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MAC-LEAP: Multi-antenna, cross layer, energy adaptive protocol☆

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With the continuous development of wireless networks, energy conservation and energy efficiency are becoming key factors in improving the network lifetime. In multi-antenna wireless networks, the energy conservation problem can be addressed using the trade-off between the transmit power and the circuit energy consumption. In this paper, we propose a cross layer protocol, MAC-LEAP, that selects the best transmission policy based on Multiple-Input Multiple-Output (MIMO) in both single-hop and multi-hop wireless networks. Various data transmission algorithms are presented in which many factors are considered in order to find the best transmission policy between each pair of nodes. An RTS/CTS handshake is used to exchange the required information to select the best transmission policy prior to data transmission. Moreover, we introduce a MIMO-based framework in Network Simulator 3 (ns-3) in which the wireless nodes may be equipped with more than one antenna. Using extensive simulations in ns-3, we compare the performance of MAC-LEAP with traditional protocols in terms of the network lifetime and the number of received packets. The simulation results show that MAC-LEAP outperforms the traditional protocols in both single-hop and multi-hop networks for various transmission distances and target Bit-Error-Rates (BER).

1. Introduction

In wireless networks, reducing the energy dissipation is paramount in order to extend the lifetime of the network. One approach to reducing the energy required for communication is to employ Multiple-Input Multiple-Output (MIMO) or multi-antenna communication [1–3]. This communication paradigm is not only a promising solution for improving the spectral efficiency, but it additionally improves the overall energy efficiency of wireless networks. Using MIMO communications, the transmit power is spread among more than one antenna that, for a particular Bit-Error-Rate (BER) requirement, results in an overall higher power gain, therefore improving the spectral efficiency [4].

While previous work has shown the benefit of using adaptive MIMO communications in wireless networks [5–7], none of these previous work has addressed the problem of energy conservation. An essential factor in reducing the node energy consumption lies in the trade-off between the transmit power and the energy consumption of the transmitter circuit. Although multi-antenna systems require a complex transceiver circuitry design that entails a high power consumption at the circuit level, using multiple antennas enables a reduction in the actual power consumption of the power amplifier thanks to the increased spectral efficiency. As a result, both the circuit power consumption and the transmit power consumption must be considered together in order to optimize the energy consumed by the communication link [8].

A number of researchers have developed approaches to optimize multi-antenna networks by selecting the optimal MIMO scheme to use for communication. Different antenna selection algorithms can be employed at both the transmitter and the receiver sides in order to choose the number of antennas based on the channel Signal-to-Noise Ratio (SNR), the system capacity, and spatial diversity [9]. For example, in a multi-user MIMO system, by considering a signal-to-interference plus noise ratio (SINR) threshold that must be met, one possible solution is to select the number of antennas that maximizes the SINR of the worst above-the-threshold user [10]. Alternatively, the number of antennas can be chosen dynamically for each node based on their transmission distance to minimize the total energy consumption [11] or based on the Channel State Information (CSI) [12,13]. If no CSI feedback is available at the transmitter, as is the case for the cross-layer protocol presented in [8] that dynamically switches between MIMO and Single-Input Multiple-Output (SIMO) communications, the number of antennas is determined by the receiver and sent back to the sender.

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In this paper, we present Multi-Antenna, Cross Layer, Energy Adaptive Protocol (MAC-LEAP), which is an energy efficient cross layer protocol designed for MIMO-based wireless networks that employs dynamic antenna selection to use the most energy efficient approach for data transmission. MAC-LEAP dynamically adjusts the number of transmitter and receiver antennas to use for the communication on a per-packet basis, based on the current remaining energy of the nodes, their distance, BER requirements, and other physical layer parameters. Based on a standard CSMA/CA protocol, MAC-LEAP utilizes Request-To-Send (RTS) and Clear-To-Send (CTS) packets to provide collision avoidance. Information regarding the transmitter location and current energy, which is required for the dynamic antenna selection, is included in the RTS packet. Using this information, MAC-LEAP runs a dynamic antenna selection algorithm at the receiver to find the most energy efficient MIMO scheme that provides the highest link lifetime. The receiver piggybacks this information onto the CTS packet so that both nodes know what MIMO scheme to use for the subsequent data transmission.

Unlike traditional protocols that use a fixed number of antennas for a specific distance and channel BER, MAC-LEAP adapts the MIMO scheme to be used for the communication according to the current remaining energy levels of both the transmitter and receiver nodes. The specific contributions of this paper are:

- We propose various dynamic antenna selection policies that consider the immediate remaining energy of the nodes as well as other factors such as distance and BER. Based on the energy level of the transmitting and receiving nodes, the algorithm selects the number of antennas that maximizes the link lifetime.
- The dynamic antenna selection policies are integrated in a cross layer protocol, MAC-LEAP, which selects the best set of antennas on a per-packet basis for the communication for both single-hop and multi-hop networks. The protocol selects the most energy-efficient MIMO scheme for both the transmitter and the receiver and uses the RTS/CTS handshake to transfer some information required by the dynamic antenna selection policy prior to the data transmission.
- We introduce a MIMO-based framework for wireless communication into Network Simulator 3 (ns-3), which, to the best of our knowledge, has not been implemented before. Based on this framework, wireless nodes in the ns-3 simulator may use more than one antenna for MIMO communication.

The remainder of the paper is organized as follows. In Section 2, we provide a review of related work in the area of MIMO technology in wireless networks. In Section 3, we present the energy consumption model of MAC-LEAP as well as the equations for meeting the BER requirements in MIMO channels. In Section 4, we describe different dynamic antenna selection policies employed in MAC-LEAP, and in Section 5, we introduce the proposed MAC-LEAP protocol. In Section 6, we compare the performance of MAC-LEAP with both fixed antenna schemes (e.g., MISO) and the E-Basic protocol [11] via extensive simulations, and discuss the results and the improvement of MAC-LEAP compared to these other protocols. Finally, conclusions are drawn in Section 7.

2. Motivation and Related Work

In contrast to Single-Input Single-Output (SISO) systems, Multiple-Input Multiple-Output (MIMO) systems employ more than one antenna at both the transmitter and the receiver. Thus, MIMO provides two main advantages for the wireless communications: spatial diversity gain and spatial multiplexing gain. The spatial multiplexing gain is obtained by extending the degrees of freedom by sending multiple orthogonal data streams simultaneously [14] which results in having a higher data rate in the system. The second benefit of MIMO, which is the spatial diversity gain, is obtained from the fact that each transmitter will send the same stream of data with more than one antenna, which increases the probability of having a reliable signal at the receiver side in order to combat fading.

As the diversity-multiplexing trade-off is discussed in many papers [15–17], both of these gain factors are simultaneously achievable at some level. Besides the above benefits of MIMO, this technology is also an energy efficient solution for wireless networks that have a limited amount of energy. Several studies have explored the issue of energy efficiency in MIMO wireless networks. In [18], 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 systems. The energy trade-off between SISO and MIMO systems is also analyzed in [19] in which it is demonstrated that a MIMO transmission performs better than SISO in terms of energy efficiency for long-range communications and vice versa for short-range communications. The protocols presented in [18] and [19] consider a fixed MIMO scheme for exchanging multiple packets between two nodes, 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.

Energy adaptation in MIMO wireless networks, which is essential for network lifetime maximization, can be applied not only at the physical layer but also at the MAC layer. In [20], a MAC protocol based on MIMO is proposed to eliminate the interference and collisions in wireless networks. With nodes equipped with multiple antennas, the transmitter uses only half of its antennas for the transmission and keeps the other half free for another simultaneous transmission in order to have collision-free communication. In [21], a MAC protocol is presented for ad-hoc networks with MIMO links, where the authors focus on the fair channel allocation problem.

In [22], the physical and MAC layers collaborate to exchange channel state information (CSI) for effective data communication. In [23], two separate error-free channels are considered for data packets and control packets. Each control packet carries the CSI and the number of antennas used by the node for the next packet transmission/reception. However, the selection of the number of antennas in [23] is not based on energy efficiency of the nodes. If no-CSI feedback is available to the transmitter such as the cross-layer protocol introduced in [8], the number of antennas should be decided by the receiver and sent back to the sender. The proposed protocol in [8] switches between MIMO and Single-Input Multiple-Output (SIMO) to achieve higher energy efficiency, which is more significant when the channels are correlated.

In [24], a clustering MAC protocol based on cooperative MIMO is proposed in which the cluster heads and all the nodes except the cooperative MIMO nodes (a subset of nodes within the cluster) use one antenna for communications. The inter-cluster packet transmission utilizes SISO, MIMO, and MISO communications which are fixed and chosen based on the node type (whether a node is a cooperative MIMO node or not) and not their energy or communication distance.

In [11] the energy and distance are taken into account in MIMO-based data transmission. The authors present E-Basic, a MIMO-adaptive CSMA/CA-based protocol in which the number of antennas is chosen on a per-packet basis based on the transmission distance and the total power consumption of the transmitter and the receiver. For every pair of nodes along a multi-hop communication path, E-Basic selects the MIMO scheme that minimizes the total energy consumption and uses this scheme for data transmission. For non-data packets, such as RTS, CTS, and ACK, E-Basic uses a fixed MIMO scheme for the communication. Although E-Basic aims at minimizing the total link power consumption, it does not focus on optimizing the power efficiency of the system while providing an energy consumption balance among the nodes. Moreover, E-Basic uses a fixed MIMO scheme for a specific distance and BER for the communication, regardless of the nodes' remaining energy.

The aforementioned communication protocols employed a fixed MIMO scheme for a particular transmission distance and BER and do not take into account the remaining energy of the nodes. Moreover, maximizing the network lifetime using a fixed 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, while at the transmitter side, the situation is reversed. Thus, in order to maximize the lifetime of the network, the transmitter and receiver remaining energies need to also be included in the selection of the most energy-efficient communication scheme. For this purpose, the energy consumption of the wireless nodes should be adapted according to the network requirements.

In [25], we considered the energy trade-off between the transmitter and the receiver for different MIMO schemes and presented 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 policy attains 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. In this paper, we extend the antenna selection model in [25] and proposed MAC-LEAP which is designed for both single-hop and multi-hop networks. Moreover, MAC-LEAP selects the most energy efficient MIMO scheme by using RTS/CTS hand-shake for transferring some information among the nodes.

To the best of our knowledge, none of the previous MIMO-based protocols selects the number of antennas adaptively for a specific distance and channel BER, and by considering the nodes' remaining energy. In MAC-LEAP, we address this issue by considering the nodes' remaining energy as well as their distance and the channel BER in selecting the most energy-efficient number of antennas for both the transmitter and the receiver. As a result, the number of antennas for the nodes is selected such that the energy level of the nodes is balanced, meaning that no node runs out of energy while the other node battery has energy to spare. In MAC-LEAP, the receiver node selects the most energy-efficient number of antennas for data transmission on a per-packet basis, during the RTS/CTS handshake.

3. System Model

In this section, we present the energy consumption model and the data transmission scheme employed in MAC-LEAP to meet a required BER. In the rest of the paper, we assume that each node is equipped with two antennas, and may use a different number of antennas adaptively for their communication. The number of antennas is selected such that the total number of received packets in the network is maximized. The required information for the antenna selection is transferred among the nodes using the MAC layer RTS/CTS packet exchange.

3.1. Energy Consumption Model

Consider a single hop communication link with a transmitter node *tx* and a receiver node *rx*. The nodes are powered through a battery, and the remaining energy of the transmitter and the receiver nodes at time *t* are defined as B^t_{tx} and B^t_{rx}, respectively. The nodes are equipped with $M = 2$ antennas and have the possibility to operate using $M_{tx} \times M_{rx}$ MIMO, with $M_{tx}, M_{rx} \in \{1, 2\}$, depending on the number of antennas selected at the transmitter and the receiver (i.e., 2×2 MIMO, 2×1 MISO, 1×2 SIMO and 1×1 SISO). Moreover, we consider a Rayleigh fading channel, and we design our system based on the IEEE 802.11 protocol with a fixed data rate and BPSK modulation. By sending or receiving a packet, the node energy will be reduced depending on the energy consumed by that packet. In this perspective, the node number of antennas, the communication distance, the channel BER, the data rate, and the node current operation state (e.g., Idle, Reception, Transmission, or Sleep) are the most important factors that determine the energy consumption. In what follows, we describe the energy consumption model used in the physical layer of MAC-LEAP.

As mentioned previously, the nodes are battery powered with initial energy levels B^0_{tx} and B^0_{rx} at the transmitter and the receiver, respectively. By sending or receiving a packet at time *t*, the residual energy stored in the devices (i.e., B^t_{tx} and B^t_{rx}) 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^{rx}_C) while at the transmitter side, it is consumed by both the transmitter circuit (P^{tx}_C) and the Power Amplifier (P_{PA}). We consider the circuit blocks of the receiver and the transmitter as discussed in [25].

