Energy Balancing in Wireless Networks with MIMO Communications

by

Hoda Sadat Ayatollahi Tabatabaei

Submitted in Partial Fulfillment of the

Requirements for the Degree

Doctor of Philosophy

Supervised by Professor Wendi Heinzelman

Department of Electrical and Computer Engineering

Arts, Sciences and Engineering

Edmund A. Hajim School of Engineering and Applied Sciences

University of Rochester

Rochester, New York

2018

"O mankind, you are those in need of Allah, while Allah is the Free of need, the Praiseworthy."

Holy Quran - Surah Fatir [15]

This thesis is dedicated to Imam Mahdi; whom the world awaits his return.

Contents

Biographical Sketch

The author, Hoda Ayatollahi was born in Tehran, Iran. She received her Bachelor of Science degree in Computer Engineering from Azzahra University, Tehran, Iran. As an intern, she worked at the MAGFA Communication and Networking company, and at the Computer Management Center of Imam Khomeini hospital. She received a Master of Science degree from Sharif University of Technology in the field of Computer Engineering (major: Computer Networking). In 2013, she began doctoral studies in the Department of Electrical and Computer Engineering at the University of Rochester. She pursued her research in the field of wireless communications and networking under the direction of Prof. Wendi Heinzelman. She received her Master of Science degree in the same field from the University of Rochester in 2016. Her current research interests lie in the areas of wireless communications and networking, MIMO, energy harvesting, and Reinforcement Learning in Wireless Networks.

The following publications were a result of work conducted during doctoral study:

- Cristiano Tapparello, Hoda Ayatollahi, Wendi Heinzelman, "CMIMO: An Energy Efficient Cluster-based Protocol for MIMO Wireless Networks", (In preparation)

- Hoda Ayatollahi, Cristiano Tapparello, Wendi Heinzelman, "MAC-LEAP: Multi-Antenna, Cross Layer, Energy Adaptive Protocol," Elsevier Ad Hoc Network (In preparation).

- Kofi S. Adu-Manu, Nadir Adam, Cristiano Tapparello, Hoda Ayatollahi and Wendi Heinzelman, "Energy-Harvesting Wireless Sensor Networks (EH-WSNs): A Review," Transactions on Sensor Networks (TOSN), (Accepted).

- Hoda Ayatollahi, Cristiano Tapparello, Malitha N. Wijesundara, Wendi Heinzelman, "Energy

Conservation in Animal Tracking," International Conference on Computing, Networking and Communications (ICNC), Maui, Hawaii, USA, Mar 5-8, 2018.

- Hoda Ayatollahi, Cristiano Tapparello, Wendi Heinzelman, "Reinforcement Learning In MIMO Wireless Networks with Energy Harvesting," IEEE International Conference on Communications (ICC), Paris, France, May 21-25, 2017.

- Hoda Ayatollahi, Cristiano Tapparello, Wendi Heinzelman, "Transmitter-Receiver Energy Efficiency: A Trade-off in MIMO Wireless Sensor Networks," Wireless Communications and Networking Conference (WCNC), New Orleans, LA, 2015.

- Cristiano Tapparello, Hoda Ayatollahi, Wendi Heinzelman, "Energy Harvesting Framework for Network Simulator 3 (ns-3)," 2nd International Workshop on Energy Neutral Sensing Systems (ENSsys 2014) in conjunction with ACM SenSys, Memphis, TN, 2014.

Acknowledgments

First and foremost, I thank God Almighty who made my life and all of its moments, a miracle. I thank him for giving me the strength, opportunity and knowledge to undertake this research study and to persevere and complete it satisfactorily. Without his blessings, this achievement would not have been possible.

I would like to express my sincere gratitude to my advisor Prof. Wendi Heinzelman for her excellent guidance, motivation, enthusiasm, immense knowledge, and continuous support during my PhD studies. I would like to thank her for her immense knowledge and the valuable time she spent on proofreading my research papers. I would like to thank her for encouraging my research and for allowing me to grow as a research scientist. Her professional support and advise in my research guided me through the difficulties in my research and lead to this dissertation.

I would like to thank Dr. Cristiano Tapparello for his mentorship over the past few years. During my time in the Wireless Communication and Networking Group (WCNG), he provided me with excellent guidance, suggestions and insight, and spent endless amount of time discussing my research difficulties and proofreading my research papers. I would like to thank all of my lab-mates and colleagues in the WCNG lab. It is my pleasure to work with them for the last 5 years.

I would also like to thank Professor Marvin Doyley, and Professor Daniel Stefankovic for acting as members of my committee, and Professor Yuhao Zhu for acting as Chairperson of the defense committee.

Most of all, I would like to thank my beloved husband, Mohammad Hossein, for his endless love, encouragement, and all the sacrifices he made during my PhD studies. He always inspires me and motivates me to continue to improve my knowledge and move my career forward. Thank you for all the time and effort you spent to provide a calm and peaceful atmosphere for me to focus on my research. Thank you for standing beside me throughout my studies and getting my PhD degree. Thank you for your support, guidance, and understanding every time that I faced a difficulty.

I would like to express the deepest gratitude to my wonderful family, who have always loved me unconditionally. I thank my loving aunt who is always like a second mother to me, my kindhearted grandfather, and my sweet and beautiful sister and her husband, for their encouragement, and patience during the time I was in the US to finish my PhD studies. Thanks for listening to my problems and providing perspective. I would not be who am I today without you all. I also show gratitude for my father who passed away many years ago and I know he is proud of me today. Above all, I would like to thank my amazing mother who have always loved me limitlessly, supported me, and stood next to me. You are my friend, my role model, and my guidance counselor. Thank you for your extraordinary strength, self-confidence, and bravery which taught me how I should manage my problems. Thank you for believing in me, encouraging me to do my best and to try new things. Thank you for supporting my dreams and ideas, even when they seem far-fetched. I would also like to thank my in-laws who have supported me throughout my studies.

Abstract

Wireless networks are vital for supporting a range of applications. With the continuous development of wireless networks, energy conservation and energy efficiency are becoming key factors in improving the network lifetime. In conventional wireless networks, the nodes are equipped with a single antenna, and the energy conservation methods are needed since the nodes have limited capacity and may run out of energy. Although energy harvesting, which provides unlimited amount of energy to the nodes when ambient energy is available, can be helpful in solving this problem, there are times when the energy source is not available. Therefore, implementing energy efficient techniques is essential in wireless networks in order to have energy consumption balance among the wireless nodes. In multi-antenna wireless networks, however, the energy conservation problem can be addressed using the trade-off between the transmit power and the circuit energy consumption. Multiple-Input Multiple-Output (MIMO) communication is a promising approach that can be efficiently used in reducing the energy consumption for communication. In MIMO systems, the transmit power is spread among more than one antenna, which results in having a high power gain and better spectral efficiency.

To this end, I propose a system for MIMO wireless networks that optimizes the energy efficiency and provides energy balance by dynamically adjusting the number of antennas based on the nodes' energy levels. Based on the nodes' distance, remaining energy, and the target Bit-Error-Rate (BER), a multi-antenna scheme is chosen for communication on a per-packet basis. The system is modeled using a Markov Decision Process (MDP) and optimized using reinforcement learning. I define the reward function based on the remaining energy, energy consumption, and the distance between the nodes and use Q-learning to find the optimal multi-antenna scheme.

In order to extend the idea into a network with more than two nodes, I propose MAC-LEAP:

Multi-Antenna, Cross Layer, Energy Adaptive Protocol for single-hop and multi-hop MIMO wireless networks. The protocol selects the most energy efficient MIMO scheme for both the transmitter and the receiver and uses the RTS/CTS hand-shake to transfer some information required by the dynamic antenna selection policy prior to the data transmission. Based on simulation results using the ns-3 network simulator, MAC-LEAP outperforms traditional protocols both in terms of network lifetime and the number of received packets in single hop and multi-hop networks. Moreover, MAC-LEAP is also implemented in a real life animal tracking application called JumboNet. I tested the protocol in three different scenarios; when the nodes have limited energy, when the nodes have unlimited energy, and when the nodes employ energy harvesting. According to the simulation results, MAC-LEAP outperforms the traditional JumboNet network in terms of energy consumption, packet delay, and packet delivery ratio.

Moreover, in order to enable network scalability, I propose Cluster-based MIMO (CMIMO), a cluster-based protocol for wireless networks in which the nodes have multiple antennas and are powered either by a non-rechargeable battery or by energy harvesting. In a cluster-based network using MIMO, the nodes are equipped with more than one antenna. CMIMO adjusts the number of antennas for communication between a normal node and a cluster-head in order to improve the energy efficiency of the network. We evaluate CMIMO in two scenarios, a network with wireless nodes with non-rechargeable batteries, and a network with mobile wireless nodes powered with energy harvesting. In both scenarios, the simulation results show that CMIMO outperforms the traditional approach in terms of number of received packets, network lifetime, percentage of dead nodes, and energy consumption.

Contributors and Funding Sources

This work was supported by a dissertation committee consisting of Professor Wendi Heinzelman from the department of Electrical and Computer Engineering, Professor Daniel Stefankovic from the department of Computer Science, Professor Marvin Doyley from the department of Electrical and Computer Engineering, and Dr. Cristiano Tapparello from the department of Electrical and Computer Engineering. All work in this dissertation was completed independently by the author. This work was funded by the National Science Foundation under research grant CNS-1239423.

List of Tables

List of Figures

Chapter-1

Introduction

Wireless communication has been the focus of many researchers in the last decade due to the wide range of applications that can benefit from it. These networks are deployed for different applications, including environmental monitoring, healthcare monitoring, disaster monitoring, traffic monitoring, and intrusion detection, among others. In most of these applications, energy-efficient communication is essential in order to maintain the network for long periods of time. However, even with very efficient communications, eventually batteries will run out and need to be replaced. An alternative is to utilize continuous energy harvesting, whereby the nodes' batteries can be recharged through energy obtained from the environment, such as solar, wind, and vibration energy.

1.1 Balancing the Nodes' Energy

Energy efficiency along with balanced energy use among the nodes are key factors in improving the lifetime of wireless networks. While overall energy efficiency ensures a reduction in the energy required to operate the network, balancing the remaining energy for the nodes is important in order to avoid the failure of a node prematurely.

There are many factors that affect the energy consumption required for communication in a wireless network. Mobility, communication distance, number of communication antennas, wireless coverage, node density, network dynamics, and network heterogeneity are some of the factors that affect the network overall energy consumption. For instance, nodes that must communicate over longer distances, require higher bit rates, and have a high mobility consume more energy than nodes that communicate over smaller distances, with lower bit rate requirements and low mobility.

The energy storage of the nodes in the network varies. Each wireless node in the network is equipped with either a capacitor, a super-capacitor, or a battery to store the energy. Capacitors or super-capacitors are used when a high amount of energy is required for communication among the nodes, while the capacity of batteries is smaller as they can be used in applications that have steady energy consumption. However, nodes equipped with these energy storage mechanisms have limited storage capacity, and can be affected by energy leakage over time, so that eventually the storage medium must be recharged or replaced.

