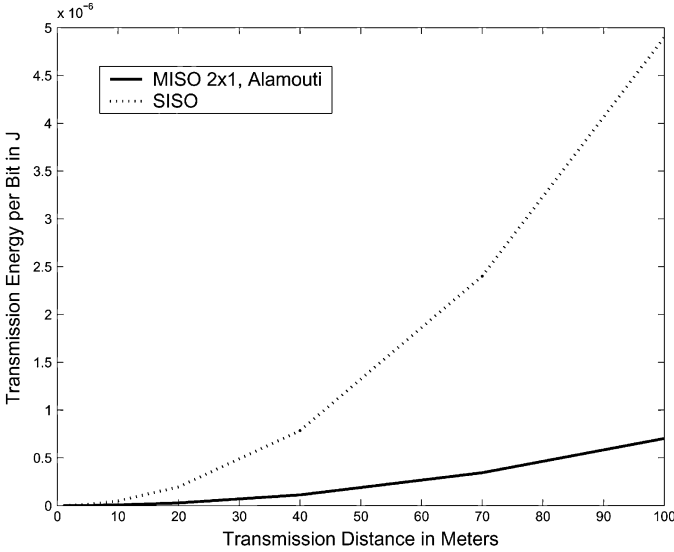
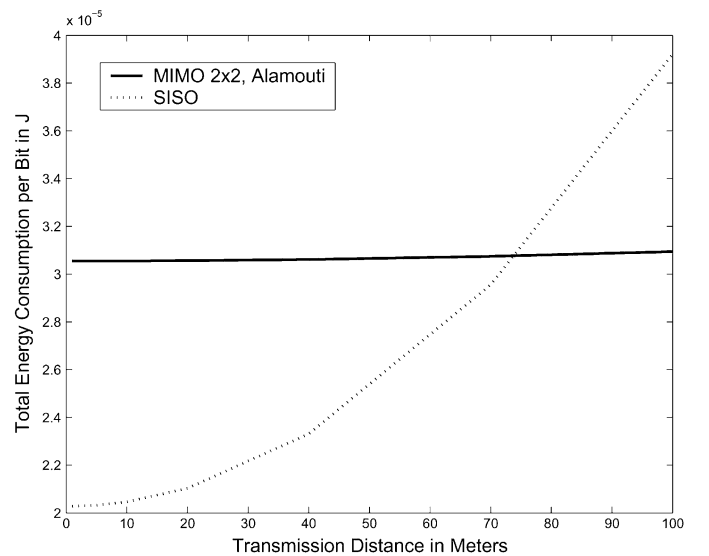
Fig. 3. Transmission energy consumption per bit over d (bound versus numeric solution).

per bit for both the MISO system and the reference SISO system according to (1) and (4). Thus, we can obtain

$$E_{bt} = (1 + \alpha) \frac{M_t N_0}{\bar{P}_b^{1/M_t}} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_t N_f + P_c / R_b. \quad (9)$$

We can also compute the $\bar{E}_b$ exactly using numerical techniques. Specifically, we find the required $\bar{E}_b$ by evaluating $\bar{P}_b$ over 10 000 randomly generated channel samples according to (6) at each transmission distance and then inverting to obtain the $\bar{E}_b$ that yields the desired $\bar{P}_b$. This numerical solution and the approximation based on the Chernoff bound are shown in Fig. 3. We see from this figure that the upper bound we obtained in (8) is quite loose: cross all distances the bound leads to roughly double the required $\bar{E}_b$. Therefore, for the best accuracy, the numerical method should be used to find the required $\bar{E}_b$, then substitute $\bar{E}_b$ into (1) and proceed through (2)–(4) to obtain E_{bt} . The value of E_{bt} over transmission distance d obtained in this manner is plotted in Fig. 4, where we see that the SISO system outperforms the MISO system when $d \leq 62$ m. In other words, the critical distance below which SISO beats MISO in terms of energy efficiency is 62 m in this particular example. If we plot the transmission energy only, we see that the MISO system deploying the Alamouti code always beats the SISO system due to the diversity gain, as shown in Fig. 5. The crossover in Fig. 4 indicates where the transmission energy savings in MISO exceeds the extra circuit energy consumption in comparison with SISO. In Fig. 6, we show that if we use the bound approximation, the crossover point will be dramatically different from the numerical solution due to the looseness of the bound.

