Transmitter-Receiver Energy Efficiency: A Trade-off in MIMO Wireless Sensor Networks

Hoda Ayatollahi, Cristiano Tapparello, Wendi Heinzelman

Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY, USA
Email: {`hayatoll, ctappare, wheinzel`}`@ece.rochester.edu`

***Abstract*—Power and energy consumption are the most important factors in extending the lifetime of Wireless Sensor Networks (WSN). Many energy efficiency techniques, that consider both the transmission and circuit power consumption have been proposed for the case of Single-Input Single-Output (SISO) WSNs. However, the power consumption of the receiver should also be considered in order to maximize the network lifetime. In this paper, we introduce a novel communication protocol for Multiple-Input Multiple-Output (MIMO) WSNs. In this protocol, the number of antennas to be used at both the transmitter and receiver are selected according to the energy consumption of the scheme, the remaining energy at the nodes, the distance between the nodes, and the target bit error rate. Starting from a policy that selects the optimal number of antennas, we then propose 3 low complexity heuristics with different information requirements. Numerical results show that our proposed communication protocols dramatically outperform the performance of a traditional fixed MIMO system in terms of energy consumption and system lifetime.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are employed in many different areas such as intrusion detection, surveillance, targeting systems, and environmental monitoring [1]. Most of these applications need to avoid battery replacement in the sensors not only to decrease the total maintenance cost but also to increase the network lifetime and its energy efficiency. To achieve this goal, the power consumption of WSNs should be managed in a way that the receiver sensor and the transmitter sensor have enough power for their sensing tasks during their communication. If one of these sensors has low energy level, the total power consumption of the system should be decreased for the benefit of the sensor lifetime. Moreover, increasing the lifetime of the low-energy sensor consequently results in better performance for the entire wireless network.

Multiple-Input Multiple-Output (MIMO) radio antenna technology is a promising approach to improve the energy efficiency of wireless communications. This technology is employed in WSNs due to its potential to dramatically improve the data throughput and radio energy efficiency without increasing the total transmission power [2] [3]. Using multiple antennas at both the transmitter and the receiver, MIMO systems spread the transmission power among different antennas in order to achieve a power gain that increases the bandwidth efficiency for the same Bit-Error-Rate (BER) requirement [2].

Although MIMO communication requires less transmission power compared to Single-Input Single-Output (SISO) communication, both the transmitter and the receiver consume more circuit energy due to the additional number of antennas that are used by the system. This is because, as the number of antennas increases, more circuit power is required by the radio device. Therefore, both the circuit and transmission power should be considered in the total energy optimization in order to devise an energy efficient communication protocol.

To address this problem, several energy efficient MIMO protocols have been proposed [3]–[6]. While these protocols consider both the circuit and the transmission power required to exchange data packets, in order to optimize the energy usage, most of them focus on minimizing the transmission power for a certain transmission distance or communication delay. Despite the fact that this is a reasonable approach in long-range SISO systems, it is not always a promising solution for short-range applications. In [6], the authors propose a method to minimize the transmission power by dynamically switching between Single-Input Multiple-Out (SIMO), Space-Time Block Coding (STBC) and Spatial Multiplexing (SM) depending on the distance between the communicating nodes. While [6] showed that SM and STBC may provide some advantages in transmission power compared to SIMO, the circuit energy consumption is not included in the analysis.

Dynamic antenna selection is another method that can be helpful in managing energy efficiency. This is related to selecting the number of antennas at the transmitter and receiver in a MIMO system, based on the specific energy requirements. In a multi-user MIMO system, by considering a signal-to-interference plus noise ratio (SINR) threshold, one possible solution is to select the number of antennas that maximizes the SINR of the worst above-the-threshold user [7]. Alternatively, to manage the energy efficiently, the number of antennas can be chosen dynamically for each neighbor node based on their transmission distance [8]. Most of these papers consider either the distance or the delay to decrease the total energy consumption. However, there are some other key factors such as sensor remaining energy and energy consumption coupled with dynamic antenna selection that are highly effective in improving the energy efficiency of MIMO systems.