A solution to these problems is to employ energy harvesting in the network, where the energy is provided through ambient sources such as vibration, electromagnetic, solar, wind, thermal, etc. [2, 3, 4, 5, 6, 7, 8]. Employing energy harvesting in wireless networks enables the nodes to continuously acquire energy to ensure network sustainability. Although the energy may be needed continuously, depending on the environment conditions, there may be an interruption in the ambient energy that can be harvested. For instance, during the day or during windy days the energy can be provided through solar or wind, respectivly, while no energy is generated during the night for solar energy harvesting and during calm weather for wind energy harvesting. Thus, even if energy harvesting is employed in the network, providing energy consumption balance among the nodes is essential to ensure that no nodes run out of energy prematurely.

1.2 Multi-Antenna Wireless Networks

In a single link communication, the transmitter and the receiver may have either one or more antennas. Depending on the number of antennas of the wireless node and certain other factors such as communication distance and channel Bit-Error-Rate (BER), the node energy consumption is different. Multiple Input Multiple Output (MIMO) is an approach whereby multiple antennas are used in the transmitter and receiver nodes. Unlike Single Input Single Output (SISO) communication, MIMO has been the focus of many researchers for the past decade due to its benefits.

MIMO technology enhances both the capacity and reliability of wireless networks and provides better energy efficiency. The signal level at the receiver side in a wireless network fluctuates and fades, which may affect the quality of the communication. The spatial diversity achieved when using MIMO provides the receiver with multiple independent copies of the transmitted signal. The higher the number of copies, the higher the probability that at least one copy is received without experiencing a deep fade.

At the circuit level, the architecture of MIMO is more complex than SISO and thus, the amount of circuit energy consumption is higher in MIMO. However, MIMO performs much better than SISO in terms of transmit energy efficiency. On the other hand, MIMO systems require less transmission energy for the same throughput requirements. Although both the circuit energy consumption and the transmit energy consumption should be taken into account in terms of the energy efficiency, MIMO is considered more energy efficient than SISO since the circuit energy consumption is often negligible compared to the transmit energy consumption.

1.3 Contributions to Energy Harvesting Wireless Networks

As noted above, one of the pressing issues in wireless networking research is how to best reduce the communication energy consumption in order to maximize the network's lifetime. While energy harvesting is a promising approach to ensure the continued operation of wireless networks, as discussed above, even with energy harvesting, there may be times when the energy source is not available, and hence it is important to ensure that the network is energy efficient and the energy usage is balanced across the nodes in the network. In addition to providing energy balance in the network, it is also important to maintain other factors such as coverage, connectivity, and resiliency to network dynamics.

This thesis aims to address these issues in MIMO wireless networks with energy harvesting in order to increase energy efficiency and maximize network lifetime. The specific contributions of my work include the following:

- I modeled the problem of dynamically adjusting the number of antennas based on the nodes' energy levels. Based on the nodes' distance, remaining energy, and the target Bit-Error-Rate, a multi-antenna scheme (MIMO, MISO, SIMO, SISO) is chosen for communication on a per-packet basis. The multi-antenna scheme is chosen such that the system total energy consumption is minimized and the lifetime is maximized. This work has been described in [9] and in detail in Chapter 3.

- I introduced a simulation framework for MIMO wireless networks for the ns-3 simulator. This framework is described in [10]. Moreover, an energy prediction model for energy harvesting is also proposed for the ns-3 simulator and is described in [11]. Both of these contributions to ns-3 are explained in detail in Chapter 3.

- I have extended the MIMO energy model described in Chapter 3 by employing energy harvesting. I modeled the system using a Markov Decision Process (MDP) and optimized the communication using reinforcement learning. The MDP states are defined based on the transmitter-receiver power consumption ratio and the actions are the four multi-antenna schemes that can be employed for communication. By using Q-learning and defining the reward function based on the remaining energy, energy consumption, and the distance, the optimal multi-antenna scheme is found on a per-packet basis. This work is presented in [12] and explained in Chapter 4.

- As a follow up to the work presented in [9] and Chapter 3, I extended the idea of balancing the nodes' energy through selection of the number of antennas to a network with more than two nodes. I proposed a protocol called MAC-LEAP: Multi-Antenna, Cross Layer, Energy Adaptive Protocol for both single-hop and multi-hop MIMO wireless networks. This work is described in [10]. Moreover, I have employed MAC-LEAP in a real life application called JumboNet [13], and evaluated MAC-LEAP in a JumboNet mobile wireless network using the Epidemic routing protocol [14]. This work is presented in [15] and described in Chapter 5.

- To improve the scalability of multi-antenna networks, I proposed Cluster-based MIMO (CMIMO), an energy efficient MIMO protocol for cluster-based networks. CMIMO employs the Online Policy from MAC-LEAP to adjust the number of antennas for the normal node-Cluster Head communication. CMIMO can be employed in both a wireless network with fixed nodes and non-rechargeable batteries, and a wireless network with mobile nodes and rechargeable energy sources. This work is described in Chapter 6.

Chapter-2

Related Work

In this chapter, we provide an overview of the previous work in terms of energy efficiency in wireless networks, MIMO wireless networks, and clustering algorithms in wireless networks.

2.1 Energy Efficiency in Wireless Networks

Energy is one of the most important factors in wireless networks since it has a direct effect on the nodes' lifetimes. By increasing the energy efficiency of the network, the network lifetime increases, and thus the data communication can continue for longer periods of time. On the other hand, by having higher energy in the nodes' buffers, more data will be transmitted for a given amount of energy consumption. There are many different approaches that can be beneficial for energy conservation in these networks, such as energy efficient routing protocols [16, 17, 18, 19, 20, 21], energy harvesting approaches [22, 23, 24, 13, 25, 26, 27], MAC protocols based on wake-up radios and duty cycling [28, 29, 30, 31], transmission power adjustment methods [32, 33, 34], and employing multi-antenna (MIMO) schemes [35, 36, 37, 38, 39, 40].

For energy efficient routing protocols, current remaining energy is considered as a routing metric. In [19], two cost functions are defined in the routing protocol that map any change of the remaining energy into a large value. In this way, higher priority is given to the nodes that have higher energy in their buffer. In [21], the cost function of the routing protocol depends on both the energy levels and the distances of the nodes. A multi-path routing protocol is introduced in [16] that provides two collision-free routes between the source and the destination in order to improve the network reliability, especially when the nodes in one of the routes run out of energy. In [17, 18] the architecture of the network is designed based on clusters in order to not only make the routing more energy efficient but also make the network more scalable. In cluster-based wireless networks, the routing is more energy efficient since the regular nodes are connected to the cluster head and the cluster heads are the only nodes that have routing overhead. Thus, the cluster heads consume more energy and other nodes can save more energy while the data is routed to the destination.

Energy harvesting is also employed in many networks to overcome the energy shortage problems. Energy harvesting is a technology whereby energy is harvested from ambient sources in the environment such as solar [22, 23], wind [24], kinetic energy [13], and thermal [25, 26]. The ambient energy is converted to electrical energy and consumed by the nodes or saved for later use. It is important to note that the nodes may still suffer from energy shortage when the ambient energy is unavailable. Therefore, even with employing energy harvesting, implementation of energy saving mechanisms is needed. For instance, in [22], a data gathering protocol with a duty-cycling MAC layer is proposed for environmental monitoring to detect environmental hazards such as floods and harsh weather conditions. The energy of the nodes is provided using solar panels and two rechargeable batteries. Although energy harvesting is employed, the proposed protocol in [22] reduces overall energy consumption in low data rate communications.

Wake-up radios are also very efficient in terms of energy consumption. The key in these schemes is to manage the energy consumption during the duty-cycle (sleep time plus the wakeup time) in order to save energy on idle listening. Moreover, synchronization is also an issue since for a successful communication both sender and receiver nodes should be awake. In synchronized protocols such as S-MAC [28] and T-MAC [29], the sender and the receiver nodes agree on a schedule for communication such that both nodes are awake during the data transmission.

In asynchronous protocols or low power listening protocols such as B-MAC [30] and X-MAC [31], preamble sampling is employed before the sender and the receiver start communicating. B-MAC is a CSMA-based MAC protocol in which is based on Clear Channel Assessment (CCA). In this protocol, the sender node sends a wakeup signal (preamble) before the data transmission to the receiver. The receiver node periodically wakes up and checks the channel for activity. As soon as a node receives the wakeup signal, it stays awake to receive the data packet. Although B-MAC is energy efficient, a node may stay awake for a while to receive the data packets destined for other nodes and waste energy. In X-MAC, this problem is solved by using a strobed preamble consisting of several short preambles. Prior to data transmission, the sender sends a sequence of these short preambles, each of which contains the destination address. When a node receives a short preamble, if the address is not itself, the nodes goes back to sleep. When the destination node receives one of these preambles, it acknowledges the sender. Thus, the sender stops sending these preambles and starts sending the data.

2.2 MIMO Wireless Networks

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 communication: 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 [41], 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 [42, 43, 44], 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 [45], 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 [46] 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 [45] and [46] 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 [47], 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 [48], a MAC protocol is presented for ad-hoc networks with MIMO links, where the authors focus on the fair channel allocation problem.

In [49], the physical and MAC layers collaborate to exchange channel state information (CSI) for effective data communication. In [50], 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 [50] 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 [51], the number of antennas should be decided by the receiver and sent back to the sender. The proposed protocol in [51] switches between MIMO and Single-Input Multiple-Output (SIMO) to achieve higher energy efficiency, which is more significant when the channels are correlated.

In [52], a cluster-based 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 communication. 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 [53] 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 where 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 conditions.

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.

2.3 Cluster-based Wireless Networks

In order to increase network scalability, a group of wireless nodes can form a cluster in which one of the nodes acts as leader (Cluster Head (CH)). A cluster-based wireless network has two or more tiers. The lowest tier are the normal wireless nodes that communicate with the CHs. The upper tiers are the CHs, which communicate with each other. Clustering has various advantages. Thanks to this architecture, communication bandwidth and redundant message exchanges among the nodes are reduced, since the normal nodes only communicate with their assigned CHs [54].

In such networks, the nodes with higher energy levels are chosen as CHs and are responsible for more complicated tasks compared to the normal nodes with lower energy levels [55]. CHs can also employ energy saving strategies and data processing techniques in order to prolong the CH's battery life and enhance the communication. Moreover, the normal nodes are not affected by the overhead caused by changes at the CH level [56].

In order to use the nodes' resources evenly, a CH rotation policy can be used. In LEACH [57], a node decides to be a CH with a probability p and broadcasts its decision to the other nodes. The nodes choose their CH according to the least communication energy required to reach the CH. The CH role is rotated among the nodes in the network. According to the CH rotation policy, each node chooses a random number between 0 and 1. If the number is less than a certain threshold, the node becomes the next CH.

Another way of choosing CHs is based on the residual energy. Unlike LEACH, which chooses the CHs randomly, in HEED [58] the nodes having high residual energy are more likely to be CHs. Moreover, HEED chooses the CHs such that the probability of two nodes becoming CHs is small if they are in each other transmission range. In HEED, all nodes have a probability of being a CH based of the ratio of their remaining energy and battery capacity. When this probability is 1 (the battery of the node is full), the node becomes a CH with $\%100$ probability. Otherwise, if the probability is less than 1, the node is a tentative CH that can change its status to a regular node if it finds a lower cost CH.