2) *Alamouti 2 × 2*: We now consider a 2 × 2 MIMO system based on the Alamouti code where the channel matrix is given by $\mathbf{H} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix}$. According to [1], this MIMO system can achieve a diversity order of 4 and an array gain of 2, which means that even less transmission energy is required compared

Fig. 4. Total energy consumption per bit over d , MISO versus SISO.Fig. 6. Total energy consumption (bound) per bit over d , MISO versus SISO.Fig. 5. Transmission energy per bit over d , MISO versus SISO.Fig. 7. Total energy consumption over d , MIMO versus SISO.

with the 2×1 MISO system under the same performance requirement. However, since the circuit energy consumption dominates the transmission energy when d is small, and the extra receiver branch in the 2×2 MIMO adds more circuit energy consumption than in the 2×1 MISO, as shown in Fig. 7 the critical distance below which SISO is more energy-efficient is even larger than the MISO case.

C. Variable-Rate Systems

So far we have compared the performance between the MIMO and SISO systems under a fixed-rate assumption, where the data rate is 10 kb/s and the modulation scheme is BPSK. We have shown that SISO can beat MIMO in terms of energy efficiency for short-range applications. However, for a data network the traffic is usually bursty and the data is communicated on a packet-by-packet basis. Suppose we have L bits in the transmitter buffer, and we have a deadline T to finish the transmission of these L bits. It has been shown in [4] that the optimal

strategy to minimize the total energy consumption is to operate on a multimode basis, which provides a significant savings of energy when the sleep mode is deployed. The transceiver spends time $T_{\text{on}} \leq T$ to transmit and receive these bits, where T_{on} is a parameter to optimize, and then returns to the sleep mode where all the circuits in the signal path are shut down to save energy. The optimized T_{on} corresponds to an optimal constellation size b (bits per symbol). Since multiquadrature amplitude modulation (MQAM) is assumed in our example, we have $b = (L/BT_{\text{on}})$, where B is the modulation bandwidth for the MIMO system.

In the previous section, we compared the energy efficiency of MISO and MIMO systems using BPSK. It is well-known [1] that MISO or MIMO systems support higher data rates than SISO in Rayleigh-fading channels. Thus, it may be possible to deploy higher constellation sizes for MISO and MIMO systems without violating the BER requirement. These larger constellation sizes will allow us to decrease the transmission

time T_{on} to reduce the circuit energy consumption E_c , where $E_c = P_c T_{\text{on}}$. Since the energy consumption in the sleep and transient modes is usually much less than that in the active mode when the circuits are properly designed for the multimode operation [4], energy consumption in these modes is neglected in our model for simplicity. However, our model can be easily modified to incorporate the energy consumption values in the sleep and transient modes when they are not negligible (e.g., when deep sub-micron CMOS technology is used [9]). As a result, for transmitters with one or two antennas, the total energy consumption per bit is given as

$$E_{\text{bt}} = (1 + \alpha) \bar{E}_b \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_t N_f + P_c T_{\text{on}} / L \quad (10)$$

where $\bar{E}_b$ is defined by the target BER and the underlying constellation size b according to the following relationship [7]

$$\bar{P}_b \approx \mathcal{E}_{\text{H}} \left\{ \frac{4}{b} \left(1 - \frac{1}{2^{\frac{b}{2}}} \right) Q \left(\sqrt{\frac{3b}{M-1} \gamma_b} \right) \right\} \quad (11)$$

for $b \geq 2$ and

$$\bar{P}_b \approx \mathcal{E}_{\text{H}} \{ Q(\sqrt{2\gamma_b}) \} \quad (12)$$

for $b = 1$, where $\gamma_b = (\|\mathbf{H}\|_F^2 / M_t) (\bar{E}_b / N_0)$ and $M = 2^b$. For simplicity, here we use the error probability formula for MQAM with square constellations (when the value of b is an even number [7]) to approximate the $\bar{P}_b$ for all the $b \geq 2$ cases. The introduced error when b is odd is negligible for our purpose.

For the $M_r = 1$ case we can apply the Chernoff bound to obtain

$$\bar{P}_b \leq \frac{4}{b} \left(1 - \frac{1}{2^{\frac{b}{2}}} \right) \left(\frac{1.5 \bar{E}_b b}{M_t N_0 (2^b - 1)} \right)^{-M_t}, \quad M_t = 1, 2$$

from which we can derive an upper bound for $\bar{E}_b$ as shown below

$$\bar{E}_b \leq \frac{2}{3} \left(\frac{\bar{P}_b}{\frac{4}{b} \left(1 - \frac{1}{2^{\frac{b}{2}}} \right)} \right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b} M_t N_0.$$

We can further simplify the bound by applying $1 - (1/2^{b/2}) \leq 1$. Finally, we obtain

$$\bar{E}_b \leq \frac{2}{3} \left(\frac{\bar{P}_b}{4} \right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t} + 1}} M_t N_0.$$

By approximating this bound as an equality, we can obtain the following analytical expression for the total energy consumption per bit according to (10)

$$E_{\text{bt}} = \frac{2}{3} (1 + \alpha) \left(\frac{\bar{P}_b}{4} \right)^{-\frac{1}{M_t}} \frac{2^b - 1}{b^{\frac{1}{M_t} + 1}} M_t N_0 \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_t N_f + P_c T_{\text{on}} / L. \quad (13)$$