In this paper, we model the problem of dynamically adjusting the number of antennas based on the sensors' energy levels. We propose an *Optimal Policy* in which an energy

---

This research was funded in part by the National Science Foundation under research grant CNS-1239423.

balancing model is applied in the network based on the various requirements of the sensors. For a specific communication slot, our approach chooses an antenna mode among SISO, MISO, SIMO, and MIMO based on their energy consumption and on the residual energy at both the transmitter and receiver nodes, in order to extend the sensors' lifetimes. In addition, we introduce an on-the-fly policy, called *Online Policy*, in which the most energy efficient antenna mode is selected before the actual data exchange. Finally, we propose two heuristic policies that act in the benefit of either the receiver or the transmitter. These policies choose the antenna mode that maximizes either the receiver (*RX Policy*) or the transmitter (*TX Policy*) lifetime.

The remainder of the paper is organized as follows. In Section II we provide a review of related work in the area of MIMO technology in WSNs. In Section III we present the system model, while in Section IV we describe the proposed energy balancing schemes for MIMO WSNs. In Section V, we compare the performances attained by the different policies via extensive simulations. Finally, conclusions are drawn in Section VI.

II. MOTIVATION AND RELATED WORK

The increasing demand for WSNs with long lifetime requires efficient management of the way in which the network resources are consumed.

The network energy performance can be improved by employing MIMO communication technology, which uses multiple receiver and/or transmitter antennas to gain better spatial diversity and energy efficiency [2]. Several studies have explored the issue of energy efficiency in MIMO WSNs. In [4], the energy efficiency of non-cooperative, half-cooperative and cooperative MIMO systems are analyzed by considering the trade-off between spatial diversity and multiplexing gains. Their results show that the energy efficiency of MIMO systems is much higher than that of SISO. The energy trade-off between SISO and MIMO systems is also analyzed in [5]. They show that a MIMO transmission scheme performs better than SISO in terms of energy efficiency for long-range applications and vice versa for short-range applications. The protocols presented in [4] and [5] consider a fixed MIMO scheme for exchanging multiple packets between two sensors, regardless of their distance and battery level. However, for different energy levels, distances, and BERs, different MIMO schemes could maximize the network energy efficiency and, therefore, the system lifetime.

In [8], the authors considered a MIMO-based wireless network in which the nodes are able to use different MIMO schemes, and presented a power-controlled channel access protocol to minimize the total power consumption. In this protocol, a suitable MIMO scheme is chosen among MIMO, MISO, SIMO, and SISO, based on the transmission distance and the transmission power. For every pair of nodes along a multi-hop communication path, they selected the MIMO scheme that minimizes the total energy consumption. However, for subsequent packet transmissions between two neighbor nodes, the protocol presented in [8] always selects the same MIMO scheme, disregarding the traffic load of a node and thus reducing the total system lifetime.

It can be noticed that all these papers do not consider the system remaining energy while minimizing the total energy consumption. The proposed communication protocols, for a particular transmission distance and BER, always select the same MIMO scheme. However, when maximizing the network lifetime, using the same MIMO scheme results in non optimal performance because the four MIMO schemes entail different energy consumptions at the transmitter and the receiver. In particular, at the receiver side, SISO and MISO have lower energy consumption than MIMO and SIMO's while at the transmitter side, the situation is reversed. Thus, in order to maximize the lifetime of the system, the transmitter and receiver remaining energies need to be also included in the selection of the best communication scheme.

In addition, although these papers studied different methods to achieve energy efficiency in MIMO WSNs, none of them investigates the problem of energy shortage at one end of the wireless communication (i.e., how to deal with the situation in which the transmitter has enough energy to perform the transmission, while the receiver does not or vice versa), and do not prevent this issue from happening.

Unlike previous work, we consider the energy trade-off between the transmitter and the receiver for different MIMO schemes and present an energy efficient model that dramatically increases the lifetime of both the transmitter and the receiver. By dynamically switching between the different MIMO schemes, namely MIMO, MISO, SIMO and SISO, our policies attain much longer system lifetime compared to wireless networks that select the MIMO scheme to be used based only on the transmission distance and on a BER threshold.