From a routing perspective, the data transmission in cluster-based networks can be divided into intra-cluster and inter-cluster communications. Both of these communication types can be either single-hop or multi-hop. Single-hop intra-cluster routing is when the normal node sends the data packets directly to the CH. Although the propagation is simple in this case, intra-cluster multi-hop routing [59, 60, 61] is required when the communication range of the CH/normal nodes is limited within the cluster.

In some of the routing protocols such as LEACH, it is assumed that the nodes have long communication range that allows direct communication. It is not very energy efficient to have direct data transmission among the nodes, especially if the sink is located very far from the nodes. Multi-hop inter-cluster routing is a solution to this issue [62]. In inter-cluster routing with multi-hop communication, CHs can be organized as a hierarchy [61, 63]. Although the maintenance of the hierarchy can be costly as the network gets larger, this provides better energy distribution among the nodes and enhances the overall energy consumption.

Chapter-3

Transmitter-Receiver Energy Trade-off in MIMO Wireless Networks

3.1 Introduction

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 wireless networks due to its potential to dramatically improve the data throughput and radio energy efficiency without increasing the total transmission power [64] [65]. 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 [64].

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 [45, 46, 65, 66]. 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 [66], 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 [66] 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 [67]. Alternatively, to manage the energy efficiently, the number of antennas can be chosen dynamically for each neighbor node based on their transmission distance [53]. 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 node's remaining energy and energy consumption coupled with dynamic antenna selection that are highly effective in improving the energy efficiency of MIMO systems.

In this chapter, we model the problem of dynamically adjusting the number of antennas based on the nodes' energy levels. We propose an *Optimal Policy* in which an energy balancing model is applied in the network based on the various requirements of the nodes. 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 nodes' 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.

3.2 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. 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.

3.2.1 Energy Consumption Model

Consider a single hop communication link with a transmitter node *tx* and a receiver node *rx*. Nodes are static and time is slotted such that every time slot includes the fixed transmission time of a packet and the subsequent retransmissions due to unsuccessful delivery. The nodes are powered through a battery and, at a generic time slot t, the remaining energy of the transmitter and the receiver nodes 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_{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 [9].

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

$$\begin{aligned} P_{C}^{rx}(M_{rx}) = M_{rx}(P_{\mathrm{ADC}} + P_{\mathrm{Mix}} + P_{\mathrm{Fil}}^{rx} + P_{\mathrm{Dem}} + \\ + P_{\mathrm{IFA}} + P_{\mathrm{LNA}}) + P_{\mathrm{Syn}}, \end{aligned} \tag{3.1}$$

where P_{ADC} represents the power consumption of the Analog-to-Digital converter (ADC), P_{Mix} is the power consumption of the mixer, P_{Fil}^{rx} 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

$$P_{tx}(M_{tx}, M_{rx}) = P_{\mathrm{PA}}(M_{tx}, M_{rx}) + P_{\mathrm{C}}^{tx}(M_{tx}), \tag{3.2}$$

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

$$P_{\mathrm{C}}^{tx}(M_{tx}) = M_{tx}(P_{\mathrm{DAC}} + P_{\mathrm{Mix}} + P_{\mathrm{Fil}}^{tx} + P_{\mathrm{Mod}}) + P_{\mathrm{Syn}}, \tag{3.3}$$

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 $P_{\mathrm{PA}}(M_{tx}, M_{rx})$ depends on the transmission power P_{out} and the modulation scheme [68], and is expressed as

$$P_{\mathrm{PA}}(M_{tx}, M_{rx}) = \left(1 + \frac{\xi}{\eta}\right) P_{\mathrm{out}}(M_{tx}, M_{rx}), \tag{3.4}$$

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 here, 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 [69]:

$$P_{\text{out}}(M_{tx}, M_{rx}) = \overline{E_b}(M_{tx}, M_{rx}) R_b \left(\frac{4\pi d}{\lambda}\right)^k \frac{M_l N_f}{G_{tx} G_{rx}}, \tag{3.5}$$

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 3.2.2. 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

$$E_{\text{pkt}}^{X}(M_{tx}, M_{rx}) = \frac{P_X(M_{tx}, M_{rx})}{R_b} N, \tag{3.6}$$

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, the number of successful packets that can be processed by the nodes using a $M_{tx} \times M_{rx}$ MIMO scheme is

$$L_X^t(M_{tx}, M_{rx}) = \frac{B_X^t}{E_{\text{pkt}}^{X}(M_{tx}, M_{rx}) \frac{1}{1 - p_{\text{pkt}}}}, \tag{3.7}$$

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 expected total number of packets that can be successfully received is given by

$$L^t(M_{tx}, M_{rx}) = \min\{L_{tx}^t(M_{tx}, M_{rx}), L_{rx}^t(M_{tx}, M_{rx})\}. \tag{3.8}$$

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.

3.2.2 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 [70]:

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

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.

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) [71], 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 [72]:

$$P_{\alpha}(\alpha) = Q\left(\sqrt{\frac{2\alpha\rho}{M_{tx}}}\right), \tag{3.9}$$

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

$$f_{\alpha}(\alpha) = \frac{\alpha^{(M_{tx}M_{rx}-1)}e^{-\alpha}}{(M_{tx}M_{rx}-1)!}, \quad \alpha > 0. \tag{3.10}$$

Thus, the average BER of the channel is

$$p_b = \mathbb{E}[P_{\alpha}(\alpha)] = \int_0^{\infty} Q\left(\sqrt{\frac{2\alpha\rho}{M_{tx}}}\right) f_{\alpha}(\alpha) d_{\alpha}. \tag{3.11}$$

By substituting Eq. (3.10) in Eq. (3.11) and solving the integral, we obtain the BER of the channel as [70]:

$$p_b = \left(\frac{1}{2}(1-\zeta)\right)^L \cdot \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left(\frac{1}{2}(1+\zeta)\right)^l, \tag{3.12}$$

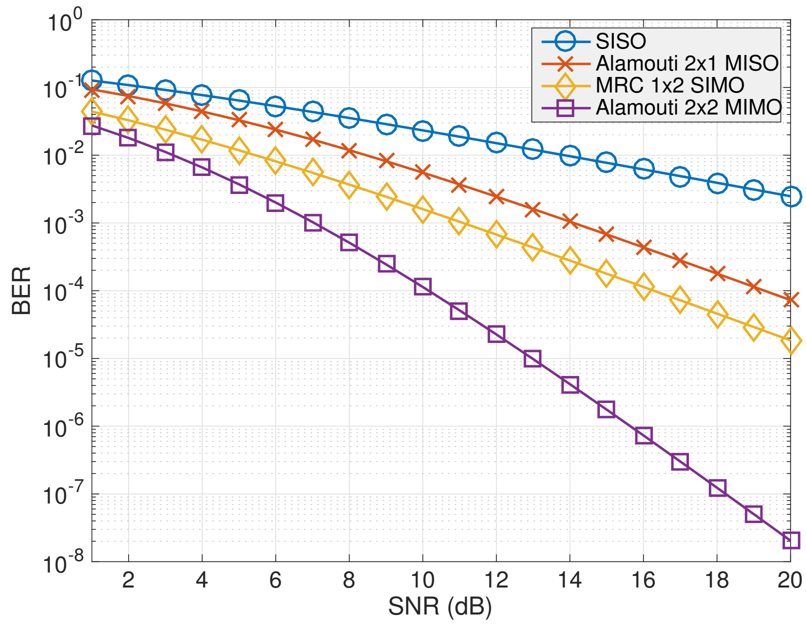


Figure 3.1: BER versus SNR for MIMO, MISO, SIMO, and SISO.

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

$$p_b = \frac{1}{2}\left(1 - \sqrt{\frac{\rho}{1+\rho}}\right). \tag{3.13}$$

Using Eq. (3.12), we can find the BER versus SNR (ρ) for different MIMO schemes in a Rayleigh fading channel with BPSK modulation, as shown in Fig. 3.1.

3.2.3 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. 3.2 for various distances, and in Fig. 3.3 for various BERs. We note that, according to the 802.11n standard that uses MIMO communications, the wireless nodes' outdoor coverage is 250 meters [73].

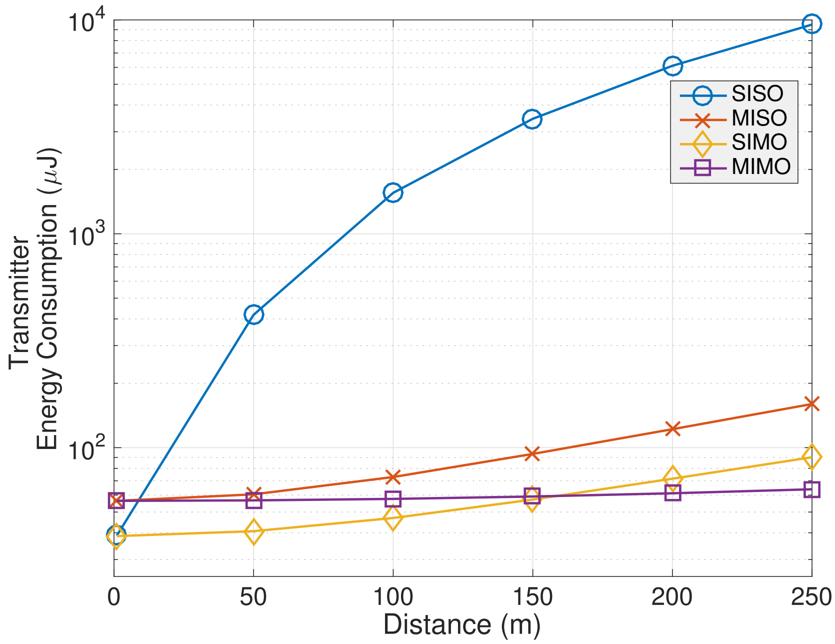
The receiver energy consumption depends only on the number of antennas so it remains constant as distance and BER vary. As shown in Fig. 3.2(b) and Fig. 3.3(b), SISO and MISO, which are two schemes that employ one antenna to receive the data, have lower receiver energy consumption than MIMO and SIMO 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. 3.2(a), in distances smaller than 5 meters, 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. 3.3(a), the transmitter consumes less energy by using SIMO in high channel BER. However, as BER decreases, MIMO is a better option in terms of the transmitter energy consumption compared to the other three antenna modes.