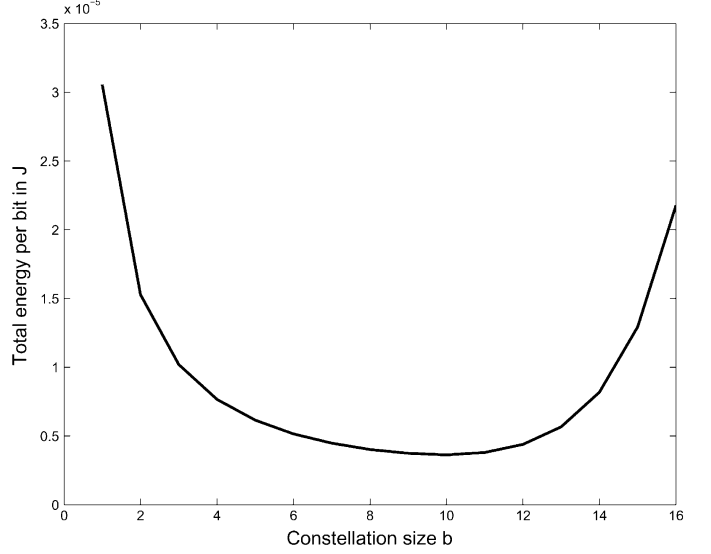


Fig. 8. Total energy consumption over b , MISO 2×1 .

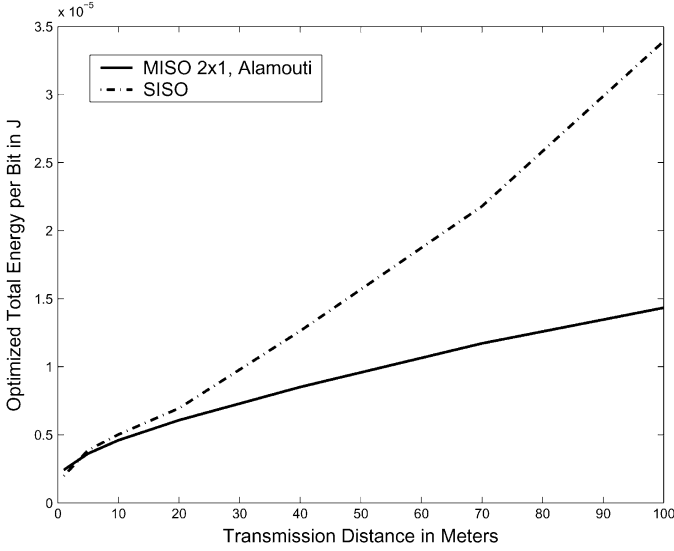
Since $T_{\text{on}} = (L/bB)$ is a function of b , we can minimize E_{bt} over the variable b . When the transmitter has one or two antennas, the first term in (13) is monotonically increasing over the integer number b (when $b \geq 2$) and the second term is monotonically decreasing over b . Therefore, there exists an optimal value for b which minimizes the total energy consumption. Since b is a discrete variable, the optimization problem is not convex. In this paper, brute-force search is used to find the optimal b . Algorithms proposed in [6] can be used to approximate this problem as a convex one, which can then be efficiently solved [13].

In addition, the bound for $\bar{E}_b$ itself is quite loose as was the case for BPSK (shown in the previous section). Thus, as in the BPSK case, we can evaluate $\bar{P}_b$ based on Monte Carlo simulations and then invert to get the required value of $\bar{E}_b$. We then substitute $\bar{E}_b$ into (10) to obtain E_{bt} .

In the next two subsections, we evaluate the Alamouti 2×1 and 2×2 schemes based on the numerical method discussed in the previous paragraph. The related parameters are the same as those in Table I with the addition of two new parameters: $L = 10$ Kb and $T = 1$ s.

1) *Optimized Alamouti 2×1* : To show the benefit of optimizing the constellation size b , we first fix the transmission distance as $d = 5$ m. The value of E_{bt} over the constellation size b for the 2×1 MISO system is plotted in Fig. 8, where we see that by using the optimal constellation size ($b_{\text{opt}} = 10$) a large amount of energy can be saved as compared with the BPSK ($b = 1$) case. The same trend applies to other transmission distances as well. The optimized result over d is plotted in Fig. 9, where we see that the critical distance over which MISO energy efficiency is dramatically decreased ($d \approx 3.8$ m in this case). The optimal constellation sizes for different transmission distances are listed in Table II.