III. SYSTEM MODEL

Consider a single hop communication link between a source node *tx* and a destination node *rx*. Nodes are static and time is slotted with a slot corresponding to the variable transmission time of a successful packet, which includes the fixed transmission time of a packet and the subsequent retransmissions due to unsuccessful delivery. The nodes are powered through an energy buffer and, at a generic time slot t, we define the transmitter and receiver residual energies as B_{tx}^t and B_{rx}^t, respectively. The nodes are equipped with M antennas and have the possibility to operate as an M_{tx}xM_{rx} MIMO scheme, with $M_{tx}, M_{rx} \in \{1, 2, \ldots, M\}$, depending on the number of antennas selected at the transmitter and the receiver. Moreover, we consider that the nodes use a BPSK modulation scheme with fixed-rate and that the channel follows a Rayleigh fading model. In what follows, we describe the energy model used to characterize the energy consumption of the different schemes.

As mentioned previously, the nodes are battery powered with initial energy levels B_{tx}^0 and B_{rx}^0 at the transmitter and the receiver sides, respectively. By sending or receiving a packet at time t, the residual energy stored in the devices (i.e.,

B_{tx}^t and B_{rx}^t) decreases over time according to the energy consumption of the selected antenna mode.

The receiver energy is consumed only using the receiver circuit block (P_{C}^{rx}) while at the transmitter side, it is consumed by both the transmitter circuit (P_{C}^{tx}) and the Power Amplifier (P_{PA}). We consider the circuit blocks of the receiver and the transmitter as discussed in [5] and [9], by defining the number of antennas at the transmitter as M_{tx} and the number of receiver antennas as M_{rx}. For simplicity, we assume that no Error Correction Code (ECC) blocks or source coding schemes are used and also no training bits are employed.

At the receiver side, the total power consumption $P_{rx}(M_{tx}, M_{rx})$ is equal to the circuit power consumption $P_C^{rx}(M_{rx})$, which is given by

$$\begin{aligned} P_C^{rx}(M_{rx}) = M_{rx}(P_{\text{ADC}} + P_{\text{Mix}} + P_{\text{Fil}}^{rx} + P_{\text{Dem}} + \\ + P_{\text{IFA}} + P_{\text{LNA}}) + P_{\text{Syn}}, \end{aligned} \tag{1}$$

where P_{ADC} represents the power consumption of the Analog-to-Digital converter (ADC), P_{Mix} the power consumption of the mixer, P_{Fil}^{rx} the power consumption of the receiver filter circuit, P_{Dem} the power consumption of the demodulator, P_{IFA} the power consumption of the Intermediate Frequency Amplifier (IFA), P_{LNA} the power consumption of the Low Noise Amplifier (LNA) and P_{Syn} the power consumption of the frequency synthesizer. The power consumption at the transmitter side $P_{tx}(M_{tx}, M_{rx})$, instead, is given by

$$P_{tx}(M_{tx}, M_{rx}) = P_{\text{PA}}(M_{tx}, M_{rx}) + P_{\text{C}}^{tx}(M_{tx}), \tag{2}$$

where P_{PA} and P_{C}^{tx} are defined before. The power consumption of the transmitter circuit P_{C}^{tx} is expressed as

$$P_{\text{C}}^{tx}(M_{tx}) = M_{tx}(P_{\text{DAC}} + P_{\text{Mix}} + P_{\text{Fil}}^{tx} + P_{\text{Mod}}) + P_{\text{Syn}}, \tag{3}$$

where P_{DAC} is the power consumption of the Digital-to-Analog Converter (DAC), P_{Mod} is the power consumption of the modulator and P_{Fil}^{tx} represents the power consumption of the transmitter filter circuit. The power consumption of the power amplifier $P_{\text{PA}}(M_{tx}, M_{rx})$ depends on the transmission power P_{out} and the modulation scheme [9], and is expressed as

$$P_{\text{PA}}(M_{tx}, M_{rx}) = \left(1 + \frac{\xi}{\eta}\right) P_{\text{out}}(M_{tx}, M_{rx}), \tag{4}$$

where η is the drain efficiency of the power amplifier, while $\xi = 3\frac{K-2\sqrt{K}+1}{K-1}$ represents the Peak-to-Average Ratio (PAR) that depends on the constellation size K. We note that for the results presented in this paper, ξ is a constant value since we only consider a BPSK modulation scheme ($K = 2$). Moreover, the transmission power P_{out} can be calculated using the formula [10]:

$$P_{\text{out}}(M_{tx}, M_{rx}) = \overline{E_b}(M_{tx}, M_{rx}) R_b \left(\frac{4\pi d}{\lambda}\right)^k \frac{M_l N_f}{G_{tx} G_{rx}}, \tag{5}$$