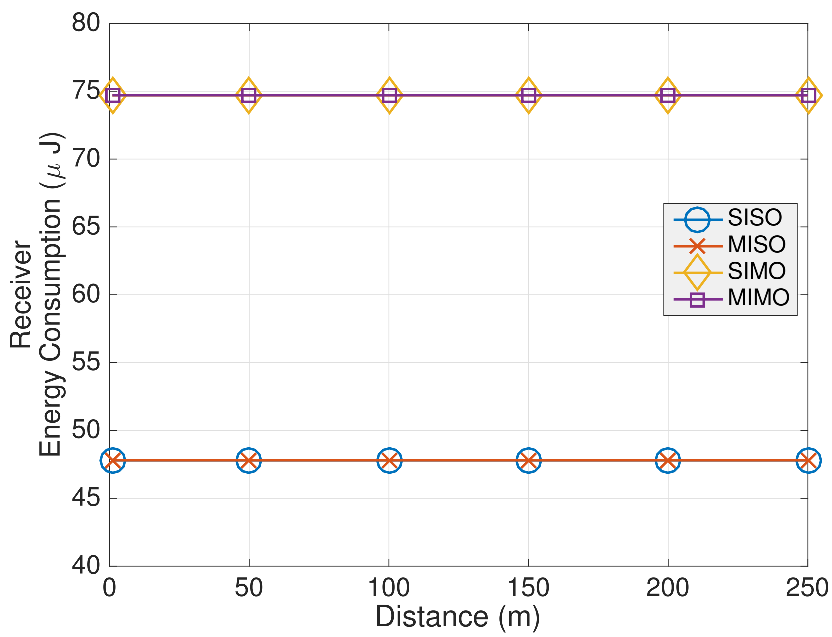
According to Fig. 3.2(b) and Fig. 3.3(b), depending on the number of antennas at the nodes, their distance or the channel BER, the employed MIMO scheme can be energy efficient either for the transmitter or the receiver. For instance, although SISO is more energy efficient than MIMO at the receiver side, 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.

3.3 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

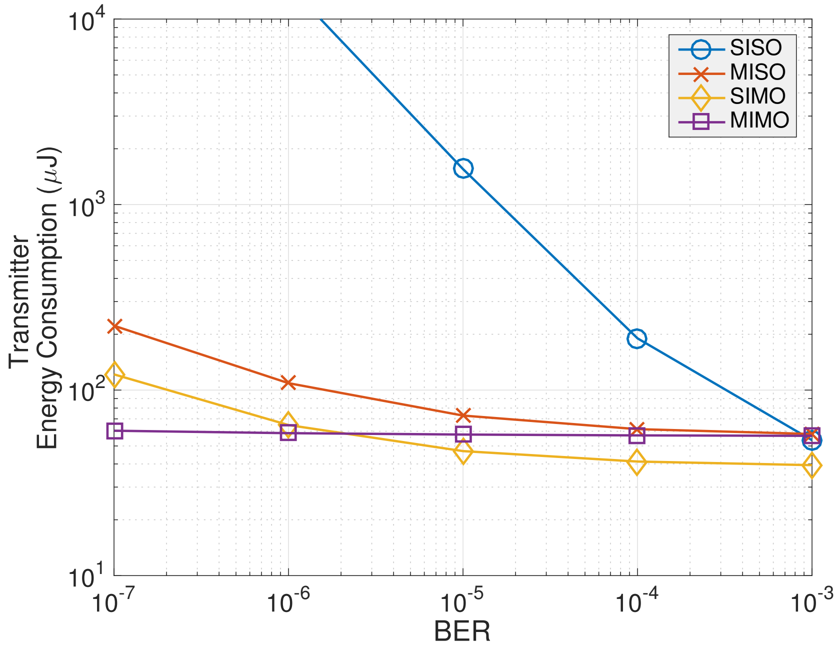


(a) Transmitter energy consumption

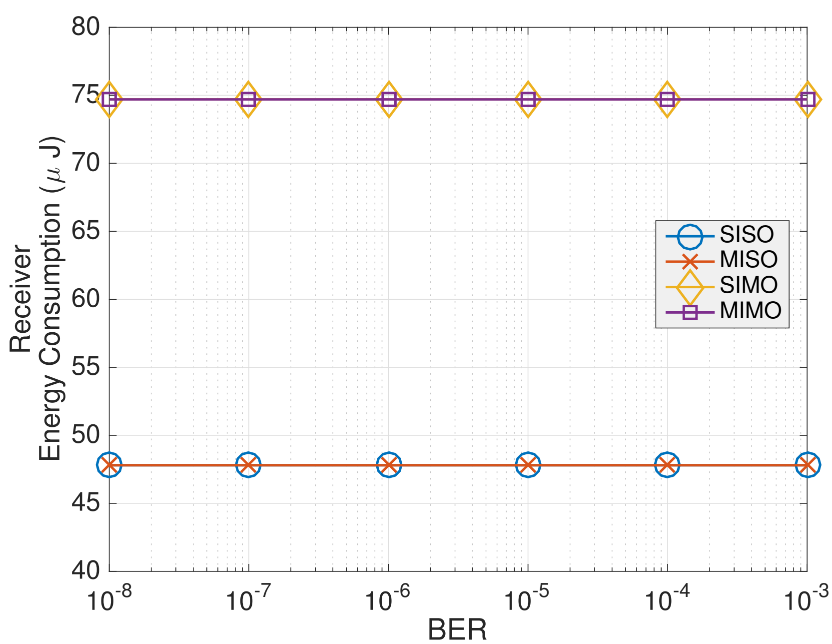


(b) Receiver energy consumption

Figure 3.2: Energy consumption per bit for (a) the transmitter node and (b) the receiver node for different distances (BER=10^{-5}).



(a) Transmitter energy consumption



(b) Receiver energy consumption

Figure 3.3: Energy consumption per bit for (a) the transmitter node and (b) the receiver node for different Bit-Error-Rates (distance = 100m).

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 complexity and requirements in term of information that needs to be exchanged between the nodes.

3.3.1 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:

$$\max \sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} \tag{3.14}$$

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 (3.14) 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 such as Mixed Integer

Linear Programming (MILP) algorithm in Matlab to solve this optimization problem.

3.3.2 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, 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}^txM_{rx}^t that provides the highest system lifetime, according to Eq. (3.8). 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., $B_{tx}^{t+1} = B_{tx}^t - E_{\text{pkt}}^{tx}(M_{tx}^t, M_{rx}^t)$ 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.

3.3.3 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 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 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 node lifetime through the RX policy and TX policy using the following equations,

$$S_{TX} = \text{argmax}_{(M_{tx},M_{rx})} L^0_{tx}(M_{tx}, M_{rx}) \tag{3.15}$$

$$S_{RX} = \text{argmax}_{(M_{tx},M_{rx})} L^0_{rx}(M_{tx}, M_{rx}) \tag{3.16}$$

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^0_{tx} and B^0_{rx}, respectively.

By combining Eq. (3.15) into Eq. (3.8), the lifetime of a system that uses the *TX Policy* is given by

$$L_{TX} = \min\{L^0_{tx}(S_{TX}), L^0_{rx}(S_{TX})\}. \tag{3.17}$$

Similarly, by combining Eq. (3.16) into Eq. (3.8), the lifetime of a system that uses the *RX Policy* is given by

$$L_{RX} = \min\{L^0_{tx}(S_{RX}), L^0_{rx}(S_{RX})\}. \tag{3.18}$$

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.

3.4 Simulation Results

In this section, we study the performance of the policies presented in Section 3.3. 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

Table 3.1: Simulation Parameters for Evaluating Transmitter-Receiver Trade-off in MIMO Wireless Network

General Parameters		Circuitry Power Consumption	
k	2	P_{DAC}	7 mW
f_c	2.5 GHz	P_{ADC}	7 mW
N	1000 bits	P_{Mix}	30.3 mW
N_f	10 dB	P_{Syn}	50 mW
N_0	-174 dBm/Hz	P_{Filt}^{tx}	2.5 mW
B	10 KHz	P_{Filt}^{rx}	2.5 mW
G_tG_r	5 dBi	P_{LNA}	20 mW
η	0.35	P_{IFA}	5 mW

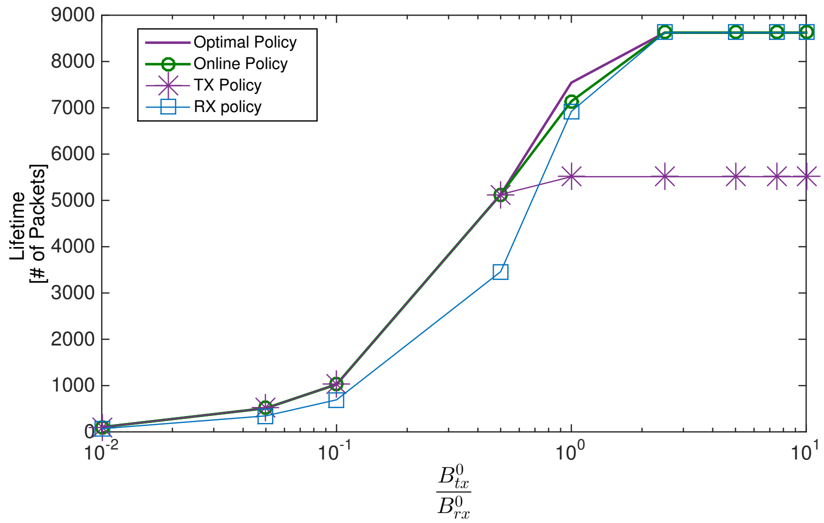


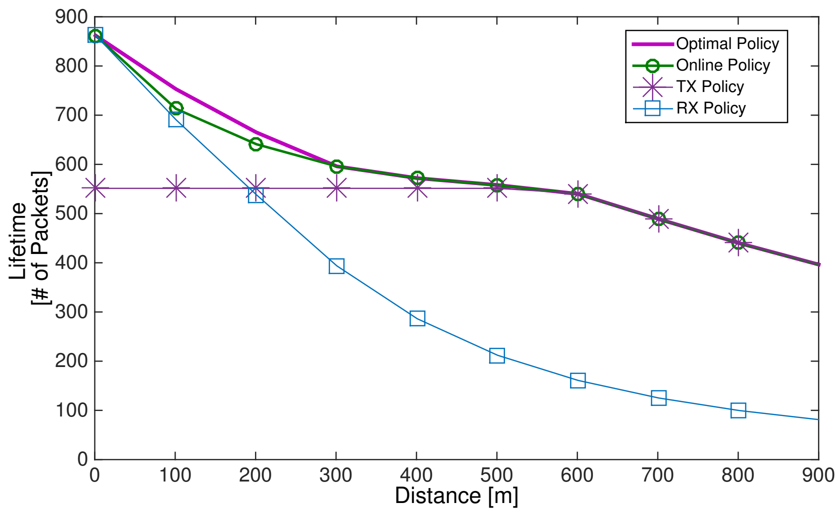
Figure 3.4: System lifetime vs. initial energy ratio at the transmitter and the receiver (d=100 m , $P_b = 10^{-5}$).

system parameters are taken from [74, 75, 76, 77] and listed in Table 5.2 for completeness. Moreover, we assume that the nodes are equipped with $M = 2$ antennas and use an orthogonal rate 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.