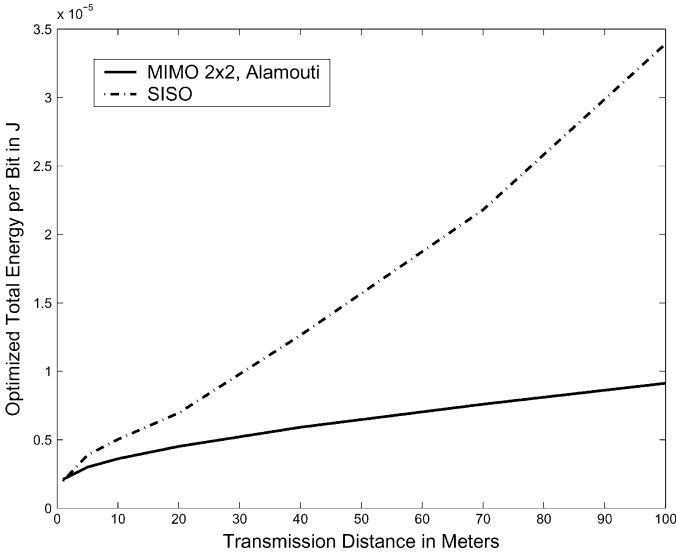
2) *Optimized Alamouti 2×2* : Since an Alamouti 2×2 system can support higher data rate than a 2×1 system, even higher constellation sizes can be deployed to decrease the transmission time without increasing the transmission energy. The optimized constellation size b is listed in Table III and the

Fig. 9. Optimized total energy consumption over d , MISO versus SISO.TABLE II
OPTIMIZED CONSTELLATION SIZE (MISO VERSUS SISO)

d (m)	1	5	10	20	40	70	100
b_{MISO}	14	10	8	6	5	4	3
b_{SISO}	12	6	5	4	4	2	2

TABLE III
OPTIMIZED CONSTELLATION SIZE (MIMO VERSUS SISO)

d (m)	1	5	10	20	40	70	100
b_{MIMO}	16	12	10	8	7	5	5
b_{SISO}	12	6	5	4	4	2	2

Fig. 10. Optimized total energy consumption over d , MIMO versus SISO.

minimized energy consumption is plotted in Fig. 10. This plot shows that the critical distance is further reduced. Specifically, the optimized MIMO system outperforms the SISO system when $d \geq 1.6$ m in this example.

The drawback of this optimization approach is that the increased constellation size increases the total power consumption although the total energy consumption is minimized, as shown

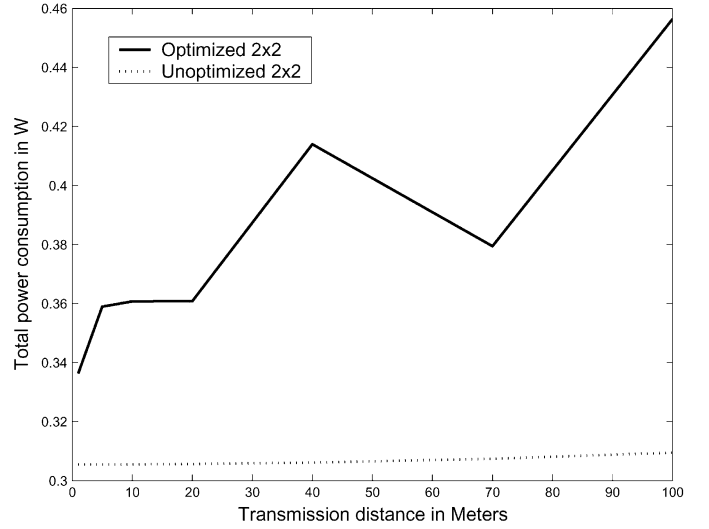
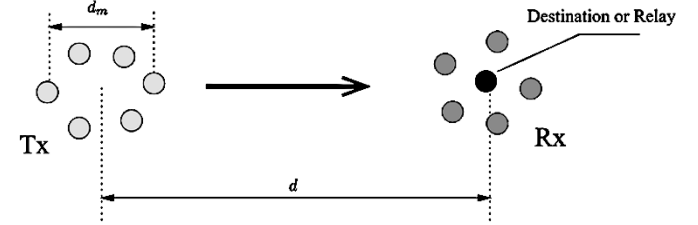
Fig. 11. Total power consumption over d , the optimized system versus the unoptimized system.

Fig. 12. Information flow in a sensor network.

in Fig. 11. This increased power consumption may not be desirable in some peak-power limited applications.

III. MIMO WITH MULTINODE COOPERATION

For sensor networks, maximizing the network lifetime is the main concern. Since sensor networks are mainly designed to cooperate on some joint task where per-node fairness is not emphasized, the design intention is to minimize the total energy consumption in the network instead of minimizing energy consumption of individual nodes. In this section, we propose a strategy to minimize the total energy consumption of multiple nodes from a network perspective. We will focus on systems without ECC, but our results can be extended to include coding using the techniques discussed in [5].