where R_b is the system bit rate, G_{tx} and G_{rx} are the transmitter and the receiver antenna gains, d is the transmission distance, λ is the carrier wavelength and k is the path loss exponent. Moreover, N_f is the receiver noise figure, which depends on the thermal noise Power Spectral Density (PSD) N_0 and on the PSD of the total effective noise at the receiver. M_l is the link margin, which shows the difference between the receiver sensitivity and the actual received power. $\overline{E_b}$ is the average energy per bit required to achieve a given BER p_b, for a BPSK M_{tx}xM_{rx} MIMO system. According to [11], it is defined as

$$p_b = \left(\frac{1}{2}(1-\zeta)\right)^H \cdot \sum_{l=0}^{H-1} \binom{l}{H-1+l} \left(\frac{1}{2}(1+\zeta)\right)^l, \tag{6}$$

where $H = M_{tx} M_{rx}$, $\zeta = \sqrt{1/\left(1 + \frac{M_{tx} N_0}{\overline{E_b} d_m}\right)}$ and d_m is a variable that depends on the STBC used by the MIMO system [11]. Given the above, we can now define the total energy required at the transmitter or the receiver to send or receive a packet of size N bits as

$$E_{\text{pkt}}^X(M_{tx}, M_{rx}) = \frac{P_X(M_{tx}, M_{rx})}{R_b} N, \tag{7}$$

where $X \in \{tx, rx\}$. Given the per packet energy consumptions $E_{\text{pkt}}^{tx}(M_{tx}, M_{rx})$ and $E_{\text{pkt}}^{rx}(M_{tx}, M_{rx})$ and time slot t, we define the remaining transmitter and receiver lifetimes as the number of successful packets that can processed by the nodes using a M_{tx}xM_{rx} MIMO scheme as

$$L_X^t(M_{tx}, M_{rx}) = \frac{B_X^t}{E_{\text{pkt}}^X(M_{tx}, M_{rx}) \frac{1}{1-p_{\text{pkt}}}}, \tag{8}$$

where $X \in \{tx, rx\}$ and $p_{\text{pkt}} = 1 - (1 - p_b)^N$ represents the packet error rate and accounts for packet retransmissions. Thus, the remaining system lifetime at time t is given by

$$L^t(M_{tx}, M_{rx}) = \min\{L_{tx}^t(M_{tx}, M_{rx}), L_{rx}^t(M_{tx}, M_{rx})\}. \tag{9}$$

IV. Dynamic Antenna Selection Policies

In a wireless sensor network, the total remaining energy and, consequently, the total lifetime of the system, depends on the lifetimes of both the transmitter and the receiver. For instance, if the transmitter has enough energy but the receiver does not, or vice versa, by choosing a fixed communication scheme, the bottleneck node will eventually be depleted. The main goal of our solution is to extend the lifetime of the system by varying the MIMO scheme over time. In what follows, we first propose an optimal antennas selection scheme (*Optimal Policy*), which balances the energy consumption between the transmitter and the receiver. We then present 3 heuristic policies, namely *Online Policy*, *TX Policy* and *RX Policy*, with different complexity and requirements in term of information that needs to be exchanged between the nodes.

A. *Optimal Policy*

The main goal of *Optimal Policy* is to maximize the system lifetime and simultaneously minimize the total energy consumption with respect to both the transmitter and receiver lifetimes. To this end, the optimal antennas selection policy can be define as the solution of the following combinatorial optimization problem:

$$\max \sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} \tag{10}$$

s.t.

$$\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E_{\text{pkt}}^{tx}(M_{tx}, M_{rx}) \leq B_{tx}^{0}$$
$$\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E_{\text{pkt}}^{rx}(M_{tx}, M_{rx}) \leq B_{rx}^{0}$$

where $E_{\text{pkt}}^{\text{X}}(M_{tx}, M_{rx})$ represents the transmitter (X=tx) and receiver (X=rx) energy consumptions of the M_{tx}xM_{rx} MIMO scheme. The value of $\alpha_{M_{tx},M_{rx}}$ represents the number of packets that are exchanged by the M_{tx}xM_{rx} MIMO scheme during the communication. As a result, by maximizing $\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}}$, the total lifetime of the system will be maximized. We note that the *Optimal Policy* works offline and only requires information about the initial energy levels and the energy consumption for each communication scheme. While the *Optimal Policy* provides an upper bound on the performance attainable by different communication policies, solving problem (10) can be computationally intensive as the number of antennas increases. However, when the number of communication schemes is small, like in our case, there are efficient algorithms to solve this optimization problem.