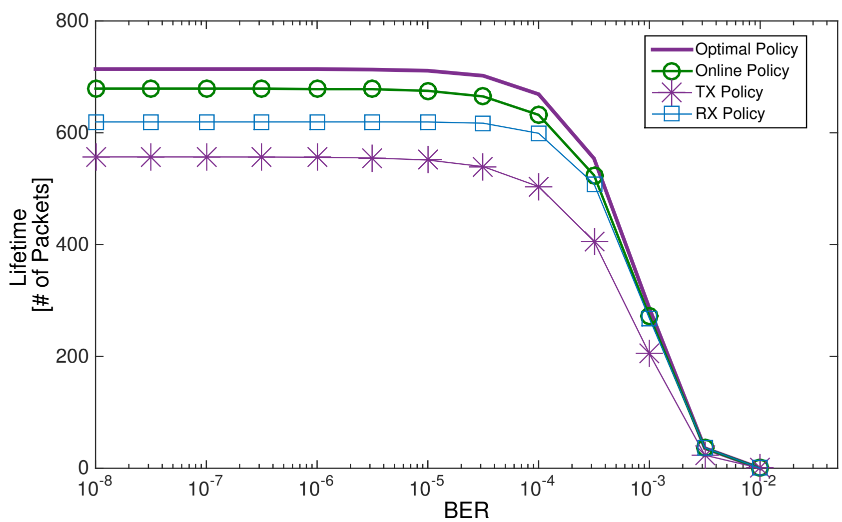
In Fig. 3.4, we show the impact of the transmitter and receiver initial energy ratio on the system lifetime. As expected, the *Optimal Policy* performs best for all the B_{tx}^0/B_{rx}^0, followed by the *Online Policy* which is able to adapt to the changes in energy levels. The *TX Policy* and *RX Policy*, 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 $B_{tx}^0/B_{rx}^0 = 1$, 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 $B_{tx}^0 = B_{rx}^0 = 10$ J.

Fig. 3.5 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 Figs 3.2 and 3.3), 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. 3.6, we show the total system lifetime as a function of the transmission distance for a fixed BER (Fig. 3.6(a)), and as a function of the BER values for a fixed distance (Fig. 3.6(b)). The *RX Policy* chooses the antenna mode that has the lowest receiver energy consumption for each distance. Thus, as shown in Fig. 3.2(b) and 3.3(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. 3.2(a) and 3.3(a), this policy selects either SIMO 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. 3.6 shows the impact on

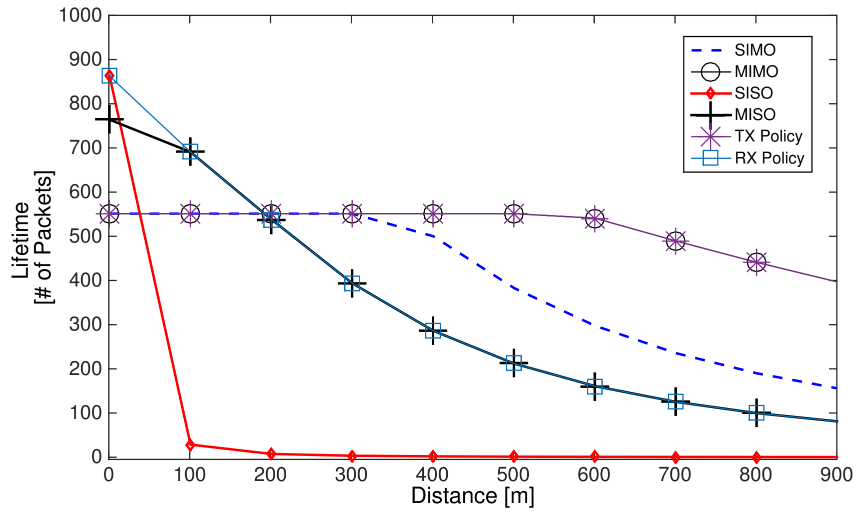


(a) Total lifetime vs. distance (p_b =10^{-5})

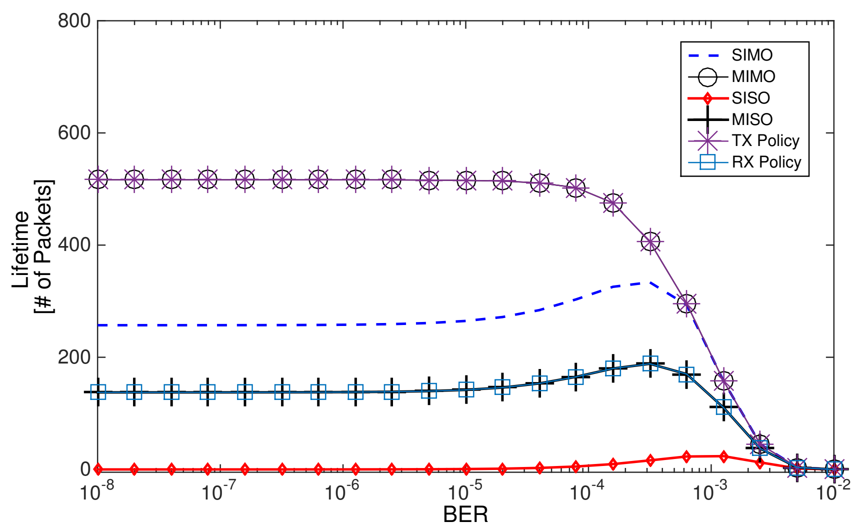


(b) Total lifetime vs. BER (d = 150 m)

Figure 3.5: 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)

Figure 3.6: System lifetime vs. distance (a) and BER (b) for the *TX Policy*, *RX Policy* and a policy that always select a fixed MIMO scheme.

the system lifetime of accounting for the nodes' energy levels in the selection of the communication schemes to be used.

3.5 Conclusions

In this chapter, 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 wireless networks.

Another solution to energy conservation is energy harvesting in which the nodes' energy is provided through an ambient source such as sun, wind, vibration, etc. Employing both energy harvesting and the proposed MIMO energy balancing model is even more beneficial in terms of energy conservation. It is also essential to find the most efficient number of antenna in such a system. Modeling this system can be done through a Markov Decision Process (MDP). In order to solve the MDP, we can use reinforcement learning to find the optimal transmission policy, which is discussed in detail in the next chapter.

Chapter-4

Q-Learning Model For Transmitter-Receiver Energy Balance

4.1 Introduction

Traditional wireless networks are equipped with battery-operated nodes that have limited capacity and thus limited lifetime. To solve this issue, employing energy harvesting in these networks is essential. Wireless networking with energy harvesting is an emerging area that has received much attention during the past few years. The energy in such networks is provided using ambient sources such as the sun, wind, or vibration. Moreover, employing multi-antenna or Multiple-Input Multiple-Output (MIMO) communication in the network results in not only a longer lifetime but also a higher spectral and energy efficiency in the network.

Energy harvesting networks can be divided into two categories based on knowledge of the energy arrival process [78]. In the first category, the online energy management framework, the nodes have the knowledge about the available energy and can make an online decision about the best course of action to take for reward maximization based on the current state and prior states. This case can be modeled as a Markov Decision Process (MDP), and an optimal solution can be found through dynamic programming, or reinforcement learning methods. For example, the MDP model proposed in [79] is based on finding the optimal power allocation policy for throughput maximization. Similarly, in [80], the authors model a wireless sensor network equipped with energy harvesting as a MDP in order to find an optimal transmission policy for communication.

In the second category, the offline energy management framework, however, knowledge of the energy harvesting process is assumed to be known ahead of time. Many offline strategies are considered for throughput maximization, by adapting the transmission rate based on the energy harvesting distribution[81], the assumed battery imperfections [82], for MIMO channels [83]. Moreover, in [84] and [85], both online and offline approaches are explored. In this work, the authors formulate both the data and energy arrivals as a Markov process and solve this MDP using a proposed learning method based on Q-learning. In [84], the authors studied the maximization of total transmitted data during the transmitter activation time and they showed that as the learning time goes to infinity, the performance reaches the optimal value. In [85], an optimal power allocation policy that maximizes the throughput is the goal of the learning process. Moreover, the state space defined in [85] for the Markov process depends on the nodes' energy and thus it is a continuous state space, which is relaxed through a linear function approximation to handle the infinite number of states. In [86], the authors studied the online and offline problems with the goal of throughput maximization in a fading channel assuming that the energy arrival follows a stochastic process. In this case, they used dynamic programming to find an optimal solution.

In practical situations, however, the exact information of the harvested energy is not known. The harvested energy varies depending on different factors, such as the weather conditions. For instance, in a wireless network utilizing solar or wind power, the amount of harvested energy will be different for sunny, cloudy, or windy days. Thus, we do not have exact information about the harvested energy in reality unless the energy arrival is highly deterministic. In order to find the best transmission policy in the situation with unknown harvesting energy arrival, we propose an approach that is based on reinforcement learning[87].

To the best of our knowledge, no prior work has considered the use of learning approaches in MIMO communication in order to find the best transmission policy in terms of maximum throughput by changing the number of antennas of the nodes. In this chapter, we consider a point-to-point MIMO wireless communication link in which we have two nodes equipped with energy harvesters and rechargeable batteries. The goal is to maximize the total throughput during a specific time that the system is running. We model the system using a finite MDP with unknown transmission probabilities and find an optimal transmission policy using Q-learning. We consider four transmitter-receiver antenna pairs in the MIMO system, each of which may result in different energy consumption for the nodes. Based on the energy consumption and the harvested energy arrival, we employ Q-learning to find the most energy efficient transmission policy.

4.2 Energy Consumption Model

We used the energy consumption model that was explained in Chapter 3. Based on this energy consumption model, the energy consumption of the transmitter and the receiver for a packet with a size of m bits are:

$$E_{tx}^{M_{tx}\times M_{rx}}(t) = \frac{P_{tx}\, m}{R_b},\ E_{rx}^{M_{tx}\times M_{rx}}(t) = \frac{P_{rx}\, m}{R_b}, \tag{4.1}$$

where $P_{tx} = P_{\mathrm{C}}^{tx}(M_{tx}) + P_{\mathrm{PA}}(M_{tx}, M_{rx})$ and $P_{rx} = P_C^{rx}(M_{rx})$ are the total energy consumption for the transmitter and the receiver, respectively.

We consider an energy harvesting system in which the nodes know the distribution of the harvested energy. However, they don't know the exact value of the incoming harvested energy in the future time slots. If we assume that the remaining energy of the transmitter node and the receiver node at time t are $B_{tx}(t)$ and $B_{rx}(t)$, and the amount of harvested energy for the nodes are $H_{tx}(t)$ and $H_{rx}(t)$, which follow a uniform distribution, the remaining energy at slot t is $B_X(t) = B_X(t-1) + H_X(t) - E_X^{M_{tx}\times M_{rx}}(t)$ for the transmitter ($X = tx$) and the receiver ($X = rx$). Thus, at time t we can define the number of packet that can be sent ($N_{tx}(t)$) and received ($N_{rx}(t)$) at the transmitter and the receiver, respectively, as

$$\begin{aligned} N_{tx}(t) &= \frac{B_{tx}(t)}{E_{tx}^{M_{tx}\times M_{rx}}(t) \times \frac{1}{1-p_{pkt}}} \\ N_{rx}(t) &= \frac{B_{rx}(t)}{E_{rx}^{M_{tx}\times M_{rx}}(t) \times \frac{1}{1-p_{pkt}}}, \end{aligned} \tag{4.2}$$

where $0 \leq t \leq T_s$, T_s is the total run time of the network, M_{tx} and M_{rx} are the number of antennas at the transmitter and the receiver nodes, respectively, and p_{pkt} is the packet's probability of error.