In a typical sensor network, information collected by multiple local sensors need to be transmitted to a remote central processor. If the remote processor is far away, the information will first be transmitted to a relay node, then multihop-based routing will be used to forward the data to its final destination. This scenario is illustrated in Fig. 12.

As we discussed in the last section, MIMO (including MISO, SIMO, and MIMO) can provide energy savings in fading channels. Thus, if we allow cooperative transmission among multiple nodes, we can treat them as multiple antennas to the destination node such that an equivalent MISO system can be constructed. By using this equivalent MISO system, the requirement on transmission energy for the long-haul transmission can be reduced. However, in order to make the cooperative transmission

possible, local data exchange is necessary before the long-haul transmission. The local information flow costs energy, which should be less than the energy saved by using the MISO structure. Another tradeoff is the transmission delay since the MISO approach has different delay characteristics than noncooperative approaches. In this section, we will compare the performance between the MISO strategy and the noncooperative approach to show which one is more energy-efficient and causes less delay.

Cooperation on the transmitting side is not the only method we can explore. On the receiving side there may also be multiple nodes around the destination node such that cooperative reception is possible. Therefore, an equivalent SIMO or MIMO system can be constructed. Similarly, local energy consumption is necessary due to the data aggregation among receiving nodes. The total delay requirement is accordingly altered.

In order to compare the performance between the noncooperative approach and the MIMO approach, some assumptions need to be made. We assume that there are M_t transmitting nodes and each has N_i bits to transmit, where $i = 1, \dots, M_t$. For the noncooperative approach, we assume that each transmitting node uses a different time slot to transmit the information to the remote node with uncoded MQAM. For the MIMO approach, the M_t nodes on the transmitting side will cooperate. Each node first broadcasts its information to all the other local nodes using different time slots. After each node receives all the information bits from other nodes, they encode the transmission sequence according to the Alamouti diversity codes [1]. Since each node has a preassigned index i , they will transmit the sequence which the i th antenna should transmit in an Alamouti MIMO system. On the receiving side, there are M_r nodes (including one destination node and $M_r - 1$ assisting nodes) joining the cooperative reception. The $M_r - 1$ assisting nodes first quantize each symbol they receive into n_r bits, then transmit all the bits using uncoded MQAM to the destination node to do the joint detection.

Since the baseband processing is simple for Alamouti codes [1], we omit the baseband processing energy for simplicity. Therefore, the total energy consumption in each node only includes the transmission energy and the analog circuit energy consumption as we discussed in the previous section for MIMO systems. For local transmissions, we assume a κ th-power path loss ($\text{loss} \propto (1/d^\kappa)$) with additive white Gaussian noise (AWGN). For long-haul transmissions, we assume a Rayleigh-fading channel with square-law path loss. Within the local cluster (for both Tx side and Rx side), if the maximum separation is d_m m, we assume each node will optimize their constellation size according to this worst-case distance. Since usually the long-haul distance between the remote node and the local cluster is much larger than d_m , we assume the long-haul transmission distance, denoted as d , is the same for each transmitting node.

The energy cost per bit for local information flow on the Tx side, denoted as $E_i^t, i = 1, \dots, M_t$, and the energy cost per bit for local information flow on the Rx side, denoted as $E_j^r, j = 1, \dots, M_r - 1$ can be calculated according to the result we obtained for SISO communication links in AWGN channels (see [4] and [6]). However, there is one thing we need to

change for calculating E_i^t . Since there are always $M_t - 1$ receivers listening during the local transmission, the total circuit energy consumption on the receiver side should be the total energy consumption of $M_t - 1$ sets of receiver circuits. The energy cost per bit for the MIMO long-haul transmission, denoted as E_b^r , can be calculated according to the MIMO results discussed in the last section. For the SISO long-haul transmission used by the noncooperative approach, the energy per bit denoted as E_i^0 can be calculated as a special case of MIMO systems where we set $M_t = M_r = 1$.

As a result, the total energy consumption E_{tra} for the noncooperative approach is given by

$$E_{\text{tra}} = \sum_{i=1}^{M_t} N_i E_i^0 \quad (14)$$

while the total energy consumption E_{MIMO} for the cooperative MIMO approach is given by

$$E_{\text{MIMO}} = \sum_{i=1}^{M_t} N_i E_i^t + E_b^r \sum_{i=1}^{M_t} N_i + \sum_{j=1}^{M_r-1} E_j^r n_r N_s \quad (15)$$

where $N_s = (\sum_{i=1}^{M_t} N_i / b_m)$ is the total number of symbols received with b_m the constellation size (bits per symbol) used in the Alamouti code.