B. Online Policy

As the name suggests, the *Online Policy* works online and chooses the best MIMO scheme to be used for the communication, at each transmission slot, on-the-fly. In the *Online Policy*, for a specific p_b and at a fixed transmitter-receiver distance, we compute the lifetime of the system for all the four antenna modes, and we select different schemes interchangeably. In particular, at each time slot t, depending on the remaining energy at the transmitter and the receiver, we choose the scheme M_{tx}^{t}xM_{rx}^{t} that provides the highest system lifetime, according to Eq. (9). The remaining energy of the system at each time slot is then updated by removing from the energy buffer the energy consumption of the communication scheme chosen in the previous time slot (i.e., $B_{tx}^{t+1} = B_{tx}^{t} - E_{\text{pkt}}^{tx}(M_{tx}^{t}, M_{rx}^{t})$ and $B_{rx}^{t+1} = B_{rx}^{t} - E_{\text{pkt}}^{rx}(M_{tx}^{t}, M_{rx}^{t})$).

We note that, unlike the *Optimal Policy* which works offline, this policy requires the additional exchange of the battery levels before each transmission round. However, the *Online Policy* can be easily extended to different communication schemes, to a situation in which the nodes are mobile and to account for additional energy consumptions or energy replenishment techniques, such as energy harvesting.

C. RX and TX Policies

In this section, we introduce two communication policies that select the antenna mode to be used according to either the receiver or the transmitter energy level. The receiver-based policy (*RX Policy*) and the transmitter-based policy (*TX Policy*) consider either the benefits of the receiver or the transmitter, and choose the communication scheme that provides the lowest energy consumption to the sensor (which, in turns, provides the best node lifetime).

TABLE I
SIMULATION PARAMETERS

General Parameters	
k	2
f_c	2.5 GHz
N	1000 bits
N_f	10 dB
N_0	−174 dBm/Hz
B	10 KHz
$G_t G_r$	5 dBi
η	0.35

Circuitry Power Consumption	
P_{DAC}	7 mW
P_{ADC}	7 mW
P_{Mix}	30.3 mW
P_{Syn}	50 mW
P_{Filt}^{tx}	2.5 mW
P_{Filt}^{rx}	2.5 mW
P_{LNA}	20 mW
P_{IFA}	5 mW

In the *RX Policy*, the antenna mode that has the lowest energy consumption (and the highest lifetime) for the receiver is chosen. The selected antenna mode is fixed throughout the entire communication for a specific receiver-transmitter distance and p_b value. The *TX Policy*, instead, chooses the antenna mode that has the lowest energy consumption, thus returning the highest lifetime, for the transmitter node. We can find the best antenna mode in terms of having the maximum sensor lifetime through the RX policy and TX policy using the following equations,

$$S_{TX} = \text{argmax}_{(M_{tx},M_{rx})}\, L_{tx}^{0}(M_{tx}, M_{rx}) \tag{11}$$

$$S_{RX} = \text{argmax}_{(M_{tx},M_{rx})}\, L_{rx}^{0}(M_{tx}, M_{rx}) \tag{12}$$

It should be noted that for the TX and RX policies, the antenna mode is fixed over time and depends only on the transmission distance, BER p_b and initial energy levels B_{tx}^{0} and B_{rx}^{0}, respectively.

By combining Eq. (11) into Eq. (9), the lifetime of a system that uses the *TX Policy* is given by