Therefore, the maximum number of packets that can be successfully received by the receiver is given by $N(t) = \min\{N_{tx}(t), N_{rx}(t)\}$.

While the network is running, the nodes receive harvested energy at every time slot t. When a node runs out of energy, it stops sending/receiving packets and start recharging its battery using the harvested energy until the battery is charged enough for the communication. Assuming that at most one packet is sent at time slot t, our goal is to maximize the throughput of the communication system R, which is defined as the total number of packets that are successfully received in the network runtime T_s:

$$R = \max_{\pi} \min \left\{ \frac{N_{tx}(T_s)}{T_s}, \frac{N_{rx}(T_s)}{T_s} \right\}, \tag{4.3}$$

where π is a particular policy that contains the sequence of (M_{tx}, M_{rx}) for all the time slots $t = 0, \ldots, T_s$.

4.3 Offline Optimal Policy with Energy Harvesting

In the offline energy management framework, the nodes have perfect knowledge of the energy harvesting process, and hence can select the communication scheme (SISO, SIMO, MIMO or MISO) for each transmission in an optimal way. The formulation is the same as Eq. 3.14 with the addition of energy harvesting. The total number of packets that can be received successfully using an offline optimal policy can be found as

$$\max \textstyle\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} \tag{4.4}$$

s.t.

$$\textstyle\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E_{\mathrm{PKT}}^{tx} \leq B_{tx}^{0} + H_{tx}^{T_s}$$
$$\textstyle\sum_{M_{tx}=1}^{M} \sum_{M_{rx}=1}^{M} \alpha_{M_{tx},M_{rx}} E_{\mathrm{PKT}}^{rx} \leq B_{rx}^{0} + H_{tx}^{T_s}$$

where T_s is the total duration that the network is running. $H_{X}^{T_s}$ represents the total harvested energy by the transmitter (X=tx) and the receiver (X=rx) until time T_s, and $E_{\mathrm{PKT}}^{\mathrm{X}}(M_{tx}, M_{rx})$ represents the transmitter (X=tx) and the receiver (X=rx) energy consumptions of the M_{tx}xM_{rx} MIMO scheme when the data packet is successfully transmitted. 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 number of received packets and thus the system throughput will be maximized.

This optimal policy works offline and requires information about the initial energy levels, the total harvested energy from the initial time until T_s, and the energy consumption for each communication scheme. Although the offline optimal policy is not reachable in practice, it provides an upper bound on the performance attainable by different communication policies. Moreover, since the number of communication schemes is small in our case, Mixed Integer Linear Programming (MILP) algorithms can efficiently solve the problem in a small amount of time.

4.4 Markov Process Model for MIMO Communication with Energy Harvesting

We model the system with a finite-state continuous-time MDP, represented by the quadruplet $\langle \mathcal{S}, \mathcal{A}, \mathcal{P}(s,a,s'), \mathcal{R}(s,a,r) \rangle$, where $\mathcal{S}$ is the set of states, $\mathcal{A}$ is the set of actions, $\mathcal{P}(s,a,s')$ defines the probability of going from a state s to a state s' when taking action a, and $\mathcal{R}(s,a,r)$ represents the reward r of selecting action a at state s. The set of states and the reward function are defined below.

In order to find the throughput in Eq. (4.3), we need to know the relationship between $\frac{B_{tx}(t)}{E_{tx}(t)}$ and $\frac{B_{rx}(t)}{E_{rx}(t)}$ for all four MIMO schemes to figure out which one maximizes the throughput. Thus, the set of states $\mathcal{S}$ contains the energy intervals that the fraction $\frac{B_{rx}}{B_{tx}}$ falls into and the set of actions $\mathcal{A} = \{a_1, a_2, a_3, a_4\} = \{\text{SISO, MISO, SIMO, MIMO}\}$, which are different numbers of antenna pairs for the transmitter and the receiver.

As stated in [9], the power consumption of the receiver node depends only on the number of antennas and thus $P_{rx}^{MIMO}(t) = P_{rx}^{SIMO}(t)$ and $P_{rx}^{SISO}(t) = P_{rx}^{MISO}(t)$. Thus, we have

$$\frac{B_{rx}(t)}{E_{rx}(t)} \lesseqgtr \frac{B_{tx}(t)}{E_{tx}(t)} \quad \Leftrightarrow \quad \frac{B_{rx}(t)}{B_{tx}(t)} \lesseqgtr \frac{E_{rx}(t)}{E_{tx}(t)}$$

where

$$\frac{E_{rx}(t)}{E_{tx}(t)} = \frac{\{P_{rx}^{SISO}(t), P_{rx}^{MISO}(t), P_{rx}^{SIMO}(t), P_{rx}^{MIMO}(t)\}}{\{P_{tx}^{SISO}(t), P_{tx}^{MISO}(t), P_{tx}^{SIMO}(t), P_{tx}^{MIMO}(t)\}} \tag{4.5}$$

Thus, in general we have 16 cases in terms of transmitter-receiver power consumption ratios that equal $\frac{E_{rx}(t)}{E_{tx}(t)}$, which can be reduced to 8 since $P_{rx}^{SISO}(t) = P_{rx}^{MISO}(t)$ and $P_{rx}^{MIMO}(t) = P_{rx}^{SIMO}(t)$. Therefore,

$$\frac{E_{rx}(t)}{E_{tx}(t)} = \frac{E_{rx}^{a_i}(t)}{E_{tx}^{a'_j}(t)} \tag{4.6}$$

where $a_i, a'_j \in \mathcal{A}$ and $i = \{1, 3\}$ and $j = \{1, 2, 3, 4\}$.

As stated in [9], for a specific distance and bit-error-rate (BER), the value of $E_{rx}(t)$ and $E_{tx}(t)$ are known. Thus, $\frac{B_{rx}(t)}{B_{tx}(t)} \in \left[\frac{E_{rx}^{a_i}(t)}{E_{tx}^{a'_j}(t)}, \frac{E_{rx}^{b_i}(t)}{E_{tx}^{b'_j}(t)}\right]$ where $a_i, a'_j, b_i, b'_j \in \mathcal{A}$ and $i = 1, 3$ and $j = 1, 2, 3, 4$.

We define the state space as $\mathcal{S}$ as $\mathcal{S} = \{s_k, s_{10}\}$, where $s_k = \left[\frac{E_{rx}^{a_i}(t)}{E_{tx}^{a'_j}(t)}, \frac{E_{rx}^{b_i}(t)}{E_{tx}^{b'_j}(t)}\right]$ with $k = \{1, 2, ..., 9\}$, and $s_{10} = \{B_{rx}(t) = 0 \text{ and/or } B_{tx}(t) = 0\}$. Thus, the system state space has ten states, nine states regarding the energy fraction intervals according obtained from Eq. (4.5) and one state where at least one of the nodes runs out of energy.

Moreover, the reward function $\mathcal{R}$ is a function of the remaining energy, energy consumption, and the distance between the nodes:

$$\mathcal{R}(s_i, a_i) = \begin{cases} \frac{1}{E_{tx}^{a_i}(t)} + \frac{1}{E_{rx}^{a_i}(t)} & s_i \neq s_{10} \\ 0 & s_i = s_{10} \end{cases} \tag{4.7}$$

where R is the system throughput, and $E_{rx}^{a_i}(t)$ and $E_{tx}^{a_i}(t)$ are the receiver and the transmitter power consumptions when action $a_i \in \mathcal{A}$ is taken at state $s_i \in \mathcal{S}$. Moreover, we tested other reward functions such as

1. $\mathcal{R}(s_i, a_i) = \begin{cases} -100 & s_i = s_{10} \\ 0 & s_i \neq s_{10} \end{cases}$

2. $\mathcal{R}(s_i, a_i) = \begin{cases} -(E_{tx}^{a_i}(t) + E_{rx}^{a_i}(t)) & s_i = s_{10} \\ 0 & s_i \neq s_{10} \end{cases}$

However, we choose the reward function in Eq. (4.7) which gives better results compared to the others.

4.5 Reinforcement Learning for MIMO Energy Harvesting MDP Model

Since the transition probabilities are not known in the MDP defined in the previous section, in order to find an optimal action-selection policy, we may use the Q-learning algorithm with three different action selection approaches. The first approach is a greedy approach in which the action with the maximum Q-value is considered at each state. The second approach is to employ Softmax action selection, in which an exploration versus exploitation tradeoff is explored and the action is chosen based on a probability in order to maximize the long-term reward. To take advantage of both action selection policies, we additionally consider a third adaptive approach that is a combination of the greedy and Softmax policies.

The updating rule for the Q-values for an action selection policy π is as follows:

$$\begin{aligned} Q^{\pi}(s_i, a_i) =& (1-\alpha)Q^{\pi}(s_i, a_i) + \\ & \alpha[\mathcal{R}_i(s_i, a_i) + \gamma \max_a Q^{\pi}(s_{i+1}, a)] \end{aligned} \tag{4.8}$$

where $0 \leq \alpha \leq 1$ is the learning rate, $0 \leq \gamma \leq 1$ is the discount factor, and $\mathcal{R}_i(s_i, a_i)$ is the reward at state s_i when taking the action a_i.

The optimal policy π^* can be found via Value Iteration. In particular, in every learning iteration, the Q-learning algorithm observes the current state $s_i \in \mathcal{S}$ and select the best action $a_i \in \mathcal{A}$. After applying action a_i, the algorithm observes the next state $s_{i+1} \in \mathcal{S}$ and the immediate reward value $\mathcal{R}_i(s_i, a_i)$. Finally, $Q_{\pi}(s_i, a_i)$ is updated according to Eq. (4.8). It can be shown that iterating this process for a sufficiently large number of learning iteration, the Q-Learning algorithm converges and returns the optimal policy π^*.

4.5.1 Greedy Action Selection Policy

Acting greedily for $Q^\pi(s_i, a_i)$ when the number of states is finite may result in reaching the optimal policy π^*. In a given state s_i, the greedy action selection policy selects the action that achieves the maximum $Q^\pi(s_i, a_i)$. In other words, it selects the a_i that leads to the highest immediate reward R_i.

The problem with the greedy policy is that it is greedy only according to the states that it explored and the energy that it is consumed, which leads to some certain remaining energy intervals of $\frac{B_{rx}(t)}{B_{tx}(t)}$. Thus, it does not have the chance to explore other remaining energy values, which leads to unexplored remaining energy intervals. One solution is to use the ϵ-greedy policy in which, with a probability $1-\epsilon$, it acts greedily and chooses the action that maximizes the Q-value. Otherwise, a random action is selected from $\mathcal{A}$ with a probability of ϵ. However, in the ϵ-greedy policy, a drawback is that it selects equally among the all actions at the time of exploration. Thus, the probability of choosing the best action is the same as the worst action.