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

$$P^{rx}_C(M_{rx}) = M_{rx}(P_{\mathrm{ADC}} + P_{\mathrm{Mix}} + P^{rx}_{\mathrm{Fil}} + P_{\mathrm{Dem}} + P_{\mathrm{IFA}} + P_{\mathrm{LNA}}) + P_{\mathrm{Syn}}, \tag{1}$$

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

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

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

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

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^{tx}_{Fil} represents the power consumption of the transmitter filter circuit. The power consumption of the power amplifier $P_{\mathrm{PA}}(M_{tx}, M_{rx})$ depends on the transmission power P_{out} and the modulation scheme [26], and is expressed as

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

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 (i.e., $K = 2$). Moreover, the transmission power P_{out} can be calculated using the following formula [27]:

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

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, in a BPSK $M_{tx} \times M_{rx}$ MIMO system. The description of BER vs. SNR for a MIMO Rayleigh fading channel is presented in Section 3.2. 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

$$E^X_{\text{pkt}}(M_{tx}, M_{rx}) = \frac{P_X(M_{tx}, M_{rx})}{R_b} N, \tag{6}$$

where $X \in \{tx, rx\}$. Given the per packet energy consumptions $E^{tx}_{\text{pkt}}(M_{tx}, M_{rx})$ and $E^{rx}_{\text{pkt}}(M_{tx}, M_{rx})$, the maximum number of packets that can be processed by the nodes using a $M_{tx} \times M_{rx}$ MIMO scheme at time t is

$$L^t_X(M_{tx}, M_{rx}) = \frac{B^t_X}{E^X_{\text{pkt}}(M_{tx}, M_{rx})}, \tag{7}$$

where $X \in \{tx, rx\}$. Thus, the maximum number of packets that can be received is given by

$$L^t(M_{tx}, M_{rx}) = \min\{L^t_{tx}(M_{tx}, M_{rx}), L^t_{rx}(M_{tx}, M_{rx})\}. \tag{8}$$

The receiver is responsible for calculating the number of packets based on the selected policy for the communication and sending the selected MIMO scheme to the transmitter.

3.2. BER Requirement in MIMO Rayleigh Fading Channel

In this section we derive the formula for channel BER in a MIMO communication. Assuming a Rayleigh fading channel in a $M_{tx} \times M_{rx}$ MIMO system, the input-output relationship is given by [28]:

$$y = \sqrt{\rho}\, Hx + n$$

where the constant ρ is the signal-to-noise ratio (SNR) at each receive antenna, y is the $M_{rx} \times 1$ received signal vector, x is the $M_{tx} \times 1$ transmitted signal vector, n is the $M_{rx} \times 1$ Gaussian noise vector with zero mean and variance of 1/2, and H is the $M_{rx} \times M_{tx}$ channel transfer matrix.

For $1 \times M_{rx}$ SIMO where Maximal Ratio Combining (MRC) is employed in the channel, for $2 \times M_{rx}$ MIMO/MISO Alamouti Space Time Block Codes (STBC) [29], and for 1×1 SISO communication, we will analyze the achieved BER assuming a Rayleigh fading channel. Using a BPSK modulation, the BER conditioned on the channel gains is given by [30]:

$$P_\alpha(\alpha) = Q\left(\sqrt{\frac{2\alpha\rho}{M_{tx}}}\right), \tag{9}$$

where $\alpha = h^T h = \sum_{i=1}^{M_{rx}} \sum_{j=1}^{M_{tx}} |h_{i,j}|^2$ is the summation of the channel powers across all receiving antennas. Since $h_{i,j}$ follows a Rayleigh fading distribution, α follows a chi-square distribution with $2M_{tx}M_{rx}$ degrees of freedom and a probability density function (pdf) of

$$f_\alpha(\alpha) = \frac{\alpha^{(M_{tx}M_{rx}-1)} e^{-\alpha}}{(M_{tx}M_{rx}-1)!}, \quad \alpha > 0. \tag{10}$$

Thus, the average BER of the channel is

$$p_b = \mathbb{E}[P_\alpha(\alpha)] = \int_0^\infty Q\left(\sqrt{\frac{2\alpha\rho}{M_{tx}}}\right) f_\alpha(\alpha) d_\alpha. \tag{11}$$

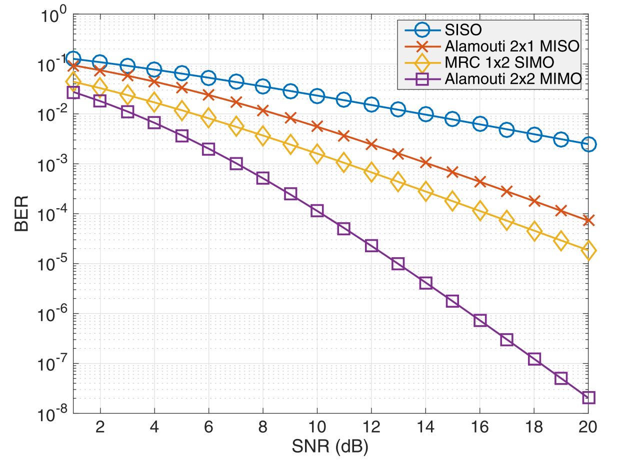


Fig. 1. BER versus SNR for MIMO, MISO, SIMO, and SISO.

By substituting Eq. (10) in Eq. (11) and solving the integral, we obtain the BER of the channel as [28]:

$$p_b = \left(\frac{1}{2}(1-\zeta)\right)^L \cdot \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left(\frac{1}{2}(1+\zeta)\right)^l, \tag{12}$$

where $L = M_{tx}M_{rx}$ and $\zeta = \sqrt{\frac{\rho/M_{tx}}{1+\rho/M_{tx}}}$.

Moreover, with the special case of 1×1 SISO communication with no diversity, we obtain the BER of a Rayleigh fading channel as

$$p_b = \frac{1}{2}\left(1 - \sqrt{\frac{\rho}{1+\rho}}\right). \tag{13}$$

Using *Eq.* (12), we can find the BER versus SNR (ρ) for different MIMO schemes in a Rayleigh fading channel with BPSK modulation, as shown in Fig. 1.

3.3. Transmitter-Receiver Energy Tradeoff

As derived above, when a transmitter node sends a packet to a receiver node, the amount of energy consumed for the transmission and reception of the packet depends on the number of antennas used by the nodes. The energy consumption of the transmitter and the receiver nodes in a single communication link is shown in Fig. 2 for various distances, and in Fig. 3 for various BERs. We note that, according to the 802.11n standard that uses MIMO communications, the wireless nodes' outdoor coverage is 250 m [31].

The receiver energy consumption depends only on the number of antennas so it remains constant as distance and target BER vary. As shown in Fig. 2(b) and Fig. 3(b), SISO and MISO, which are two schemes that employ one antenna to receive the data, have lower receiver energy consumption than MIMO and SIMO in which more than one antenna is used at the receiver side. Although SISO and MISO consume less energy than MIMO and SIMO, they have higher transmit power. Since the transmitter energy consumption depends on many parameters including the distance, BER, and the number of antennas, its value changes as distance and BER vary. As demonstrated in Fig. 2(a), in distances smaller than 5 m, when the transmitter node uses one antenna to send the data (SISO and SIMO), its energy consumption is lower than using two antennas (MIMO and MISO).

Considering a fixed distance between two nodes, as shown in Fig. 3(a), the transmitter consumes less energy by using SIMO in high target BER. However, as BER decreases, MIMO is a better option in terms of the transmitter energy consumption compared to the other three antenna modes.

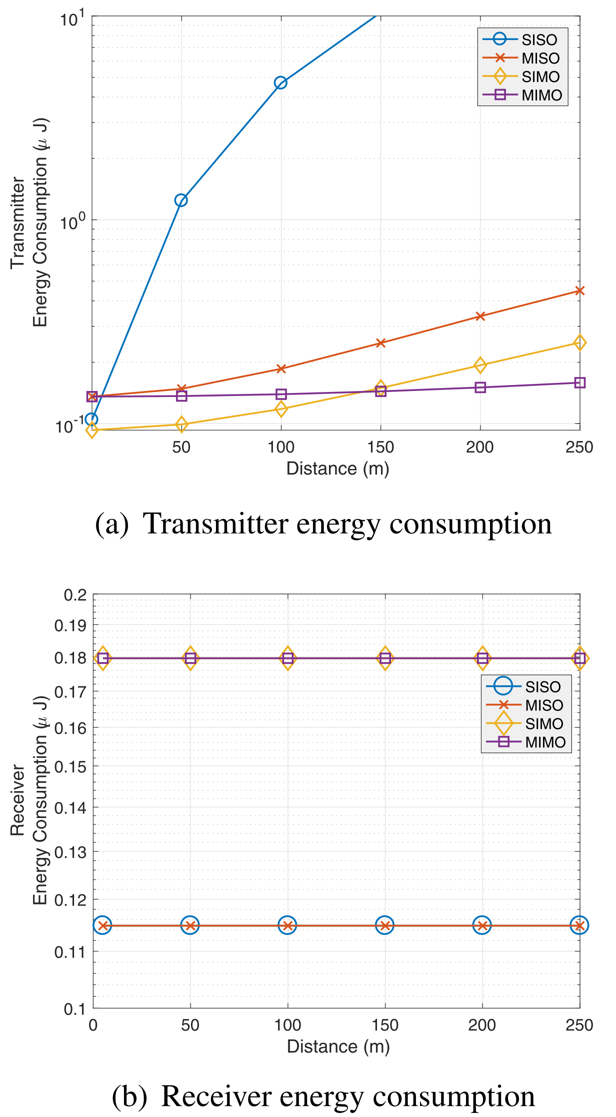


Fig. 2. Energy consumption per bit for (a) the transmitter node and (b) the receiver node for different distances (BER=10^{-5}).

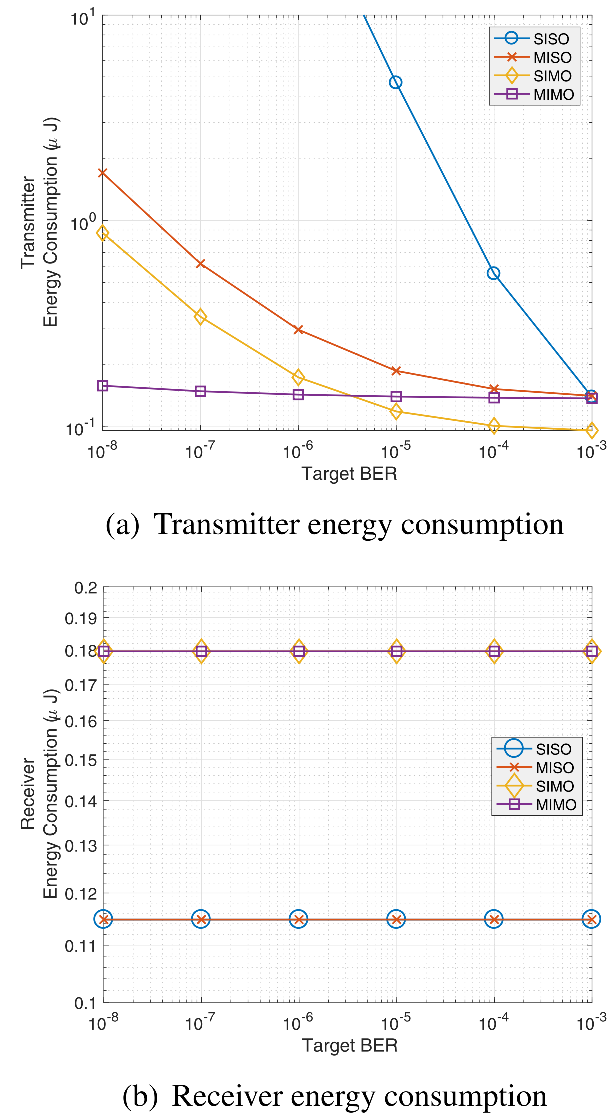


Fig. 3. Energy consumption per bit for (a) the transmitter node and (b) the receiver node for different target Bit-Error-Rates (distance = 100 m).

According to Fig. 2(b) and Fig. 3(b), depending on the number of antennas at the nodes, their distance or the target BER, the employed MIMO scheme can be energy efficient either for the transmitter or the receiver. For instance, although SISO is more energy efficient than MIMO at the receiver side, it is not a very good option at the transmitter for long-distance communications. This energy trade-off between the transmitter and the receiver, raises the question of which MIMO scheme is more beneficial to use in the wireless networks. MAC-LEAP exploits this energy consumption trade-off to find the most energy efficient number of antennas pair for the transmitter side and the receiver side.

4. Dynamic Antenna Selection Policies

In a wireless 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 provides a balance between the energy consumption at the transmitter and the receiver. We then present 3 heuristic policies, namely *Online Policy*, *TX Policy* and *RX Policy*, with different complexities and requirements in term of information that needs to be exchanged between the nodes.

4.1. Optimal Policy

The main goal of *Optimal Policy* is to maximize the total number of received packets and simultaneously minimize the total energy consumption with respect to both the transmitter and receiver lifetimes. It is assumed that an RTS/CTS handshake is used before sending the data. To this end, the optimal antenna selection policy can be defined as the solution of the following combinatorial optimization problem:

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

s.t.

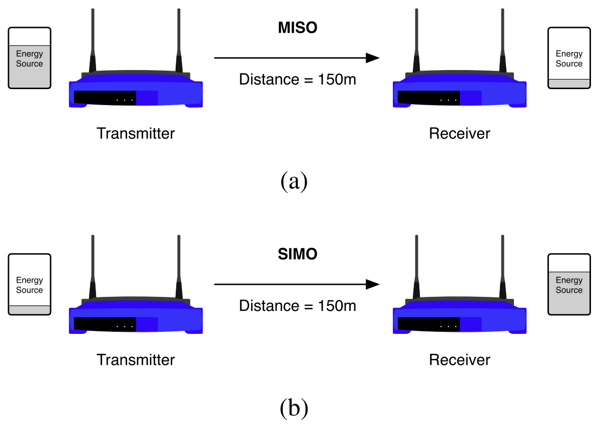


Fig. 4. An example of how MAC-LEAP works in a single communication link when (a) the transmitter's energy is higher, and (b) the receiver's energy is higher.