$$L_{TX} = \min\{L_{tx}^{0}(S_{TX}), L_{rx}^{0}(S_{TX})\}. \tag{13}$$

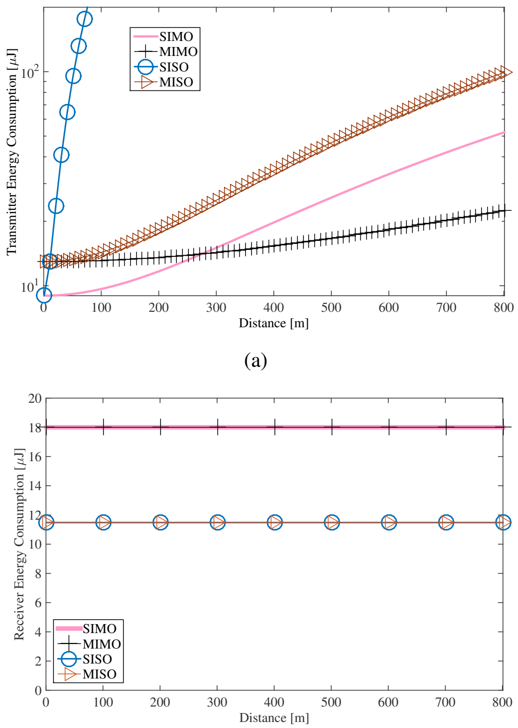
Similarly, by combining Eq. (12) into Eq. (9), the lifetime of a system that uses the *RX Policy* is given by

$$L_{RX} = \min\{L_{tx}^{0}(S_{RX}), L_{rx}^{0}(S_{RX})\}. \tag{14}$$

We note that the TX and RX policies aim to maximize the lifetime of the system by maximizing only the transmitter or receiver lifetime. While the number of antennas to be used for the communication is fixed between different time slots, by additionally including the nodes' battery levels in the selection of the communication schemes, both policies provide longer lifetime to the system when compared to communication protocols that only rely on the distance between the nodes and target BER for the selection of the communication scheme.

V. SIMULATION RESULTS

In this section, we study the performance of the policies presented in Section IV. For all the policies, we provide some insight on the achievable lifetime by varying the transmission distance, BER, and the initial energy in the transmitter and receiver buffer. For all the results of this section, the system parameters are taken from [12]–[15] and listed in Table I for completeness. Moreover, we consider that the nodes are equipped with $M = 2$ antennas and use an orthogonal rate



(a)

(b)

Fig. 1. Transmitter (a) and Receiver (b) energy consumption of MIMO, MISO, SIMO, and SISO antenna modes vs. transmission distance, for $p_b = 10^{-5}$.

1 Alamouti code, which results in $d_m = 1$. Thus, the nodes have the possibility to operate as 2x2 MIMO, 2x1 MISO, 1x2 SIMO, or 1x1 SISO.

We start by analyzing the energy consumptions of the considered MIMO schemes at the transmitter and receiver nodes. Fig. 1 shows the energy consumption of the different communication schemes as a function of the distance and the required target BER $p_b = 10^{-5}$, for the transmitter (Fig. 1(a)) and receiver (Fig. 1(b)). As expected, the power consumption at the receiver is independent from the communication distance and BER (see Eq. (1)). Thus, the receiver energy consumption, as shown in Fig. 1(b), is constant for all the antenna modes and only depends on the number of antennas used by the communication scheme. The transmitter energy consumption, instead, depends on both the transmission distance and BER (see Eq. (2)). It can be noted that, in contrast to the receiver side, the MISO and SISO schemes require a higher energy when compared to MIMO and SIMO. This is because, while the SISO scheme uses a lower number of antennas and thus requires a lower circuit power (see Eq. (3)), most of the transmitter energy is spent on the power amplifier in order to overcome the channel impairments and target the fixed BER. Moreover, the SIMO scheme takes advantage of the additional receiver antennas to improve the packet reception probability, thus requiring, for the same BER, a lower transmission energy.

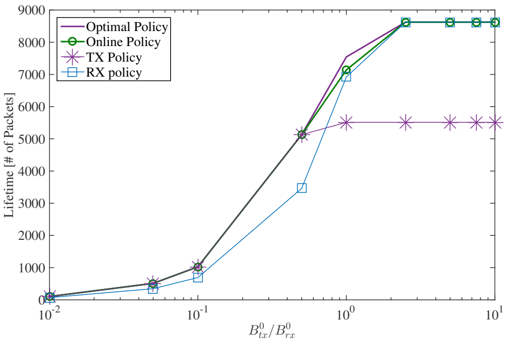
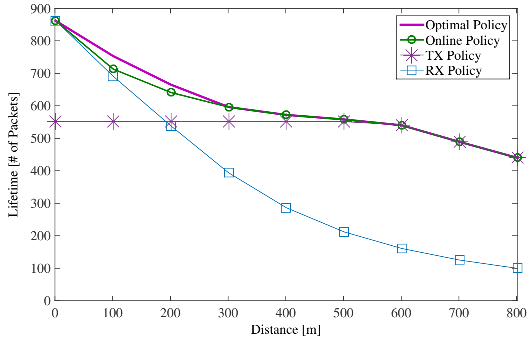


Fig. 2. System lifetime vs. initial energy ratio at the transmitter and the receiver ($d = 100$ m , $P_b = 10^{-5}$).