The total delay required is defined as the total transmission delay. For a fixed transmission bandwidth B , we assume the symbol period is approximately $T_s \approx (1/B)$. For the noncooperative approach, the total delay T_{tra} is given as

$$T_{\text{tra}} = \sum_{i=1}^{M_t} \frac{N_i}{b_i^0} T_s \quad (16)$$

where b_i^0 is the constellation size used by node i . For the MIMO approach, the total delay T_{MIMO} includes both the local transmission delay and the long-haul transmission delay. Accordingly, T_{MIMO} is given by

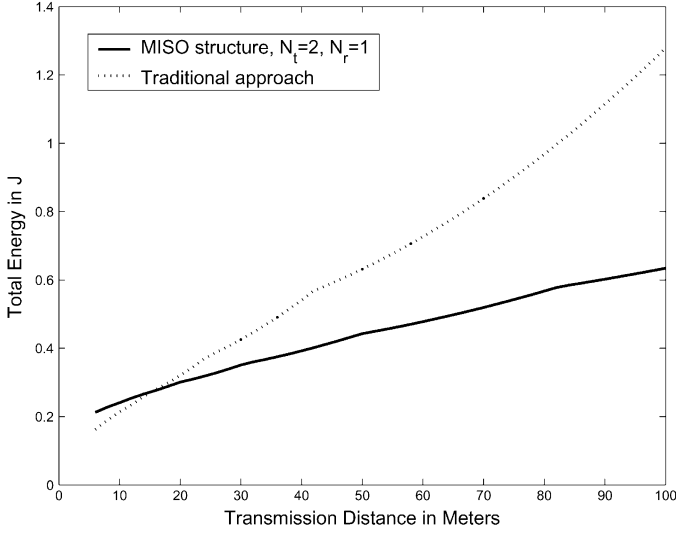
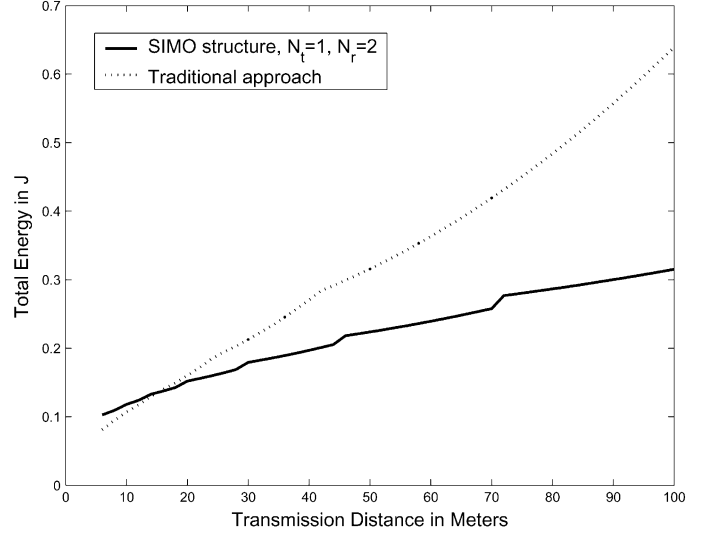
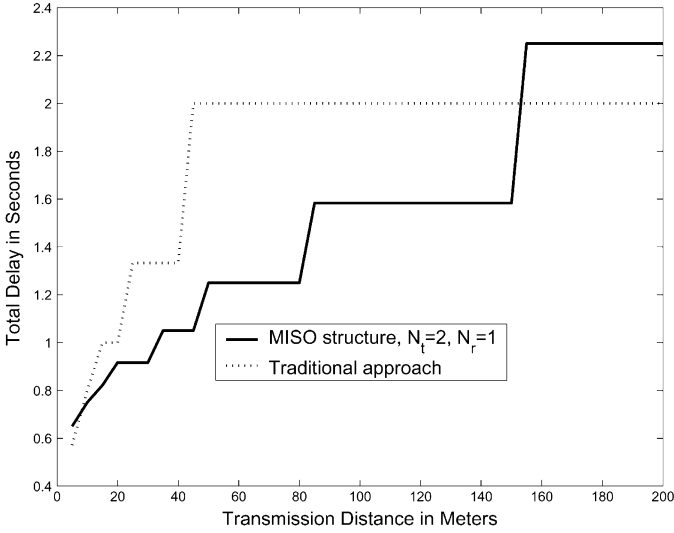
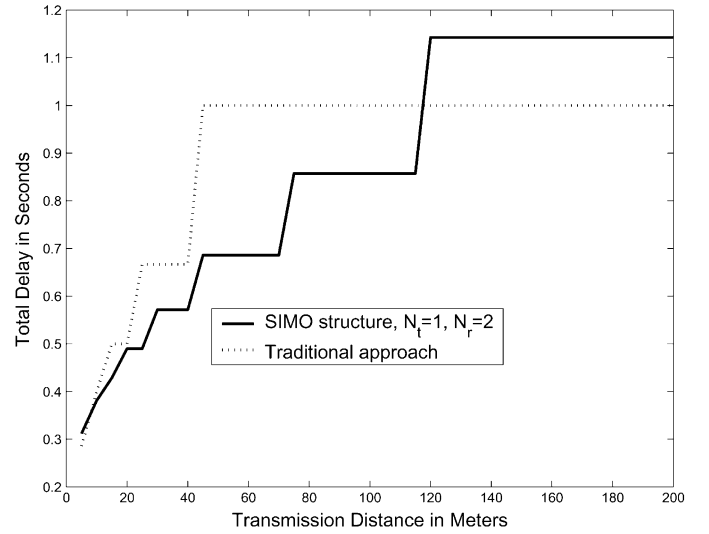
$$T_{\text{MIMO}} = T_s \left(\sum_{i=1}^{M_t} \frac{N_i}{b_i^t} + \frac{\sum_{i=1}^{M_t} N_i}{b_m} + \sum_{j=1}^{M_r-1} \frac{n_r N_s}{b_j^r} \right) \quad (17)$$