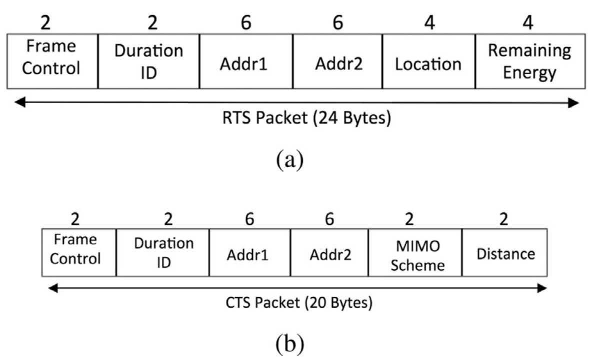


Fig. 5. The fields and the size (in bytes) of (a) the RTS packet, and (b) the CTS packet in the MAC-LEAP protocol.

$$\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E^{tx}_{\mathrm{PKT}} \leq B^0_{tx}$$
$$\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E^{rx}_{\mathrm{PKT}} \leq B^0_{rx} \tag{14}$$

where

$$E^{tx}_{\mathrm{PKT}} = E^{tx}_{\mathrm{RTS}} + E^{rx}_{\mathrm{CTS}} + E^{tx}_{\mathrm{DATA}}(M_{tx}, M_{rx}) + E^{rx}_{\mathrm{ACK}}$$
$$E^{rx}_{\mathrm{PKT}} = E^{rx}_{\mathrm{RTS}} + E^{tx}_{\mathrm{CTS}} + E^{rx}_{\mathrm{DATA}}(M_{tx}, M_{rx}) + E^{tx}_{\mathrm{ACK}}$$

$E^{\mathrm{X}}_{\mathrm{RTS}}$, $E^{\mathrm{X}}_{\mathrm{CTS}}$, $E^{\mathrm{X}}_{\mathrm{DATA}}(M_{tx}, M_{rx})$, and $E^{\mathrm{X}}_{\mathrm{ACK}}$ represent the transmitter (X=tx) and the receiver (X=rx) energy consumptions when an RTS packet, a CTS packet, a DATA packet with M_{tx}xM_{rx} MIMO scheme, and an ACK packet are transferred, respectively. The value of $\alpha_{M_{tx},M_{rx}}$ represents the number of packets that are exchanged by the $M_{tx} \times M_{rx}$ 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 and thus the number of received packets will be maximized. Moreover, RTS, CTS, and ACK packets are transmitted with a fixed multi-antenna scheme (e.g. MISO) at maximum distance and thus, they have fixed energy consumption values for all packets.

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 (14) can be computationally intensive as the number of antennas increases. However, when the number of communication schemes is small, like in our case, Mixed Integer Linear Programming (MILP) algorithms can efficiently solve the problem in a small amount of time.

4.2. 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. In the *Online Policy*, for a specific p_b and at a fixed transmitter-receiver distance, we compute the number of received packets in the system for all 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 $M^t_{tx} \times M^t_{rx}$ that results in having the highest number of received packets for the system, according to Eq. (8). 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., $B^{t+1}_{tx} = B^t_{tx} - E^{tx}_{\mathrm{pkt}}(M^t_{tx}, M^t_{rx})$ and $B^{t+1}_{rx} = B^t_{rx} - E^{rx}_{\mathrm{pkt}}(M^t_{tx}, M^t_{rx})$).

The aforementioned process for dynamic antenna selection in the online policy is applied only for the data packets. The number of antennas employed for transferring the RTS, CTS, and ACK packets is fixed for all distances and BER values among the nodes.

We note that, unlike the *Optimal Policy* that 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.

4.3. RX and TX Policies

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

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 BER value.

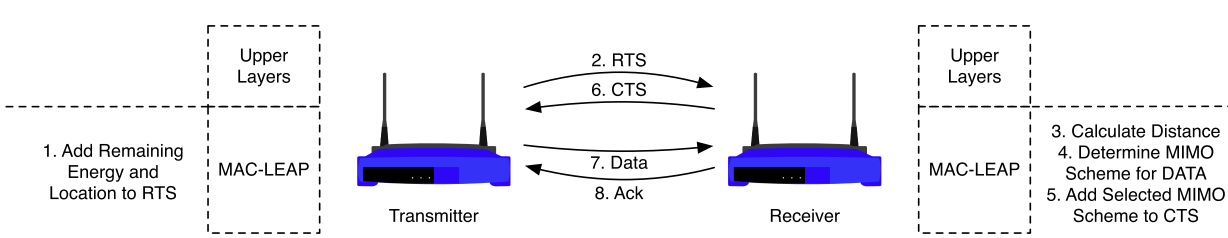


Fig. 6. An example of how MAC-LEAP works in a single communication link.

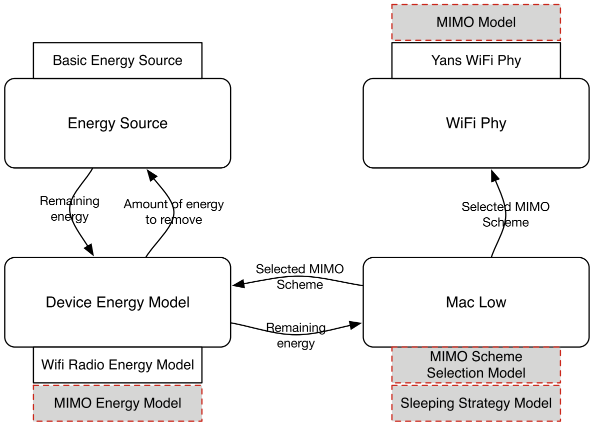


Fig. 7. Wireless MIMO framework in ns-3.

Table 1
Simulation parameters.

General parameters	
k	2
f_c	5.15 GHz
N	2000 bytes
N_f	10 dB
N_0	−174 dBm/Hz
$G_t = G_r$	2 dB
η	0.35
M_l	10dB
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
WiFi parameters	
WiFi node's range	250 m
Fixed MIMO scheme	MISO
Number of nodes	9
Initial energy	5 J
Minimum required energy	0.1 J
R_b	1Mbps
R_g	50kbps
B	22MHz

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 number of received packets through the TX policy and the RX policy using the following equations,

$$S_{TX} = \text{argmax}_{(M_{tx}, M_{rx})} L_{tx}^0 (M_{tx}, M_{rx}) \tag{15}$$

$$S_{RX} = \text{argmax}_{(M_{tx}, M_{rx})} L_{rx}^0 (M_{tx}, M_{rx}) \tag{16}$$

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. (15) into Eq. (8), the maximum number of received packets in a system that uses the *TX Policy* is given by

$$L_{TX} = \min\{L_{tx}^0(S_{TX}), L_{rx}^0(S_{TX})\}. \tag{17}$$

Similarly, by combining Eq. (16) into Eq. (8), the maximum number of received packets in a system that uses the *RX Policy* is given by

$$L_{RX} = \min\{L_{tx}^0(S_{RX}), L_{rx}^0(S_{RX})\}. \tag{18}$$

We note that the TX and RX policies aim to maximize the lifetime of the system and the number of received packets 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. Moreover, similar to the online policy, the number of antennas used for transmitting the RTS, CTS, and ACK packets is fixed for all distance and BER values among the nodes in the TX and RX policies.

5. MAC-LEAP

In this section, we describe the details of the MAC-LEAP protocol.

5.1. Protocol Overview

As shown in Figs. 2 and 3, depending on the distance and BER, the transmitter energy consumption of SISO, MISO, SIMO, and MIMO are different while the receiver energy consumption depends only on the number of receiver antennas, and hence it is constant over various distances and BERs. Based on the communication distance and the number of antennas, one of these four MIMO schemes is the most energy efficient to use.

Consider the sample scenario shown in Fig. 4 in which we have two nodes with a distance of 150 m. The traditional methods choose the MIMO scheme with the least energy consumption and send the packets with the same scheme during the communication until one of the nodes runs out of energy. In MAC-LEAP, however, there is also another factor that plays an important role in making the decision for the number of antennas; the nodes' remaining energy. Based on the remaining energy of the nodes, the most energy efficient MIMO scheme is selected for the communication, and this MIMO scheme will be changed according to the nodes' remaining energy over time.

In the example shown in Fig. 4, MAC-LEAP uses MISO and SIMO interchangeably depending on several factors including the nodes' remaining energy. When the receiver has much lower remaining energy than the transmitter, MAC-LEAP chooses MISO (Fig. 4(a)) while when the transmitter has lower remaining energy than the receiver, SIMO is chosen (Fig. 4(b)). Using MISO, the receiver consumes less energy since it employs only one antenna, but the transmitter consumes more energy compared to the SIMO scheme. By employing dynamic antenna selection for energy adaptation in MAC-LEAP, a balance is provided between the transmitter and the receiver energy consumption, which increases the system lifetime.

5.2. Protocol Description

To minimize collisions among the transmitted packets in the network, we use channel sensing in the MAC layer. Based on the IEEE 802.11 Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), the transmitter node requests the channel before sending data by transmitting a RTS packet to the receiver. If the RTS is correctly received, the receiver node replies by sending a CTS packet back to the sender. By receiving the CTS packet, the transmitter realizes that the channel is free and the data packet will be sent. Finally after receiving the data packet, the receiver sends back an ACK packet.

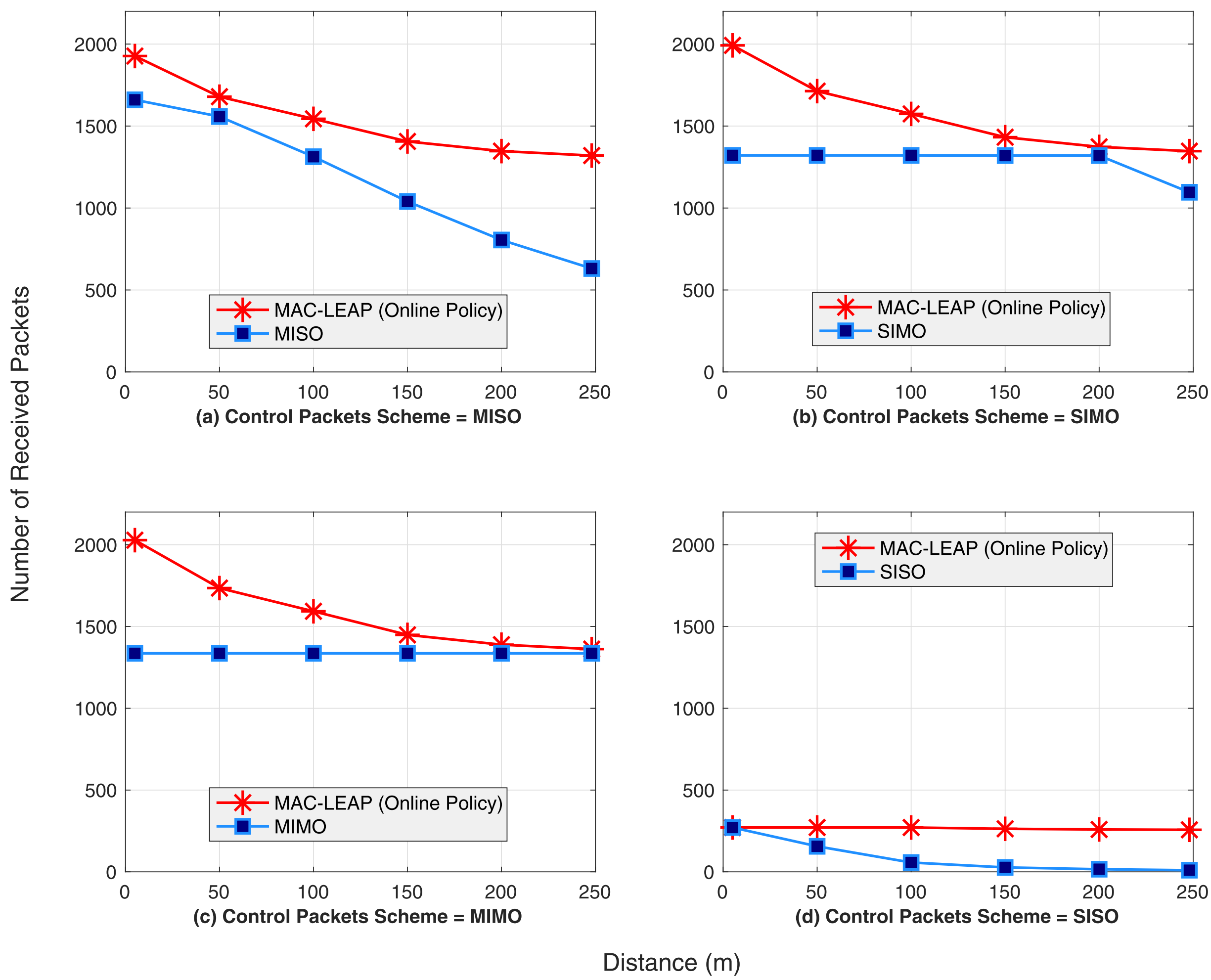


Fig. 8. Number of received packets versus distance for four different fixed schemes used for sending control packets in a single communication link: (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO (Target BER= 10^{-5}).

Since the energy consumption model described in Section 3 is used to calculate the best number of antennas for data transmission, it requires knowledge of the nodes' distance and remaining energy. This information is transferred among the nodes using the MAC layer. For a specific communication link, the receiver is responsible for finding the most efficient MIMO scheme. Thus, the transmitter must send its information to the receiver before the data transmission. The required information is passed through the RTS packet to the destination. Finding the MIMO scheme at the receiver side, the transmitter is notified about the number of antennas for data transmission through the CTS packet. The fields for the RTS and the CTS packets in MAC-LEAP are shown in Fig. 5.