4.5.2 Softmax Action Selection Policy

To overcome the problem in the ϵ-greedy policy, Softmax action selection can be employed to find the optimal policy $\pi^*(\tau, s, a)$ using an exploration versus exploitation tradeoff [87] with different probabilities for the action selection. In this case, the action a_i at state s_i is chosen with probability $p(s_i, a_i)$ based on the Boltzmann distribution:

$$p(s_i, a_i) = \frac{e^{\frac{Q(s_i, a_i)}{\tau}}}{\sum_{j=1}^{4} e^{\frac{Q(s_i, a_j)}{\tau}}} \tag{4.9}$$

where $\tau > 0$ is a parameter called temperature. With high temperatures, all actions are equiprobable while with low temperatures, the Softmax action selection policy becomes the same as the greedy policy.

4.5.3 Adaptive Action Selection Policy

The third action selection policy is an adaptive action selection policy, which is given by a combination of both the Softmax and the greedy action selection policies described above. During the exploration phase, when the iteration is below a certain value in the learning process, the action a is chosen based on the Softmax policy from Eq. (4.9). After exploring all of the environment, when the Q-table is set, we switch to the exploitation phase in which the action is selected according to the greedy policy. Therefore, the adaptive action selection policy is as follows[88]:

$$\pi(\delta, \tau, s, a) = \begin{cases} \text{Softmax policy } \pi(\tau, s, a) & \Delta \leq \delta \\ \quad \text{according to Eq. (4.9)} & \\ \text{argmax}_{a \in \mathcal{A}} Q(s, a) & \text{Otherwise} \end{cases} \tag{4.10}$$

where Δ is a uniform random number drawn at each time step, and $0 \leq \delta \leq 1$.

4.6 Simulation Results

In this section, we evaluate the performance of the proposed learning algorithm for MIMO energy harvesting systems presented in Section 4.5, and compare it with other available methods. We assume a Rayleigh fading wireless channel with a channel data rate of $R_b = 1$ Mbps, and an average path loss that falls off with the square of distance (d^2). The simulation parameters are listed in Table 5.2. We use the circuitry power consumption employed in [9]. We use Matlab to simulate the different options, and the results are averaged over 50 runs.

The nodes can operate in four different antenna modes: 2×2 MIMO, 2×1 MISO, 1×2 SIMO, or 1×1 SISO and they start their communication as soon as their remaining energy is greater than or equal to the minimum required energy threshold (as listed in Table 5.2). We assume that the harvesting process follows a uniform distribution $\mathcal{U}[0, H_{Max}]$ for both nodes and their harvesting processes are either the same or correlated (harvested energy of the receiver is a multiplication of that of the transmitter). In the following figures, we consider two cases: the first one is when both nodes' harvesting processes follow a uniform distribution and have the same harvested energy at

Table 4.1: Simulation Parameters for Evaluating QLearning Algorithm in MIMO Wireless Network with Energy Harvesting.

General Parameters	
n (Path loss exponent)	2
W (Constellation size)	2
m (Packet Size)	2064 bytes
N_0	-174 dBm/Hz
$G_t G_r$	5 dBi
M_l	10dB
N_f	10 dB
η	0.35
Distance	250 m
Harvested Energy	$\mathcal{U}$[0,0.004]J
Maximum Harvested Energy(H_{Max})	0.004 J
Initial Energy of the [Transmitter, Receiver] Nodes	[3,1] J
Minimum Required Energy at the [Transmitter, Receiver] Nodes	[1,2] J

Q-Learning Parameters	
δ	0.01
Discount Factor (γ)	0.7
Learning Rate (α)	0.7
Temperature (τ)	500
Learning Iterations (k)	1440×3000
Time Frame	one day = 1440 time slots

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

each time slot ($H_{rx} = H_{tx}$). The second one is when both nodes' harvesting processes follow a uniform distribution but the value of the harvested energy of the nodes are different but correlated (e.g., $H_{rx} = 0.8 \times H_{tx}$). In the most of the results, we employed the first type of the harvester (in which both nodes harvests the same amount of energy) unless noted otherwise.

Moreover, we compare the performance of the proposed protocol with the following policies;

- *Online Policy:* the nodes choose their number of antennas on-the-fly and based on the incoming harvested energy and their current remaining energy. At each time slot, the nodes choose the number of antennas such that the throughput is maximized by solving Eq. (4.3).

- *Offline Optimal Policy:* the nodes know the total harvested energy in the future and have perfect knowledge of the remaining energy and energy arrivals. Having perfect knowledge of the energy, according to Eq. (4.4), the nodes select the optimal number of antennas for all the slots of the entire network lifetime.

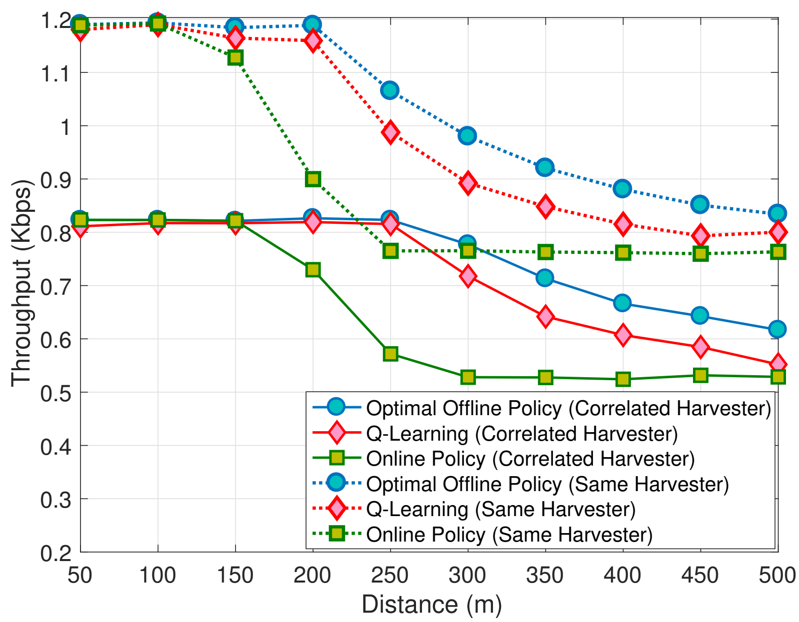


Figure 4.1: System throughput versus the communication distance.

We analyze the proposed algorithm in terms of various distances, initial energies of the nodes, and network running time (i.e., time frame T_s in Eq. (4.3)), and energy consumption for different harvesting processes. Moreover, each time frame consists of a number of time slots in which the nodes can transmit/receive at most one packet. Each time slot equals to one minute.

In Figure 4.1, the throughput is measured and compared with the online policy as a function of the distance between the nodes. As distance grows, the transmit energy consumption grows, which results in having fewer packets received and thus having lower throughput. The Optimal Offline Policy provides an upper bound for the maximum throughput, but this is not necessarily achievable in practice. The throughput of the proposed Q-learning approach is better than that of the online policy especially for large distances due to the learning process in which the Q-values are updated based not only on the energy consumption of the different schemes, but also based on the incoming harvested energy.

In Figure 4.2, the total energy consumption of the transmitter and the receiver is shown as a function of the communication distance. Since the number of packets and therefore the throughput is higher for large distances for the Q-learning compared to the online policy, the total energy consumption for Q-learning is also higher. However, for small distances the throughput of the online policy is slightly higher than the Q-learning (see Figure 4.1) which results in having higher energy consumption for the online policy. In Figure 4.3, we change the network running time T_s and measure the

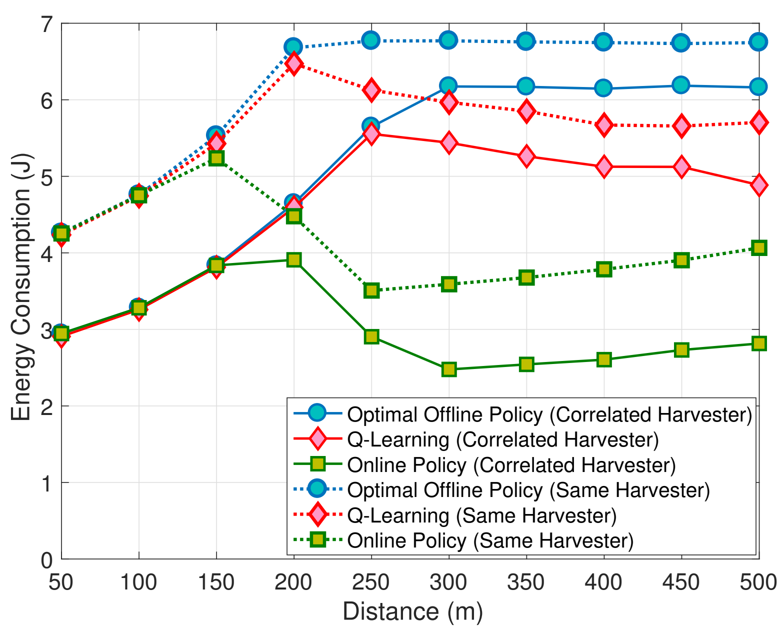


Figure 4.2: Total system energy consumption versus the communication distance.

throughput for the proposed method. Since the maximum time frame is 2 days (2×1440 time slots), we assumed that the number of learning iterations is $2 \times 1440 \times 3000 \approx 8 \times 10^6$. As expected, as the size of the time frame gets larger, the number of received packets and thus the throughput increases as well.

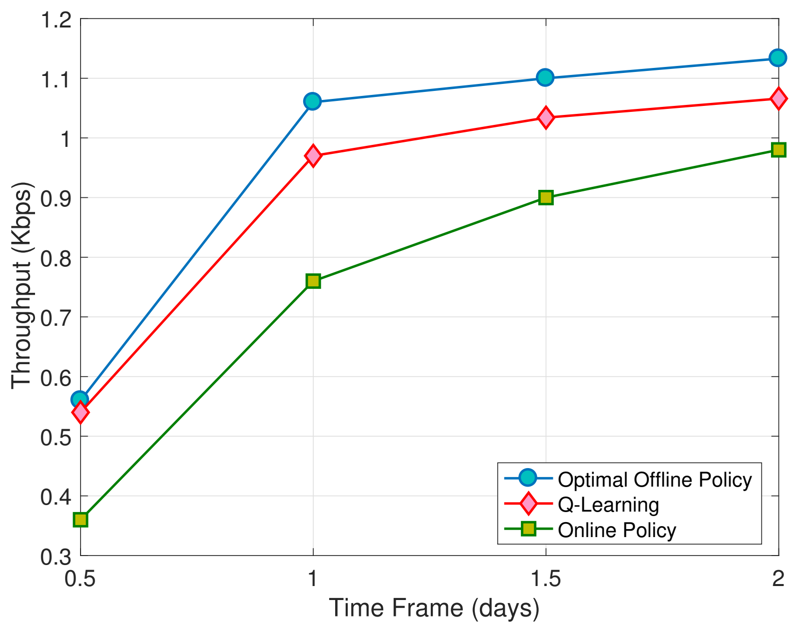


Figure 4.3: System throughput versus the time frame (days).