where b_i^t and b_j^r are the constellation sizes used during the local transmission on the Tx side and the Rx side, respectively. The first and the third terms in the total delay are the local delay values contributed by the Tx side and the Rx side, respectively, and the second term is the delay caused by the long-haul MIMO transmission.

To give numerical examples, we assume that $d_m = 1$ m, $B = 10$ kHz, $n_r = 10$, and all the transmitting nodes have the same number of bits to transmit, i.e., $N_i = 20$ kb. We will discuss the MISO, SIMO, and MIMO cases in more detail below.

A. MISO Case

We first consider the case where only transmitter cooperation is allowed. For simplicity, we set $M_t = 2$ and $M_r = 1$. The total energy consumption of the MISO approach and the noncooperative approach is plotted over the long-haul transmission distance

Fig. 13. Total energy consumption over d (MISO).Fig. 15. Total energy consumption over d (SIMO).Fig. 14. Total delay over d (MISO).Fig. 16. Total delay over d (SIMO).

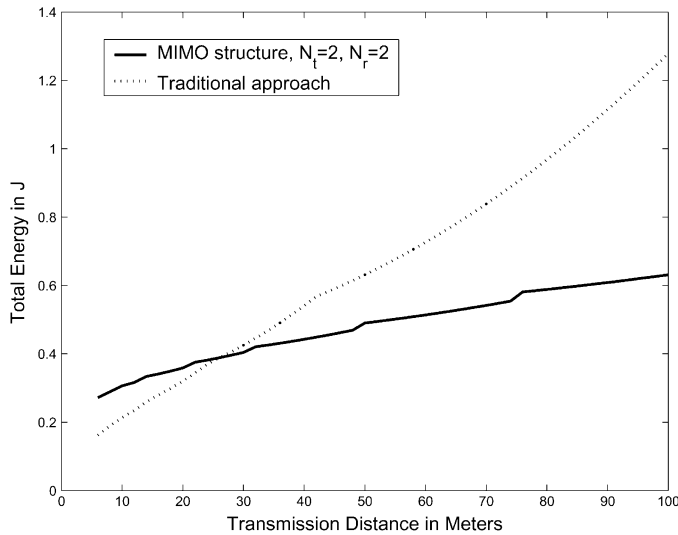
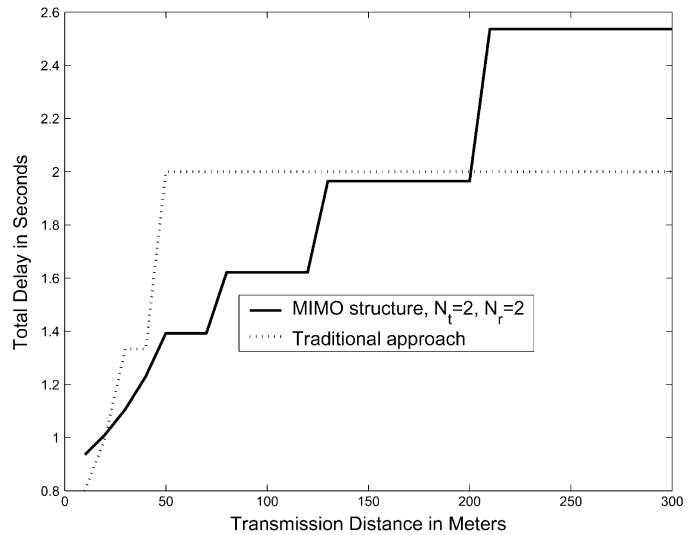
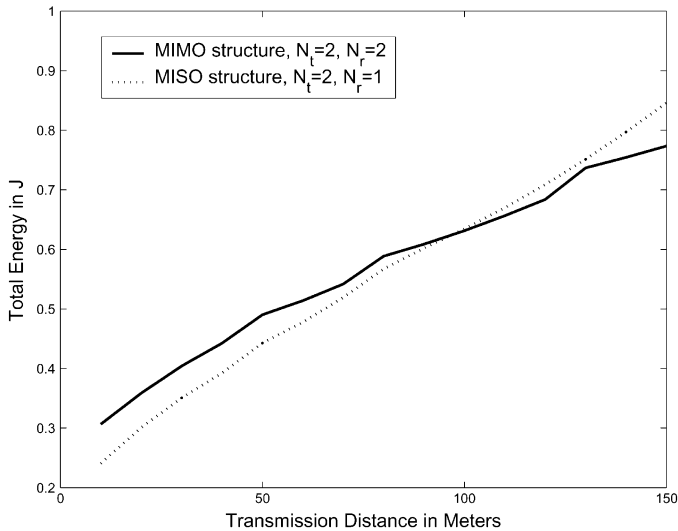
d in Fig. 13. We see that when $d \geq 15$ m the MISO approach becomes more energy-efficient than the traditional approach for this particular example. When d is around 100 m, about 50% energy savings is possible by using the MISO strategy and the savings is increased roughly in a linear fashion over d .