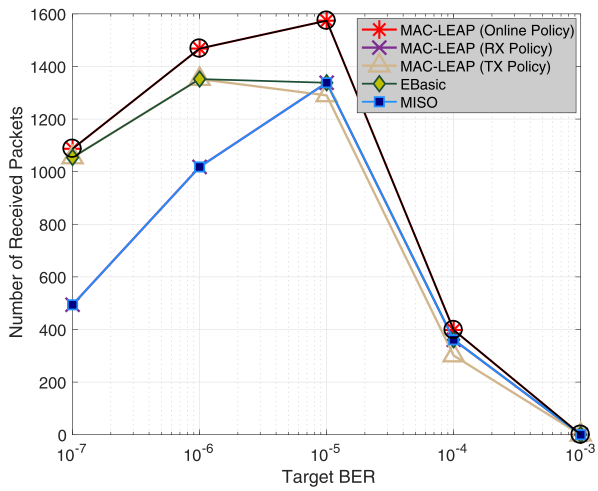
In MAC-LEAP each node is equipped with a non-rechargeable energy source (e.g., a battery). As demonstrated in Fig. 6, the transmitter node sends its remaining energy as well as its location in the RTS packet; the receiver node retrieves its own remaining energy from the energy source and calculates the distance between the nodes. Using this calculated distance and the remaining energy of both nodes, the node selects the MIMO scheme to use for data communication according to one of the policies described in Section 4, and sends this information to the transmitter through the CTS packet. Then, the data packet is transmitted by the sender using the selected MIMO scheme.

Moreover, a sleeping strategy is also implemented in MAC-LEAP, which results in reducing the energy consumption of the nodes during their idle listening. During the idle listening state, the nodes are active but either they are not transmitting or receiving packets, or they may receive some packets that are destined for another node. Therefore, if a node receives an RTS or CTS packet destined for another node, the node sets its Network Allocation Vector (NAV) and switches into the sleep mode for the duration of the NAV to save energy.

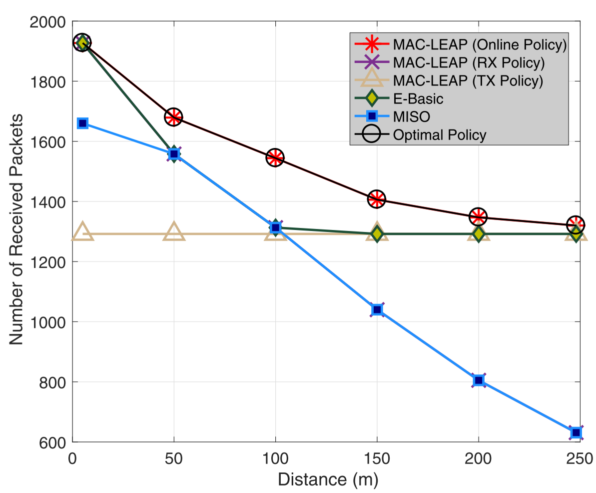
5.3. Ns-3 Implementation

Ns-3 is a popular network simulator [32]. However, ns-3 does not support multi-antenna for wireless communications. In this work, we extend the ns-3 WiFi, wireless channel and energy models to support MIMO communications. In Fig. 7, we present the proposed ns-3 extensions, where the modules developed to support MIMO communication are highlighted with dashed red lines. Some of the ns-3 modules that are employed in this work are described below.

- *Energy Source:* This module stores the energy of the node, decreases the amount of consumed energy from the remaining energy, and notifies the node about its current energy. It also notifies the node if the energy sources is drained or recharged. Different implementations of energy source, such as a basic energy source, lithium ion battery, or RV battery, are provided with ns-3.
- *Device Energy Model:* This module describes the energy that is required to power a particular device. In this module, the en-



(a) Number of received packets versus target BER (Distance=100 m).



(b) Number of received packets versus distance (Target BER=10^{-5}).

Fig. 9. Number of received packets versus (a) target BER and (b) distance in a single communication link with two nodes.

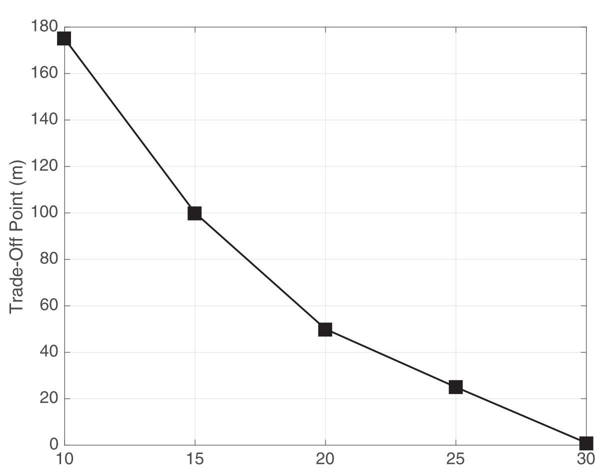
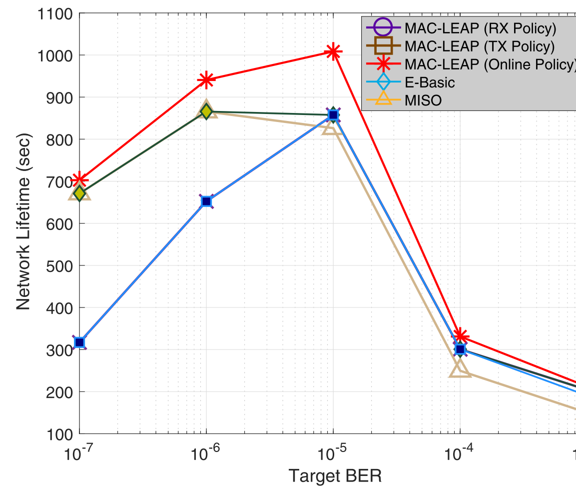
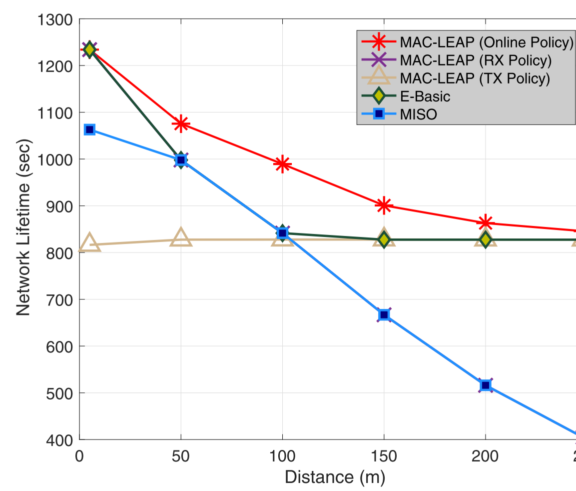


Fig. 10. Trade-off point between TX and RX policies versus link margin in a single communication link with two nodes.



(a) Network lifetime versus target BER (Distance=100 m).



(b) Network lifetime versus distance (Target BER=10^{-5}).

Fig. 11. Network lifetime versus (a) target BER and (b) distance in a single communication link with two nodes.

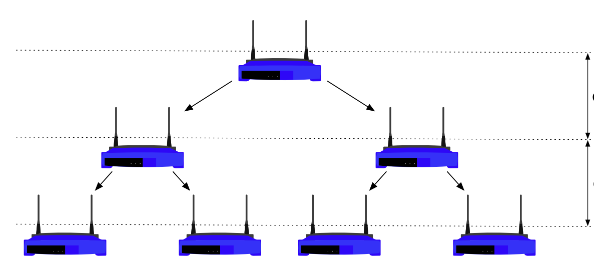
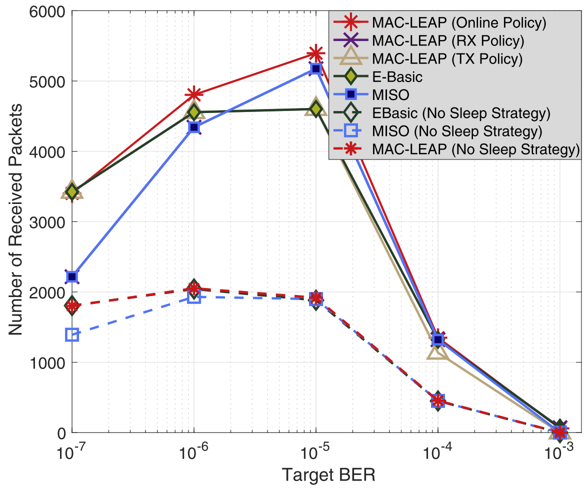
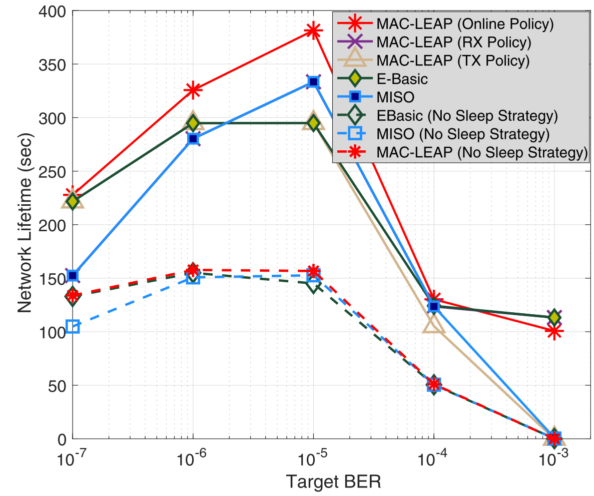


Fig. 12. Binary Tree network topology with height of every level equal to distance d.

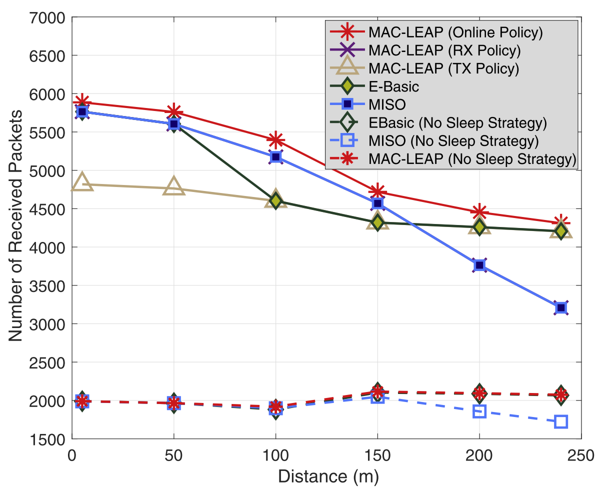
ergy consumption is calculated based on the current state of the device. It is connected to the *Energy Source* in order to decrease the Energy Source's residual energy. The energy consumption of the wireless communication is implemented in ns-3 by the WiFi Radio Energy Model. This model is designed for a WiFi radio device and calculates the energy consumption based on the different radio states such as idle, sleep, busy, transmis-



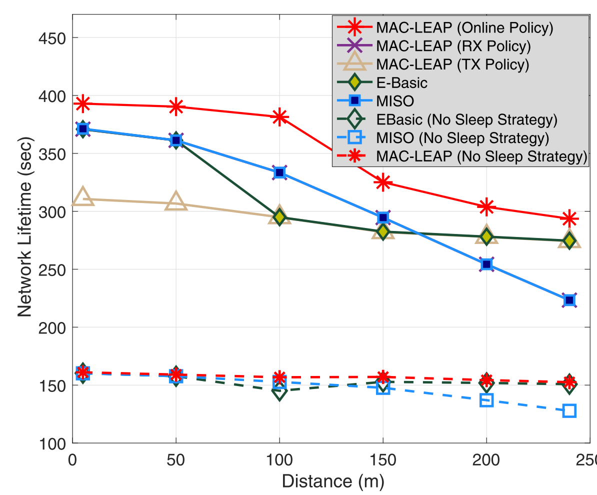
(a) Number of received packets versus target BER (Distance=100 m).



(a) Network lifetime versus target BER (Distance=100 m).



(b) Number of received packets versus distance (Target BER=10^{-5}).



(b) Network lifetime versus distance (Target BER=10^{-5}).

Fig. 13. Number of received packets versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having equal initial energy of 5 J.

Fig. 14. Network lifetime versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having equal initial energy of 5J.

sion, reception, etc. Since the WiFi Radio Energy Model does not support multi-antenna communication, we designed a new energy model called MIMO Energy Model in which the energy consumption of the MIMO device is calculated based on its state of operation, the number of antennas used for the communication, and the energy consumption model presented in Section 3.

- *Mac Low:* The MAC layer is implemented in the *Mac Low* module. This is based on an RTS/CTS handshake in the CSMA/CA protocol. MAC-LEAP selects the most efficient number of antennas based on the content of the RTS and CTS packets, and also the remaining energy that it obtained from the *Device Energy Model*. *Mac Low* notifies the physical layer regarding the chosen number of antennas. Moreover, in order to reduce the nodes' energy consumptions, we added a sleeping strategy inside the MAC layer that puts the nodes into a sleeping state for the duration of the Network Allocation Vector (NAV), if they receive a packet that is not destined to them.
- *WiFi Phy:* This module includes the physical layer, which receives or sends the packets to the wireless channel. The current physical layer model in ns-3 used for wireless communication is the *YansWiFiPhy*. By receiving the number of antennas from the MAC layer, the physical layer is responsible for transmitting the packets to the channel, using the link model of the selected MIMO scheme.