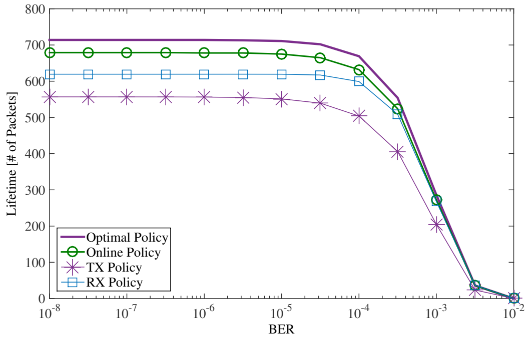
In Fig. 2, we show the impact of the transmitter and receiver initial energy ratio on the system lifetime. As expected, the *Optimal Policy* performs best for all the B^0_{tx}/B^0_{rx}, followed by the *Online Policy* which is able to adapt to the changes in energy levels. The *TX Policy* and *RX Policy*, instead, perform as the optimum schemes for low and high battery ratios, respectively. This is because, as the energy availability of the transmitter (receiver) becomes higher, the receiver (transmitter) becomes the limiting node in the system. Thus, maximizing its lifetime is equivalent to maximizing the lifetime of the system. We note that, for $B^0_{tx}/B^0_{rx} = 1$, the performance gain of the *Optimal Policy* with respect to the other policies is much higher than the other policies compared to the other initial energy ratios. Moreover, the differences between the policies is much more evident for the situation in which the transmitter and receiver nodes have the same amount of energy. Therefore, in what follows, we fix $B^0_{tx} = B^0_{rx} = 10$ J.

Fig. 3 shows the performance of the proposed policies for various communication distances and BER values. As the distance and BER increase, also the system energy consumption increases (see Fig. 1), and thus, the number of successful packets that can be exchanged between the transmitter and the receiver (i.e., system lifetime) consequently decreases. The *Optimal Policy* always provides the highest lifetime for the system but, as the communication distance and BER increase, the other policies attain very close performance. This is because, at high distances and BER, the transmitter and the receiver consume progressively more energy, thus making either the transmitter or the receiver the limiting node.

Finally, we compare the total system lifetime attained by a fixed MIMO scheme with the performance of the *TX Policy* and *RX Policy*. To this end, in Fig. 4, we show the total system lifetime as a function of the transmission distance for a fixed BER (Fig. 4(a)), and as a function of the BER values for a fixed distance (Fig. 4(b)). The *RX Policy* chooses the antenna mode that has the lowest receiver energy consumption for each distance. Thus, as shown in Fig. 1(b), one of the communication schemes with lowest receiver energy consumption (i.e., SISO and MISO) is selected, and the system lifetime is then limited by the transmitter node, which entails a higher energy consumption. The *TX Policy*, instead, selects the antenna mode that has lowest transmitter energy consumption. As illustrated in Fig. 1(a), this policy selects either SIMO

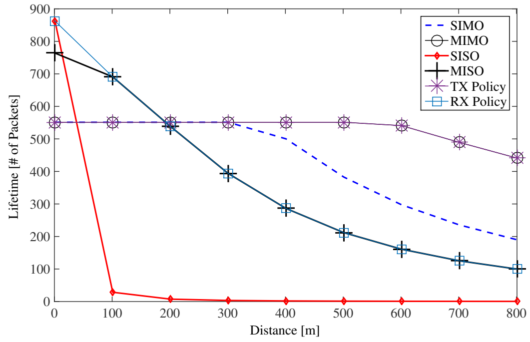


(a) Total lifetime vs. distance ($p_b = 10^{-5}$)

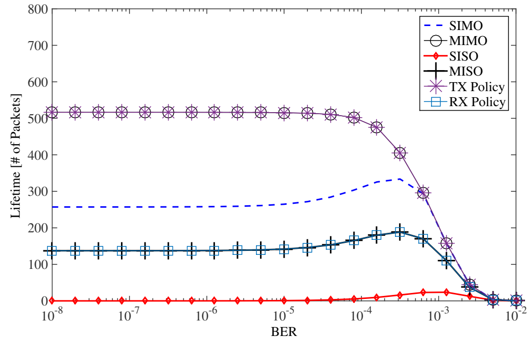


(b) Total lifetime vs. BER ($d = 150$ m)

Fig. 3. System lifetime vs. distance (a) and BER (b) for the *Optimal Policy*, *Online Policy*, *TX Policy*, and *RX Policy*.