The delay performance comparison between the MISO approach and the noncooperative one is plotted in Fig. 14, where we see that when the distance is within a certain range the delay is smaller for the MISO case. Since MISO links have larger capacity than SISO links, larger constellation sizes are chosen in favor of reducing circuit energy consumption when the distance is short. As a result, the long-haul transmission delay reduction due to the use of higher constellation size overcomes the local delay cost. When the transmission distance becomes large, the transmission energy becomes dominant such that the optimized constellation for both the MISO approach and the noncooperative approach is quaternary phase-shift keying (QPSK). As a result, the delay caused by the long-haul transmission will be the same for the two approaches, while the

MISO approach incurs some extra delay for local information flow. From Figs. 13 and 14, we see that there exists a sweet window (from 8 to 155 m in this example), where we can reduce both energy consumption and delay by using the MISO strategy.

B. SIMO Case

We now consider the case where only receiver cooperation is allowed with $M_t = 1$ and $M_r = 2$. The total energy consumption of the SIMO approach and the noncooperative approach is drawn over different long-haul transmission distances d in Fig. 15. Similar to the MISO case, there exists a threshold (15 m for this example) above which the SIMO strategy becomes more energy-efficient. The delay performance comparison between the SIMO approach and the noncooperative approach is drawn in Fig. 16. Similar to the MISO case, there exists a sweet window where both energy and delay can be reduced.

Fig. 17. Total energy consumption over d (MIMO).Fig. 19. Total delay over d (MIMO).Fig. 18. Total energy consumption over d (MIMO versus MISO).

C. MIMO Case

We finally consider the case where cooperation on both sides is allowed with $M_t = 2$ and $M_r = 2$. The total energy consumption of the MIMO approach and the noncooperative approach is drawn over the long-haul transmission distance d in Fig. 17. Since the MIMO structure involves more local energy consumption compared with the MISO or SIMO structure, the threshold distance above which MIMO becomes more energy-efficient is increased. However, since MIMO requires less transmission energy for the long-haul transmission, the total energy consumption will become smaller compared with MISO or SIMO when d is large enough. The total energy consumption values of MIMO and MISO are drawn over d in Fig. 18, where we see that MIMO becomes more energy-efficient than MISO when the distance is larger than 100 m for this example. The delay performance of MIMO is drawn in Fig. 19. Similar to MISO and SIMO cases, a sweet window also exists where we can reduce both energy and delay.

IV. CONCLUSION

We show that the traditional belief that MIMO systems are more energy-efficient than SISO systems in Rayleigh-fading channels may be misleading when both the transmission energy and the circuit energy consumption are considered. We demonstrate that in short-range applications, especially when the data rate and the modulation scheme are fixed, SISO systems may outperform MIMO systems as far as the energy efficiency is concerned. However, by optimizing the constellation size, we can extend the superiority of MIMO systems in terms of energy efficiency down to very short distances.

We also investigate the energy efficiency of cooperation among nodes for both information transmission and reception. By allowing cooperation, we can treat the equivalent system as a MIMO system. By applying the energy minimization result to this equivalent MIMO system, we show that over certain distance ranges both the total energy consumption and the total delay can be reduced, even when we take into account the energy and delay cost associated with the local information exchange.

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