6. Simulation Results

In this section, we evaluate the performance of MAC-LEAP using the different policies described in Section 4 and under various settings. We assume a Rayleigh fading wireless channel with an average path loss that falls off with square of distance (d^2). The initial parameters for the simulation setting are listed in Table 1. We use the circuitry power consumption employed in [33–36] and set the channel data rate R_b to 1 Mbps, the data generation rate at the transmitter node R_g to 50 kbps, the channel bandwidth B

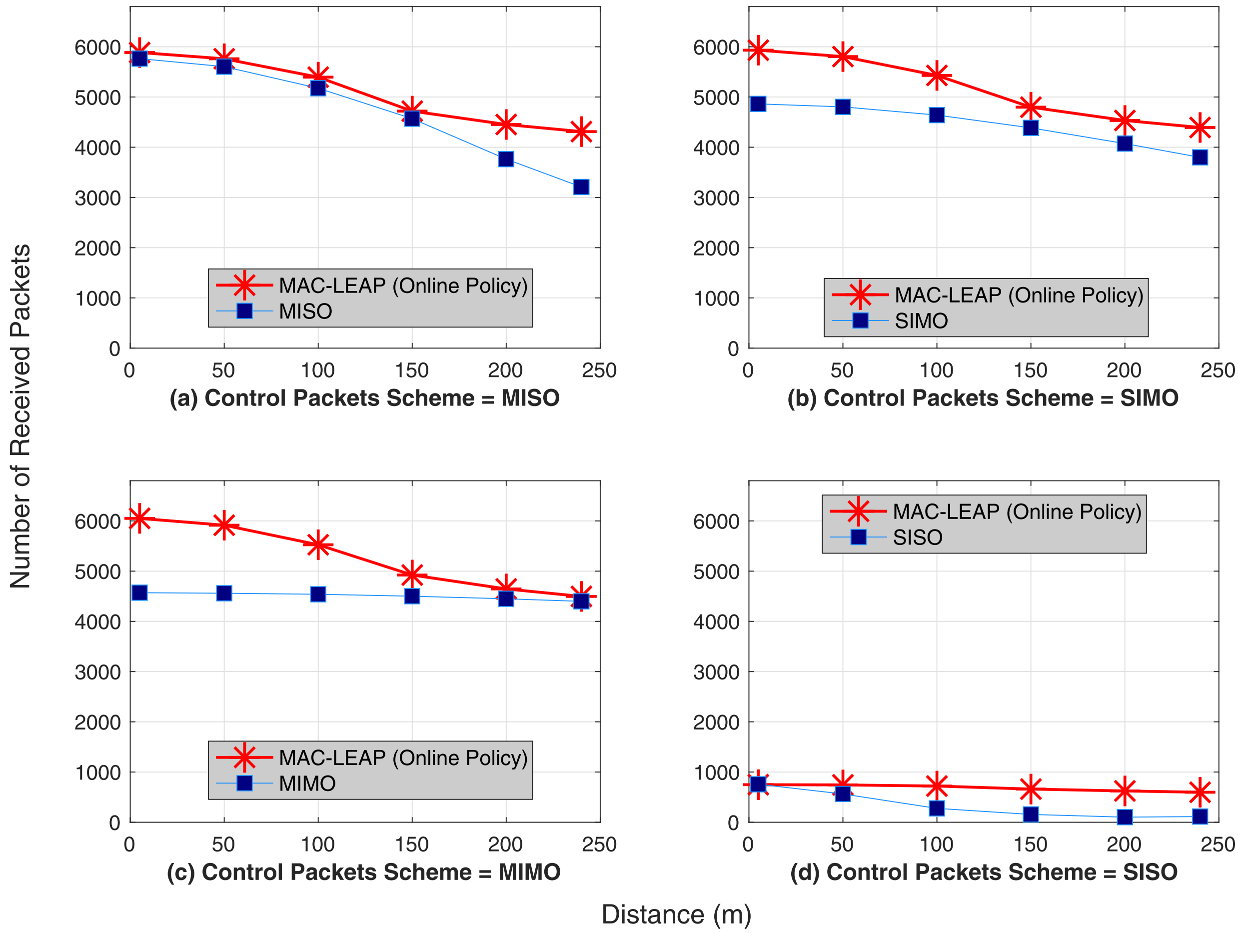


Fig. 15. Number of received packets versus distance with four different fixed schemes used for control packets (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO in a Binary Tree network (target BER= 10^{-5}) with nodes having equal initial energy of 5J.

to 22MHz, and the link margin M_l, which is a parameter related to the hardware, to 10 dB. When utilizing the sleeping technique, the energy consumption during the Idle, Busy and Switching states are zero. We use the ns-3 network simulator with the changes described in Section 5, and the results are averaged over 150 runs, unless noted otherwise.

The nodes have the possibility to operate as 2 × 2 MIMO, 2 × 1 MISO, 1 × 2 SIMO, or 1 × 1 SISO. For sending RTS, CTS, and ACK packets, the nodes use a fixed MIMO scheme with a fixed number of antennas, while for sending the DATA packets, depending on the policy selected in MAC-LEAP, the most efficient MIMO scheme is used for the communication. Since the receiver node is not aware of the most efficient MIMO scheme before receiving the RTS packet from the transmitter, we consider as the default number of antennas for the receiver in the fixed scheme to be one. The transmitter, however, uses two antennas for the non-data packets as the default value. Thus, the default multi-antenna scheme for non-data (control) packets is assumed to be MISO, unless noted otherwise.

Moreover, the maximum WiFi range for each node is fixed to 250 m, and MAC-LEAP sends the control packets (RTS, CTS, and ACK) with the highest transmit power in order to be received by all nodes in their communication range.

In the following subsections, we first analyze the performance of MAC-LEAP for a single communication link (two nodes), and then for different network topologies, which consider both single and multi-hop communications. The comparison is made among MAC-LEAP using the online policy, RX policy, and TX policy, the protocols in which a fixed number of antennas is used in all situations (MIMO, MISO, SIMO, and SISO) [19,26], and the E-Basic protocol presented in [11]. In addition, we compare the performance of MAC-LEAP with a revised version of E-Basic and a revised fixed scheme (e.g., MISO with sleeping strategy), which include the same sleeping strategy adopted by MAC-LEAP.

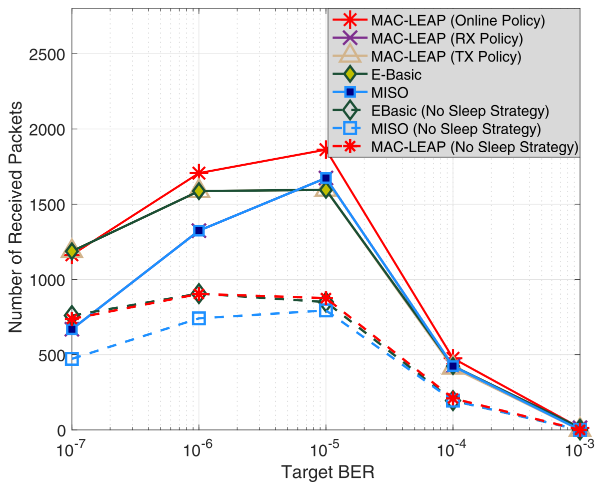
For all the results presented in this section, we evaluate the network lifetime, the total received packets, and the network throughput. We define the network lifetime as the simulation time when the first node runs out of energy in the network, the number of received packets as the total number of packets that are successfully received by all nodes in the network, and the network throughput as:

$$\text{Thr} = \frac{\text{Packet}_{recv} \times N}{T} \tag{19}$$

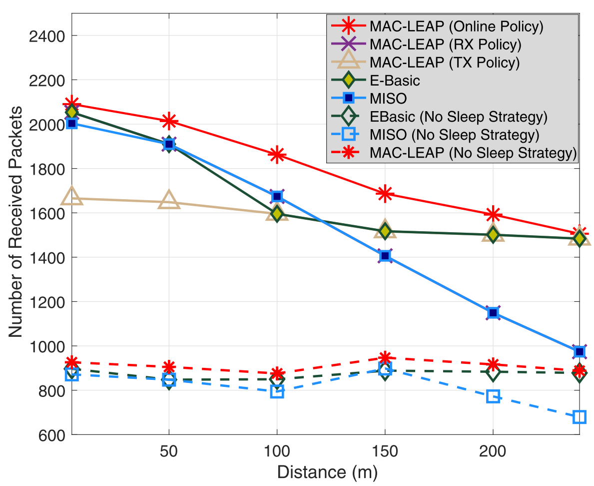
where Packet_{recv} is the total number of successfully received packets by all nodes in the network, N is the data packet size, and T is the time when the last packet is received in the network.

6.1. Single Communication Link

In this section, we consider two nodes that are connected through a wireless communication link. Assuming that both nodes have the same initial energy of 5 J, we evaluate the performance of MAC-LEAP in terms of the number of received packets and network lifetime for various distances and target BERs. It is assumed that the data generation rate is 50 Kbps and the traffic flow between the two nodes continues until the end of the simulation or until the nodes run out of energy.

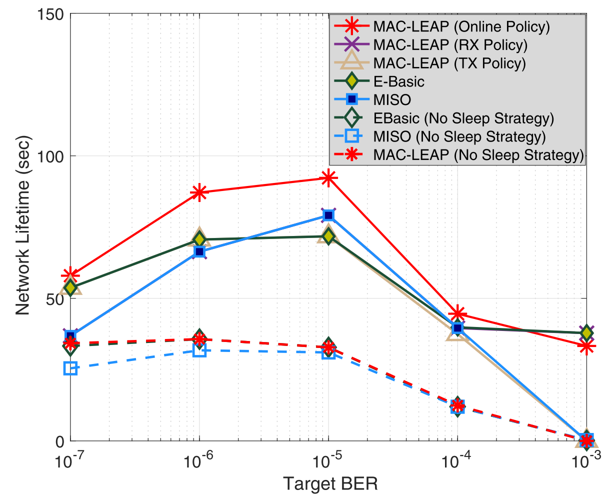


(a) Number of received packets versus target BER (Distance=100 m).

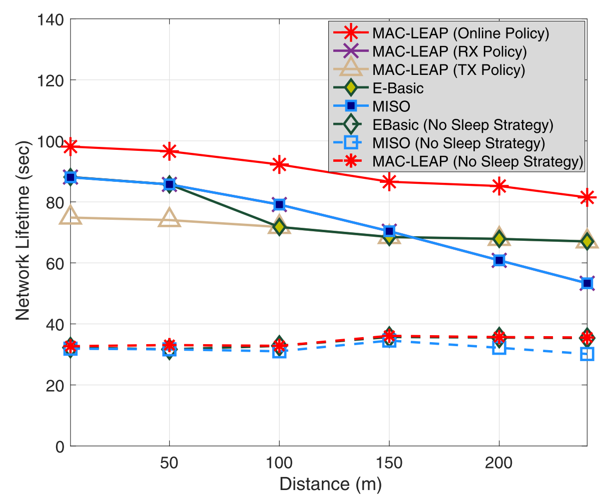


(b) Number of received packets versus distance (Target BER=10^{-5}).

Fig. 16. Number of received packets versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having uniform initial energy distribution in [1, 5] J.



(a) Network lifetime versus target BER (Distance=100 m).



(b) Network lifetime versus distance (Target BER=10^{-5}).

Fig. 17. Network lifetime versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having uniform initial energy distribution in [1, 5] J.

In Fig. 8, we show the performance of MAC-LEAP (Online Policy), and the four fixed schemes (i.e., the nodes always use either SISO, SIMO, MISO, or MIMO for communication). In Fig. 8(a), for instance, MAC-LEAP is compared with the case when the nodes communicate using MISO. Moreover, in this figure, MAC-LEAP uses MISO as the scheme for control packets as well. In all four cases, MAC-LEAP (Online Policy) performs much better than the fixed schemes in terms of number of received packets.

Fig. 9(a) shows the number of received packets versus target BER for the single communication link for the different comparison approaches. As the target BER increases, the energy per bit (E_b) decreases, which results in having a higher number of received packets. However, when the target BER is larger than 10^{-5}, the number of packets drops due to the high probability of error in the channel.

As illustrated in Fig. 9(b), the total number of packets delivered by MAC-LEAP (Online Policy) in a single communication link is the same as the performance of the optimal policy. Moreover, MAC-LEAP (Online Policy) outperforms both the E-Basic protocol and the fixed MISO scheme. As the communication distance increases, since the energy consumption of the transmitter is higher, the number of sent packets and thus the number of received packets drops. Moreover, for distances smaller than 100 m, the RX policy is a better option for MAC-LEAP compared to the TX policy since the transmission power is relatively low. However, for larger distances (d > 100 m), the TX policy performs better than the RX policy since the transmitter has a much higher energy consumption. We note that the trade-off between the TX and RX policies depends on the link margin (M_l). Although the link margin is a parameter that depends on the hardware, the point at which the TX and RX policies cross each other decreases as the link margin increases, as shown in Fig. 10.