(a) Total lifetime vs. distance ($p_b = 10^{-5}$)



(b) Total lifetime vs. BER ($d = 600$ m)

Fig. 4. System lifetime vs. distance (a) and BER (b) for the *TX Policy*, *RX Policy* and a policy that always select a fixed MIMO scheme.

or MIMO at each distance since these two antenna modes have lower transmitter energy consumption than SISO and MISO. Moreover, SIMO and MIMO have the same lifetime when distance is less than 250 m. This is because, in that interval, the total system lifetime is limited by the receiver node that requires a higher energy consumption for receiving the packets. In addition, Fig. 4 shows the impact on the system lifetime of accounting for the nodes' energy levels in the selection of the communication schemes to be used.

VI. CONCLUSIONS

In this paper, we analyzed the transmitter-receiver energy trade-off and propose a new energy balancing model that selects the best communication scheme to be used in a MIMO system, considering the energy of both the transmitter and the receiver. Starting from the formulation of an optimal policy, we then propose three heuristic policies that not only rely on the transmitter and receiver energy consumptions, but also take into account the remaining energy in the nodes' buffers. Our numerical results show that the proposed policies outperform in terms of system lifetime a simple policy that selects a fixed MIMO scheme according to the transmission distances and BER. Moreover, results show that the heuristic policies perform close to the optimal solution, thus making them suitable for implementation in a MIMO-based WSN.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002.
[2] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge University Press, 2003.
[3] L. Dai and Q. Zhou, "Energy efficiency of MIMO transmission strategies in wireless sensor networks," in *Proc. of CCCT*, Aug. 2004.
[4] W. Liu, X. Li, and M. Chen, "Energy efficiency of MIMO transmissions in wireless sensor networks with diversity and multiplexing gains," in *Proc. of ICASSP*, Montreal, Quebec, Canada, May 2005.
[5] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Select. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.
[6] Y. Zhang and H. Dai, "Energy-efficiency and transmission strategy selection in cooperative wireless sensor networks," *Journal of Communication and Networks*, vol. 9, no. 4, pp. 473–481, Dec. 2007.
[7] M. Sadek, A. Tarighat, and A. H. Sayed, "Active antenna selection in multiuser mimo communications," *IEEE Trans. Signal Processing*, vol. 55, no. 4, pp. 1498–1510, Apr. 2007.
[8] M. Z. Siam, M. Krunz, S. Cui, and A. Muqattash, "Energy-efficient protocols for wireless networks with adaptive MIMO capabilities," *Journal Wireless Networks*, vol. 16, no. 1, pp. 199–212, Jan. 2010.
[9] S. K. Jayaweera, "Energy analysis of MIMO techniques in wireless sensor networks," in *Proc. of CISS*, Princeton, NJ, USA, Mar. 2004.
[10] J. G. Proakis, *Digital Communications*. McGraw-Hill, 2000.
[11] T. M. Duman and A. Ghrayeb, *Coding for MIMO Communication Systems*. Wiley, 2007.
[12] M. Steyaert, B. D. Muer, P. Leroux, M. Borremans, and K. Mertens, "Low-voltage low-power cmos-rf transceiver design," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 281–287, Jan. 2002.
[13] T. H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*. Cambridge University Press, 1998.
[14] S. Willingham, M. Perrott, B. Setterberg, A. Grzegorek, and B. McFarland, "An integrated 2.5GHz $\Sigma\Delta$ frequency synthesizer with $5\mu s$ settling and 2 Mb/s closed loop modulation," in *Proc. of IEEE ISSCC 2000*, San Francisco, CA, USA, Feb. 2000.
[15] M. Steyaert, B. D. Muer, P. Leroux, M. Borremans, and K. Mertens, "Low-voltage low-power CMOS-RF transceiver design," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 281–287, 1997.