When considering the network lifetime, which is shown in Fig. 11, employing the Online Policy in MAC-LEAP results in a higher network lifetime due to the perfect energy balance it provides between the nodes, thereby preventing a node from running out of energy while the other one has energy in the buffer. E-Basic follows the best lifetime between the RX policy and TX policy. Similarly, as shown in Fig. 9(b), the drop in Fig. 11(b) is due to the high

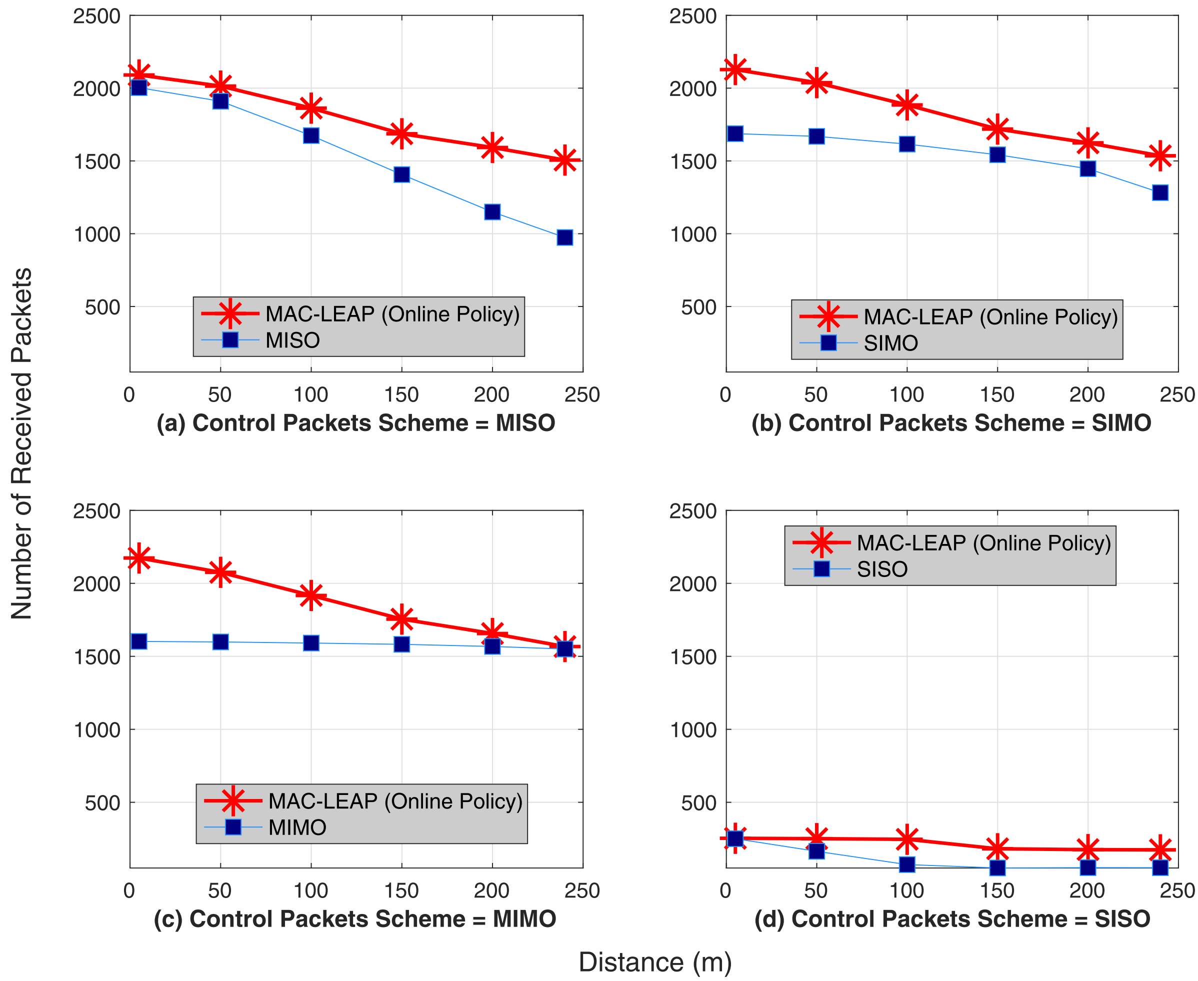


Fig. 18. Number of received packets versus distance with four different fixed schemes used for control packets: (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO in a Binary Tree network (target BER= 10^{-5}) with uniform energy distribution.

transmit power consumption required when transmitting data over long distances. The network lifetime shown in Fig. 11(a) follows as for the results described in Fig. 9(a).

6.2. Binary Tree Network with Single-hop Communication

In this section we analyze the performance of a Binary Tree network. This network has 9 nodes, organized according to the topology shown in Fig. 12. All nodes may transmit or receive packets to/from other nodes in their WiFi range. In what follows, we analyze the performance of MAC-LEAP when all nodes have the same initial energy of 5 J, and when initial energy of each node follows a random variable, uniformly distributed in [1, 5] J. Each node can send data to its connected neighbors that are located at a level that is lower than the level of sender node as shown in Fig. 12. Each new data flow is started after the previous flow start time by one second delay. Moreover, at each flow, the sender node transmits data for a period of 1 second and stops transmitting for the next 1 second to avoid overflow of the node's queue. Each data flow has a data generation rate of 50 Kbps and continues until the end of the simulation or until either the sender node or the receiver node runs out of energy.

6.2.1. Binary Tree Network with Single-hop Communication with Equal Energy Distribution

In this section we assume that all nodes in the Binary Tree network have the same initial energy of 5 J. As shown in Fig. 13(b), the number of received packets in MAC-LEAP (Online policy) is much higher than E-Basic (with sleep strategy), especially when the distance is less than or equal to 100 m. The maximum difference between these two protocols occurs at $d = 100$ m, where MAC-LEAP is able to deliver 17% more packets than E-Basic (Sleep strategy). Moreover, in the mid-BERs, MAC-LEAP (Online policy) shows better performance than the other protocols according to Fig. 13(a). As expected, the original E-Basic protocol and MISO are able to deliver a much lower number of packets compared to MAC-LEAP, especially for distances greater than 50 m and target BER less than 10^{-4}.

As shown in Fig. 14, MAC-LEAP (Online policy) clearly provides better lifetime for the network, and its gain is more significant for mid-distances and mid-BERs. Unlike MAC-LEAP, original E-Basic and original MISO have much lower lifetime since they do not include the sleeping strategy to limit the nodes' energy consumption when idle listening.

According to the comparison made in Fig. 15 between MAC-LEAP and the fixed schemes, MAC-LEAP achieves a higher number of received packets compared to others. The maximum gain over all distances in terms of number of received packets for MAC-LEAP is 34%, 33%, 23%, and more than 400%, when compared to MISO, MIMO, SIMO, and SISO, respectively.

6.2.2. Binary Tree Network with Single-hop Communication with Uniform Energy Distribution

We now evaluate the performance of our protocol for the Binary Tree network where the nodes have a uniformly distributed initial energy in [1, 5] J. According to Fig. 16, the number of re-

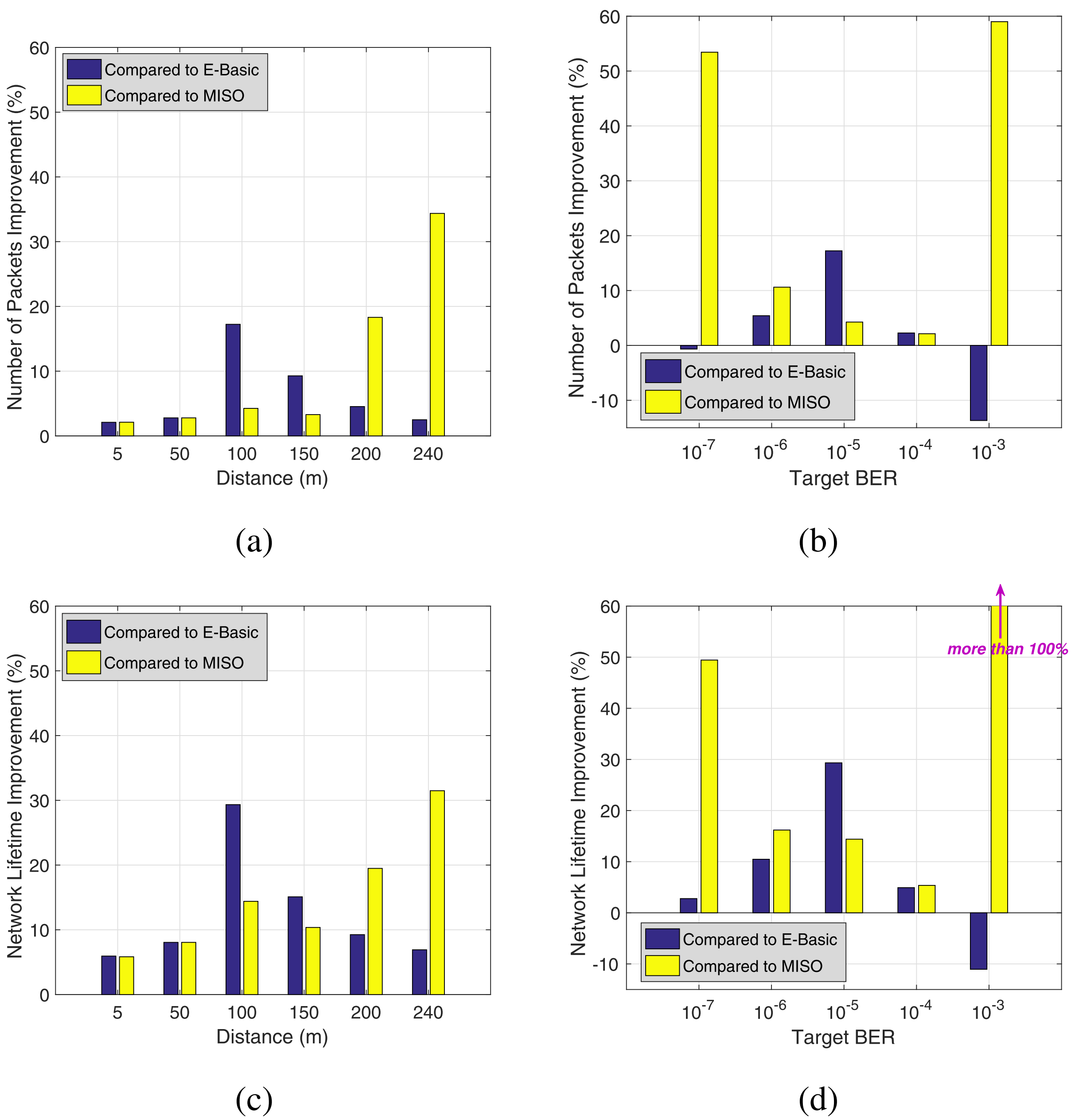


Fig. 19. Improvement of MAC-LEAP compared with E-Basic (with sleep strategy) and MISO (with sleep strategy) in terms of number of received packets (a) vs. distance, and (b) vs. target BER, and in terms of the network lifetime (c) vs. distance, and (d) vs. target BER, in a Binary Tree network with 9 nodes having the same initial energy of 5 J.

ceived packets in MAC-LEAP is higher due to the adaptive antenna selection, and is more significant in smaller distances and target BERs. The maximum gain of MAC-LEAP (Online policy) in terms of number of received packets is about 19% more packets than E-Basic (with sleep strategy) over all distances and target BERs. Moreover, according to Fig. 16(b), the trade-off point between RX and TX policies is at a distance of 50 m. For small distances, MAC-LEAP (RX policy) works slightly better than MAC-LEAP (TX policy) since the receiver consumes slightly more energy than the transmitter. However, as the distance increases, the transmission power increases and dominates the receiver energy consumption, which results in the TX policy being able to deliver more packets than the RX policy.

As shown in Fig. 17(a), the maximum improvement in terms of the network lifetime of MAC-LEAP (Online policy) in various target BER is 28% and 58% compared to E-Basic (with sleep strategy) and MISO (with sleep strategy), respectively. By changing the distances in Fig. 17(b), among the nodes in the tree network, MAC-LEAP achieves maximum improvement of 28% and 53% in terms of lifetime compared to E-Basic (with sleep strategy) and MISO (with sleep strategy).

As described before, MAC-LEAP adapts the number of antennas at the nodes based on different factors including their current remaining energy. Therefore, it achieves a higher number of packets compared to fixed schemes in the Binary Tree network, as shown in Fig. 18. The maximum gain in terms of number of packets for MAC-LEAP is 55%, 36%, 26%, and 262% compared to MISO, MIMO, SIMO, and SISO, respectively.

6.2.3. Improvement on Binary Tree Network with Single-hop Communication

In this section, we summarize the results by demonstrating the average improvement in the network by using MAC-LEAP in terms of both network lifetime and the total number of received packets.

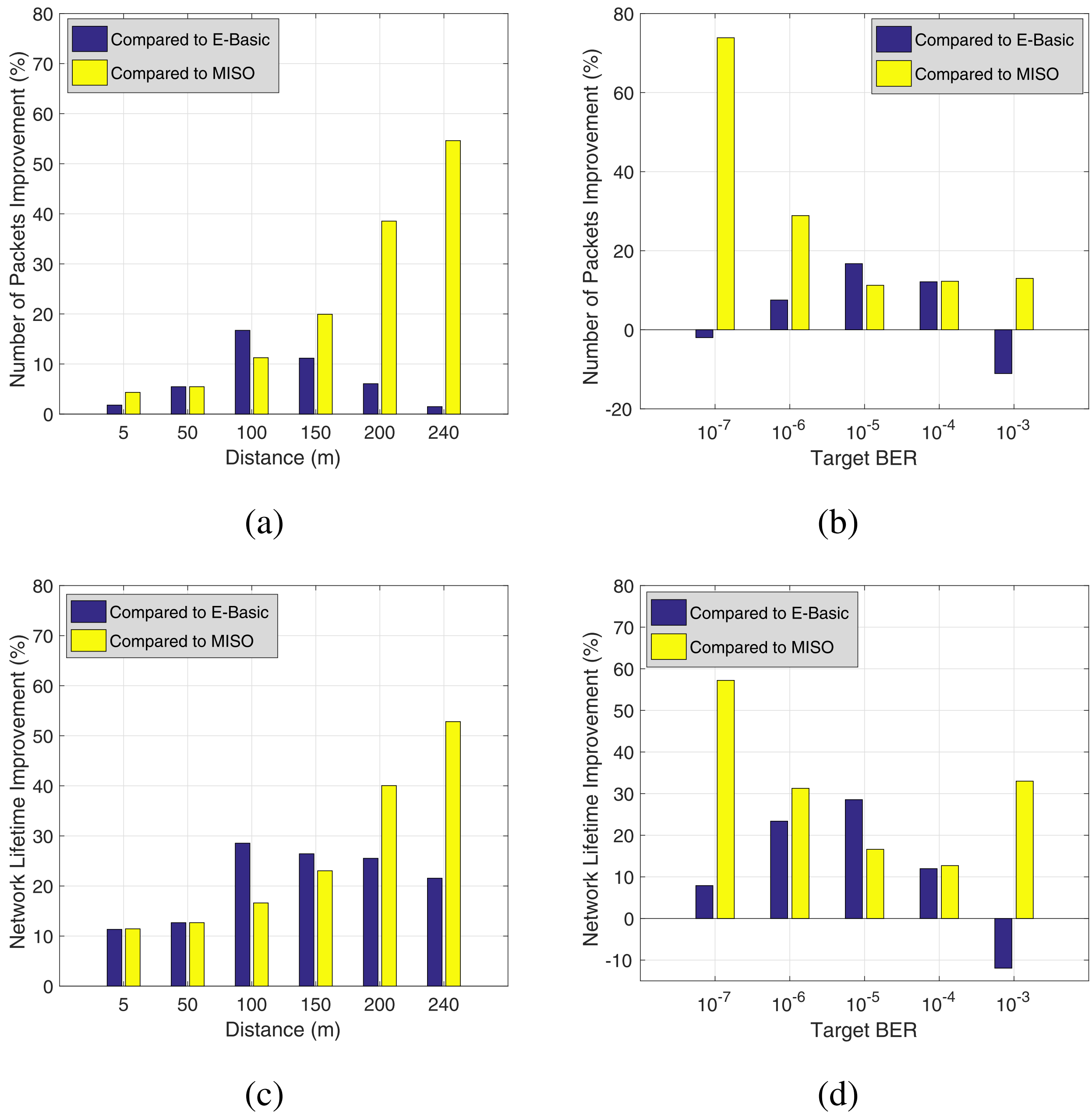


Fig. 20. Improvement of MAC-LEAP compared with E-Basic (with sleep strategy) and MISO (with sleep strategy) in terms of number of received packets (a) vs. distance, and (b) vs. target BER, and in terms of the network lifetime, (c) vs. distance, and (d) vs. target BER, in a Binary Tree network with 9 nodes having the uniform initial energy distribution in [1, 5] J.

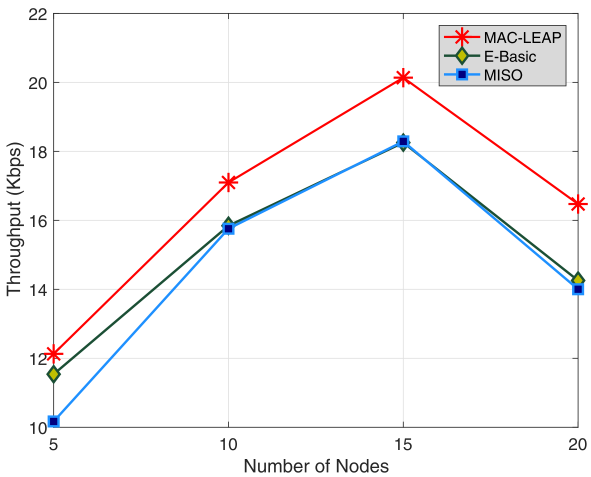
The comparison is between MAC-LEAP, E-Basic, and MISO when the sleep strategy is employed in all of them.

Fig. 19 shows MAC-LEAP improvement compared to E-Basic and MISO when the sleep strategy is employed and all nodes have the same initial energy of 5 J. MAC-LEAP improves the number of received packets up to 38% and 48% compared to MISO for various distances (Fig. 19(a)) and various target BERs (Fig. 19(b)). MAC-LEAP increases the number of received packets up to 17% compared to E-Basic for various distances and target BERs (according to Fig. 19(a) and Fig. 19(b)). Network lifetime is improved by 52% for various distances and by 75% for different target BERs compared to MISO as shown in Fig. 19(c) and Fig. 19(d). Moreover, MAC-LEAP increases the network lifetime by a maximum of 26% for various distances and target BERs compared to E-Basic when the sleep strategy is employed.

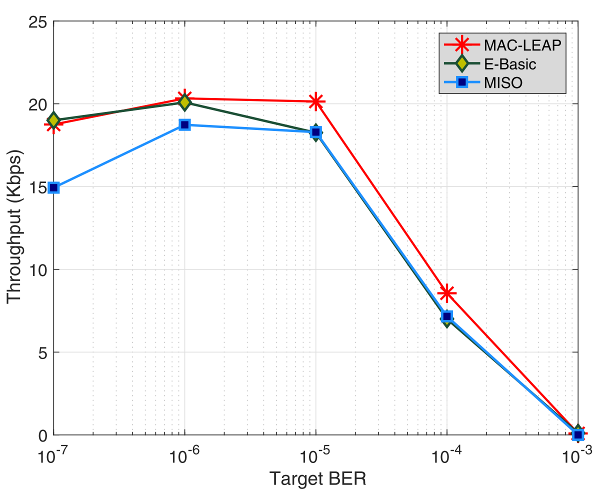
According to Fig. 20(a) and Fig. 20(b), MAC-LEAP improves the number of received packets compared to MISO by a maximum of 54% for various distances and by a maximum of 74% when the target BER is changing in the Binary Tree network with uniform initial energy distribution. It also increases the number of packets by a maximum of 17% (vs. distance and vs. target BER) compared to E-Basic with sleep strategy. As shown in Fig. 20(c) and Fig. 20(d), by employing MAC-LEAP in a Binary Tree network with uniform initial energy distribution, the network lifetime is improved up to 53% and 29% (for different distances), and 57% and 29% (for different target BER) compared to MISO and E-Basic, respectively.

6.3. Random Network with Multi-hop Communication

In this section we analyze the performance of MAC-LEAP in a random network when all nodes have the same initial energy of



(a) Average network throughput versus number of nodes (Target BER = 10^{-5}).



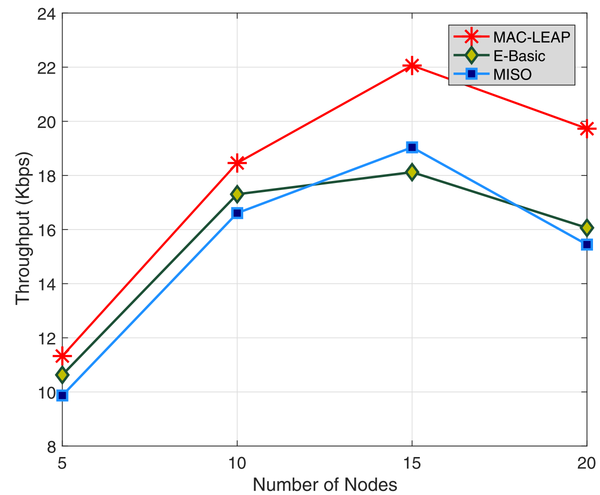
(b) Average network throughput versus target BER (Number of Nodes=15).

Fig. 21. Network throughput in the random network with nodes having the same initial energy of 5 J and without employing the sleep strategy in the nodes.

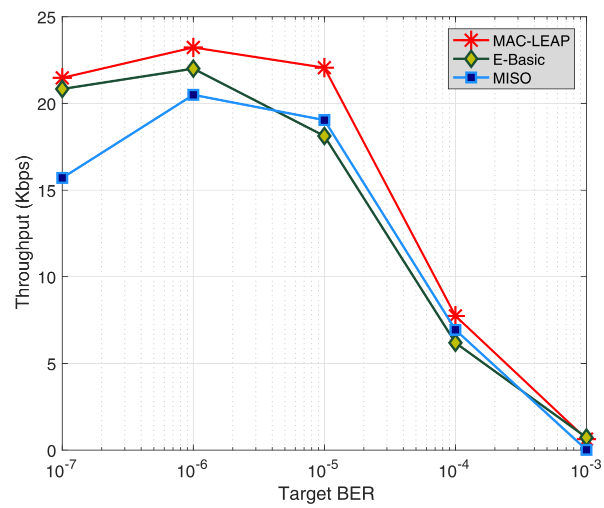
5 J, and when the nodes' initial energies follow a uniform distribution in [1, 5] J. We present the results for different numbers of nodes uniformly distributed in a 700 m by 700 m square area. The results presented in this section are averaged over 10 random network topologies while, for each topology, the results are averaged over 10 different channel realizations. Moreover, the nodes are mobile with different velocities that follow a uniform distribution of [0,0.05] m/s. The mobility pattern is constant velocity mobility model in which each node moves to a different location by a constant velocity. Optimized Link State Routing (OLSR) is used for routing to support multi-hop communication. All nodes can send/receive packets to/from other nodes. In this section, MAC-LEAP refers to the MAC-LEAP protocol uses the online-policy.

6.3.1. Traffic Pattern

In the random network, it is assumed that all nodes, can send and receive packets. We generate a data flow with data generation rate of 50 Kbps for each pair of nodes and the flow continues until the end of the simulation or until the nodes run out of energy. For



(a) Average network throughput versus number of nodes (Target BER = 10^{-5}).



(b) Average network throughput versus target BER (Number of Nodes=15).

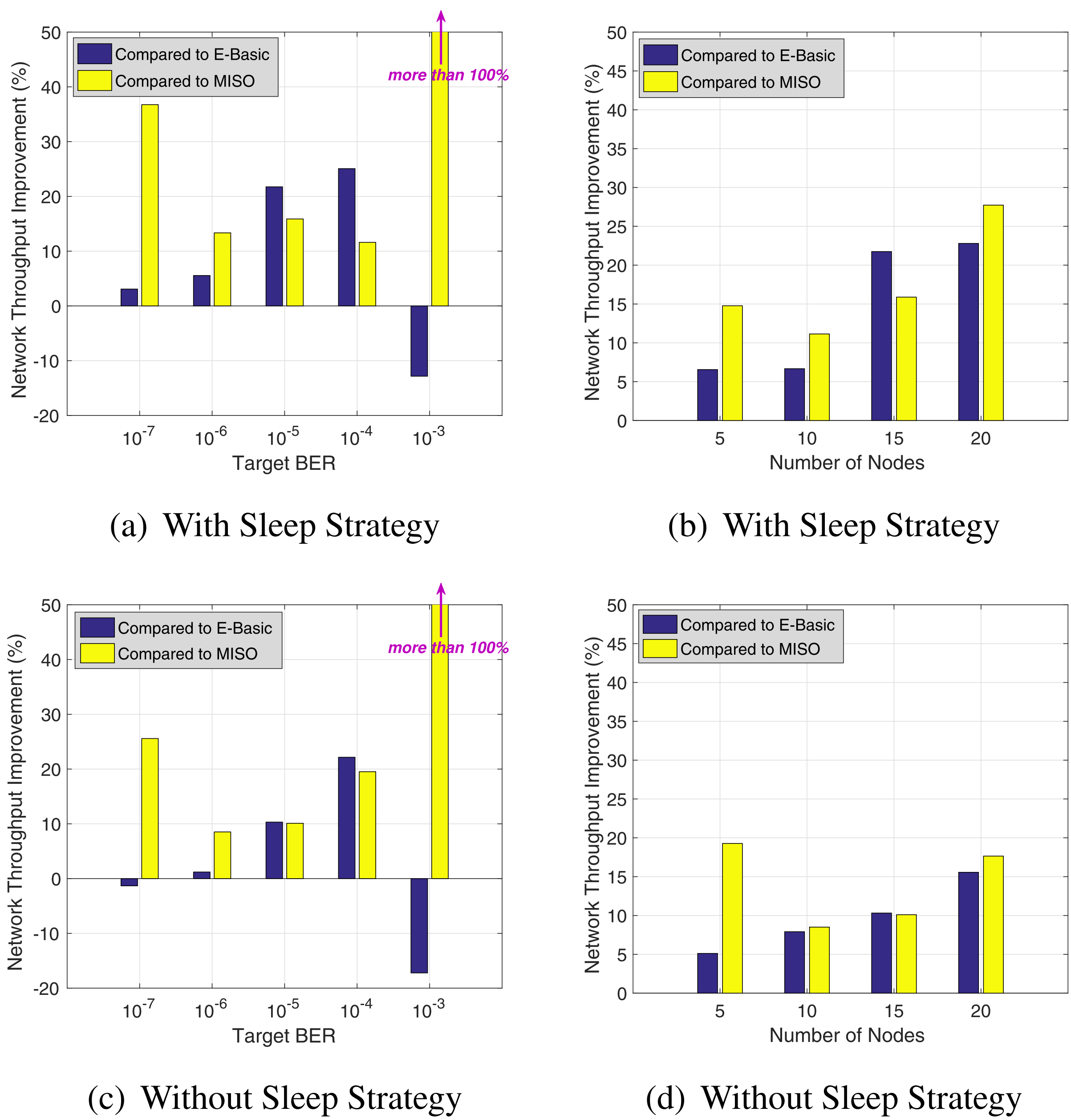
Fig. 22. Network throughput in the random network with nodes having the same initial energy of 5 J and with employing the sleep strategy in the nodes.

instance, if we have 15 nodes in the network, a total of $15 \times 14 \times 2 = 420$ traffic flows are generated in the network. Each new data flow is started after the previous flow start time by one second delay. Moreover, at each flow, the sender node transmits data for a period of 1 second and stops transmitting for the next 1 second to avoid overflow of the node's queue. The transmitter continues this data flow until either the sender node or the receiver node runs out of energy.

6.3.2. Random Network with Multi-hop Communication and Equal Initial Energy Distribution

In this section we assume that all nodes have equal initial energy of 5 J. We compare MAC-LEAP with E-Basic and MISO with/without sleep strategy in terms of the network throughput (defined in Eq. (19)) when the number of nodes and the target BER in the network are changing.

In Fig. 21, the average network throughput is shown when the sleep strategy is not employed in MAC-LEAP, E-Basic, and MISO. As



(a) With Sleep Strategy (b) With Sleep Strategy

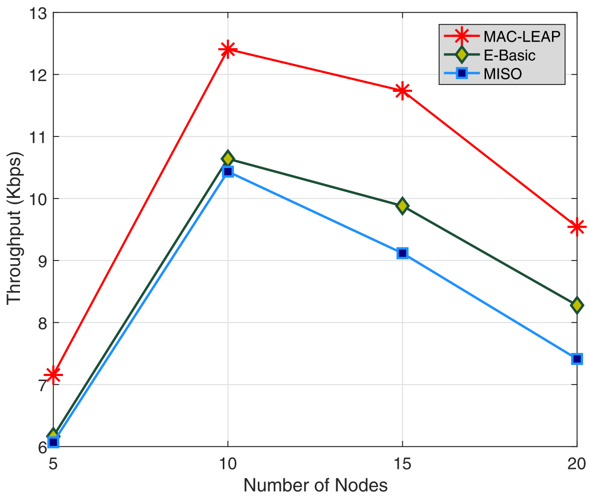
(c) Without Sleep Strategy (d) Without Sleep Strategy

Fig. 23. Improvement of MAC-LEAP compared with E-Basic (with sleep strategy) and MISO (with sleep strategy) (a) vs. target BER and (b) vs. number of nodes, and improvement of MAC-LEAP compared with E-Basic (without sleep strategy) and MISO (without sleep strategy) (c) vs. target BER and (d) vs. number of nodes in a random network with nodes having the same initial energy of 5 J.

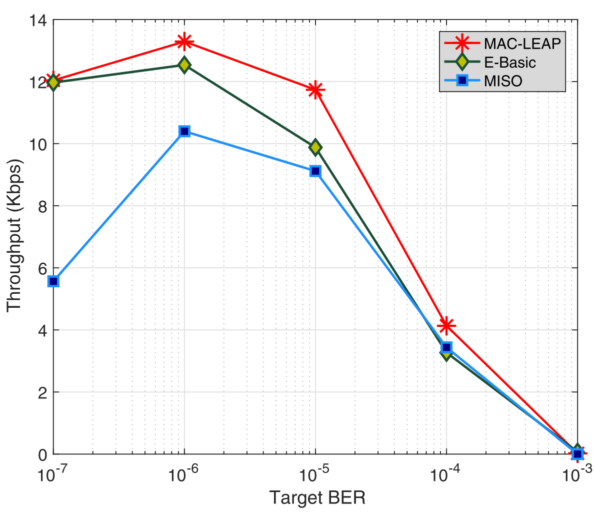
the number of node grows in the network, more data packets are transferred in the network. According to Fig. 21(a), due to higher packet transmission rate, the throughput increases as the number of nodes grows. MAC-LEAP greatly improves the average network throughput compared to E-Basic and MISO since the Online policy in MAC-LEAP provides energy consumption balance among the nodes in the network. The energy consumption balance has a high impact on the number of received packets per second in the random network with OLSR routing for data communication.

Fig. 21(a) demonstrates the variation of average network throughput when the target BER is changing in a random network when all nodes have the same initial energy and they employ the sleep strategy. As the target BER increases, the probability of packet reception decreases and thus the network throughput becomes lower. Moreover, MAC-LEAP improves the network throughput compared to E-Basic and MISO especially when the target BER is less than or equal to 10^{-5}.

As shown in Fig. 22, when the sleep strategy is employed in the nodes, the network throughput is higher than the network without sleep strategy (Fig. 21). MAC-LEAP greatly increases the network throughput compared to E-Basic and MISO as shown in Fig. 22(a) and Fig. 22(b). Fig. 23 shows the improvement percentage of MAC-LEAP compared to E-Basic and MISO in terms of network throughput with/without sleep strategy when all nodes in the network have 5 J of initial energy. For various target BER, MAC-LEAP increases the network throughput by at most more than 100% (with and without sleep strategy) compared to MISO, and by at most 25% (with sleep strategy) and 22% (without sleep strategy) compared to E-Basic, respectively (Figs. 23(a) and 23(b)). Moreover, for various number of nodes in the network the network throughput improvement by MAC-LEAP is at most 23% (with sleep strat-

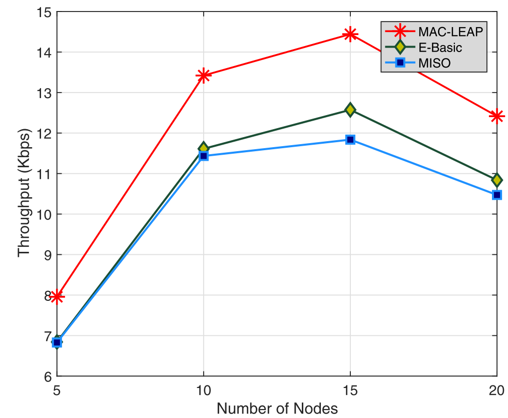


(a) Average network throughput versus number of nodes (Target BER = 10^{-5}).

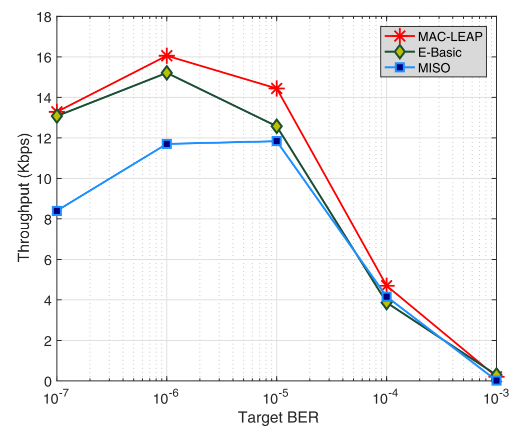


(b) Average network throughput versus target BER (Number of Nodes=15).

Fig. 24. Network throughput in the random network with nodes having the uniform initial energy distribution of [1,5] J and without employing the sleep strategy.



(a) Average network throughput versus number of nodes (Target BER = 10^{-5}).



(b) Average network throughput versus target BER (Number of Nodes=15).

Fig. 25. Network throughput in the random network with nodes having the uniform initial energy distribution of [1,5] J and employing the sleep strategy.

egy) and 15% (without sleep strategy) compared to E-Basic, and at most 28% (with sleep strategy) and 19% (without sleep strategy) compared to MISO, respectively (Figs. 23(c) and 23(d)). At target BER of 10^{-3}, MAC-LEAP and E-Basic performance is very close with/without sleep strategy. They receives very small number of packets and thus their throughput is very low. Their throughput values (e.g. 0.09 Kbps and 0.1 Kbps for MAC-LEAP and E-Basic) and their number of packets (e.g. 3 and 4 packets for MAC-LEAP and E-Basic) are very close but since the values are very small, the improvement percentage of E-Basic compared to MAC-LEAP is high at target BER of 10^{-3}.

6.3.3. Random Network with Multi-hop Communication and Uniform Initial Energy Distribution

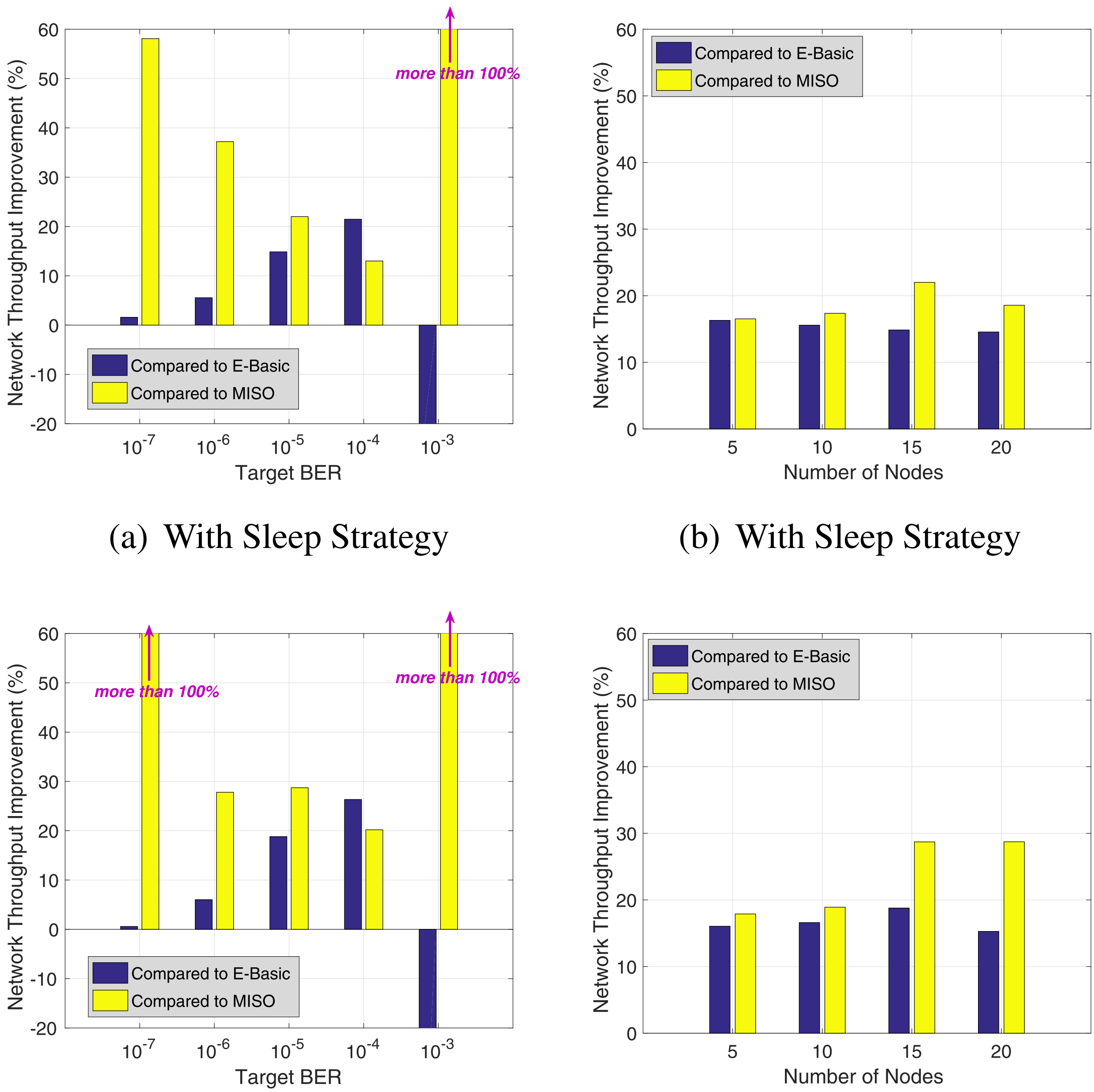
We now consider a random network in which each node's initial energy is selected by a random variable, uniformly distributed in [1, 5] J.

Average network throughput when the nodes have uniform initial energy distribution of [1,5]J is shown in Figs. 24 and 25. In Fig. 25 all nodes in MAC-LEAP, E-Basic, and MISO employ sleep strategy to save more energy and send more packets. In Fig. 24, however, the results for MAC-LEAP, E-Basic, and MISO protocols are represented when the nodes don't employ the sleep strategy.

As shown in Fig. 24(a), when the nodes employ the sleep strategy, the average network throughput varies between 1.5 Kbps and 3.2 Kbps when the number of nodes in the network changes from 5 to 20 in MAC-LEAP. MISO and E-Basic provide similar average network throughput in this case. By altering the target BER in the network as shown in Fig. 24(b), the average network throughput decreases as the target BER increases since more packets are lost in high target BERs.

By employing the sleep strategy in the nodes, MAC-LEAP increases the network throughput (shown in Fig. 25) compared to Fig. 24 when no sleep strategy is employed. Moreover, MAC-LEAP gains better network throughput compared to both E-Basic and MISO in various target BER and number of nodes in the network.

Fig. 26 shows the improvement percentage of MAC-LEAP compared to E-Basic and MISO when the nodes have uniform initial energy distribution. By employing the sleep strategy, MAC-LEAP improves the network throughput by maximum of 22% and more than 100% for various target BER, and by an average of 16% and 22%



(a) With Sleep Strategy (b) With Sleep Strategy

(c) Without Sleep Strategy (d) Without Sleep Strategy

Fig. 26. Improvement of MAC-LEAP compared with E-Basic (with sleep strategy) and MISO (with sleep strategy) (a) vs. target BER and (b) vs. number of nodes, and improvement of MAC-LEAP compared with E-Basic (without sleep strategy) and MISO (without sleep strategy) (c) vs. target BER and (d) vs. number of nodes in a random network with nodes having the Uniform initial energy distribution in [1,5] J.

for different numbers of nodes, compared to E-Basic and MISO, respectively. Moreover, without sleep strategy, MAC-LEAP improves the network throughput by maximum of 26% and more than 100% (vs. target BER) and 19% and 29% (vs. number of nodes) compared to E-Basic and MISO, respectively.

7. Conclusions

In this paper, we proposed a new cross-layer energy-adaptive protocol (MAC-LEAP) for multi-antenna wireless networks. MAC-LEAP dynamically adjusts the number of antennas at the transmitter and the receiver sides based on the remaining energy of the nodes such that the number of received packets is maximized. Employing a CSMA/CA protocol, MAC-LEAP utilizes RTS and CTS packets to not only provide collision avoidance but also to transfer energy related information among the nodes. Thus, unlike the traditional protocols, MAC-LEAP takes current energy levels of the nodes into account and adapts the number of antennas accordingly, and includes a sleep strategy in order to increase its energy efficiency. Moreover, we propose various dynamic antenna selection policies (optimal policy, online policy, RX policy, and TX policy) each of which can be used in MAC-LEAP, and considers the nodes' energy levels, communication distance, and channel BER.

Finally, we implemented a new MIMO-based framework for wireless networks in ns-3. Based on this framework, the wireless nodes equipped with one or more antennas are able to communicate with each other. Through extensive simulations in ns-3, we compared MAC-LEAP with three different antenna selection policies (online policy, RX policy, and TX policy) with traditional protocols in different network topologies. The simulation results show that MAC-LEAP (online policy) outperforms the traditional protocols with or without sleep strategy implementation.

For future work, we intend to employ MAC-LEAP in networks with energy harvesting in which the nodes' energy is provided through ambient sources. In this case, finding the optimal antenna selection to maximize the energy efficiency is more challenging since the future evolution of the remaining energy is more difficult to predict.

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