In Figure 4.4, the system throughput is demonstrated versus different values of initial energy of the nodes. With higher initial energy of the nodes, the lifetime of the network and thus the throughput gets larger. Figure 4.5 shows a comparison of the network throughput of the Q-learning, online policy, and offline optimal policy approaches. As we increase the number of learning iterations, the Q-learning algorithm improves the Q-table by the knowledge it learned from the environment. Since we assumed that the distribution of the harvested energy is known, we learn the optimal Q-table in an offline manner for each time frame. Moreover, before the nodes start sending packets in a time frame, the Q-learning algorithm learns the optimal Q-table for the incoming time frame.

In Figure 4.5, it is assumed that the time frame is one day and the trend of the Q-learning is shown as the number of (offline) learning iterations grows. With a high learning rate ($\alpha = 0.7$) the Q-learning converges faster than with a low learning rate ($\alpha = 0.01$) since with higher learning rates,

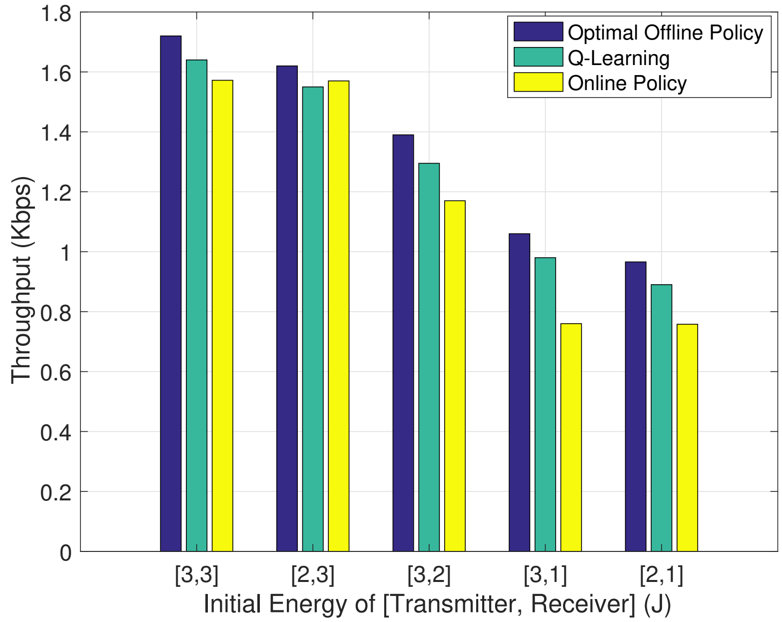


Figure 4.4: System throughput versus the initial energy of the nodes.

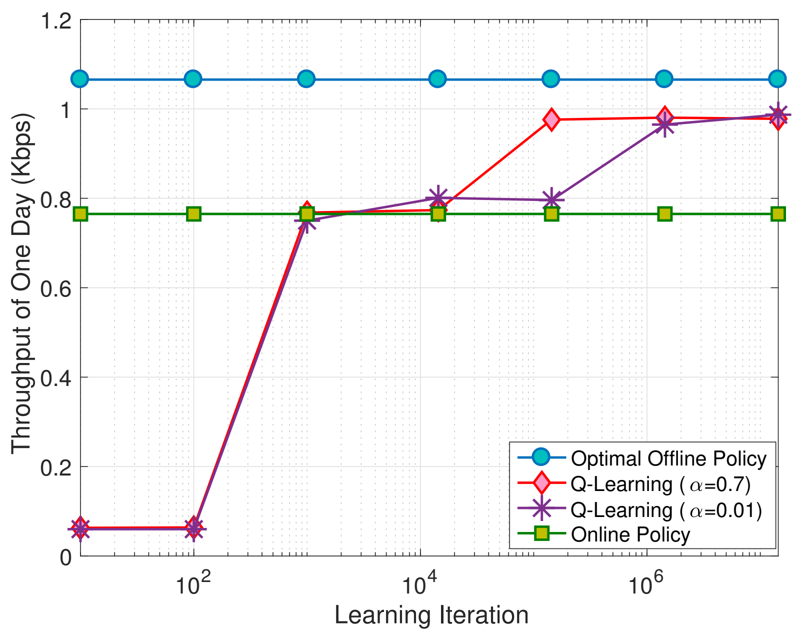


Figure 4.5: System throughput for one day versus the number of learning iterations.

the algorithm gives more credit to the newly acquired rewards than the previous ones. After around 10^3 learning iterations, the Q-learning and the online policy cross each other and when the number of iterations is larger than this value, the Q-learning converges to a value near the optimal policy.

4.7 Conclusions

In this chapter, we introduce a new framework for throughput maximization for MIMO wireless links with energy harvesting. We model the problem as an MDP and find the solution using Q-learning. Our proposed solution achieves higher throughput for various distances, various initial energies of the nodes, different harvesting processes, and in different network operating times compared to an online policy. We also compared the proposed learning algorithm with an Optimal Offline policy, and we observe that our proposed algorithm converges to the Optimal Policy, especially for large distances, and various network time frames and the nodes' initial energy.

In order to make the situation more realistic, the network should be extended from two nodes to a network with more nodes. By having more nodes in the network, the problem becomes more complicated since more parameters will be added to the framework, such as the most energy efficient routing path, and the best scheduling data transmission algorithm between a node and its neighbors. In the next chapter, we propose an energy efficient protocol called MAC-LEAP that is designed for MIMO wireless networks with at least two nodes.

Chapter-5

MAC-LEAP: Multi-Antenna, Cross Layer, Energy Adaptive Protocol

5.1 Introduction

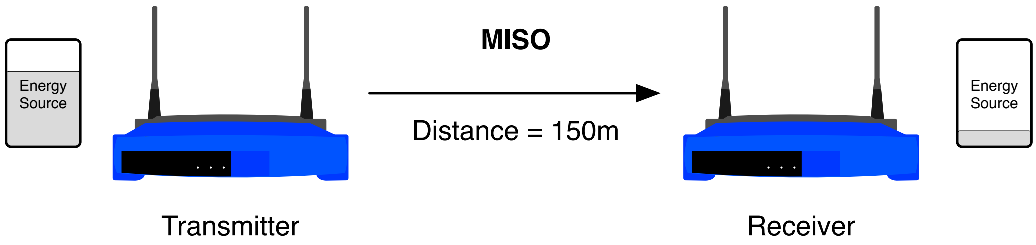
With the continuous development of wireless networks, energy conservation and energy efficiency are becoming key factors in improving the network lifetime. In multi-antenna wireless networks, the energy conservation problem can be addressed using the trade-off between the transmit power and the circuit energy consumption. In this chapter, we propose a cross layer protocol, MAC-LEAP, which 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 transmision 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).

Multi-Antenna, Cross Layer, Energy Adaptive Protocol (MAC-LEAP) 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 RTS and 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.

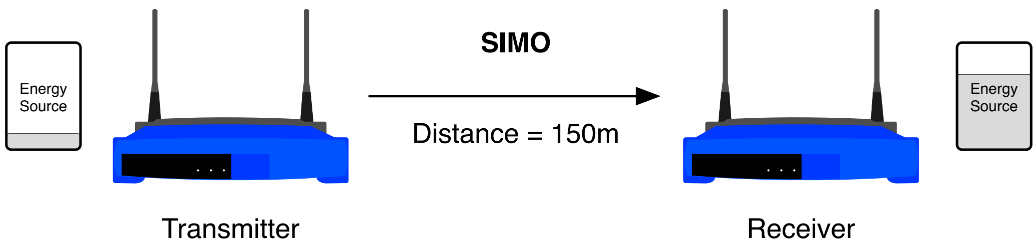
Unlike traditional protocols that use a fixed number of antennas for a specific distance and target BER, MAC-LEAP adapts the MIMO scheme to be used for the communication according to the current remaining energy levels of both the transmitter and receiver nodes. The specific contributions of this chapter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

- The dynamic antenna selection policies proposed in Chapter 3 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.



(a)



(b)

Figure 5.1: 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.

5.2 Protocol Overview

As shown in Figs. 3.2 and 3.3, 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. 5.1 in which we have two nodes with a distance of 150 meters. 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 communityunication, and this MIMO scheme will be changed according to the nodes' remaining energy over time.

In the example shown in Fig. 5.1, 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. 5.1(a)) while when the transmitter has lower remaining energy than the receiver, SIMO is chosen (Fig. 5.1(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.

5.3 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 Request-To-Send (RTS) packet to the receiver. If the RTS is correctly received, the receiver node replies by sending a Clear-To-Send (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.

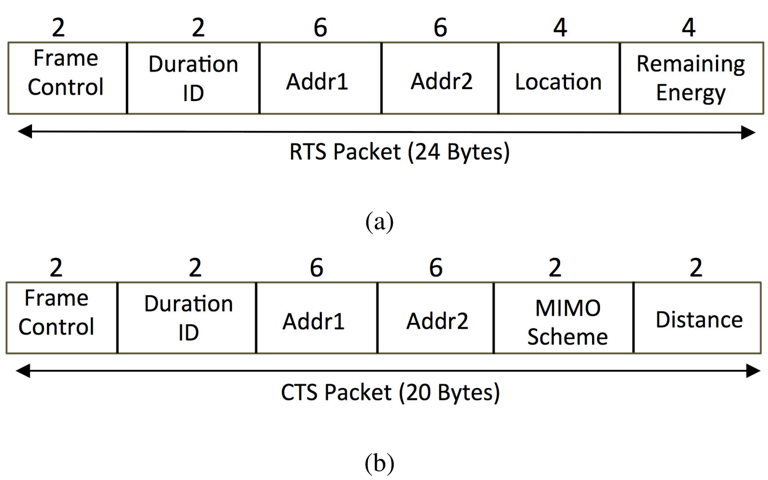


Figure 5.2: The fields and the size (in bytes) of (a) the RTS packet, and (b) the CTS packet in the MAC-LEAP protocol.

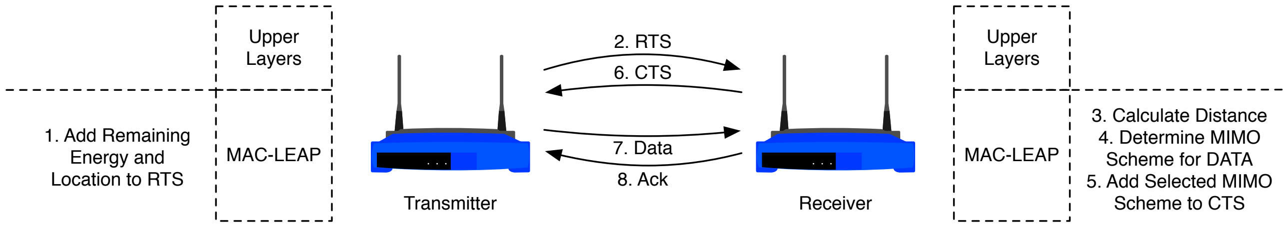


Figure 5.3: An example of how MAC-LEAP works in a single communication link.

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. 5.2.

In MAC-LEAP each node is equipped with a non-rechargeable energy source (e.g., a battery). As demonstrated in Fig. 5.3, 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 3.3, 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.

5.4 Ns-3 Implementation

Ns-3 is a popular network simulator [89]. 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. 5.4, 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.

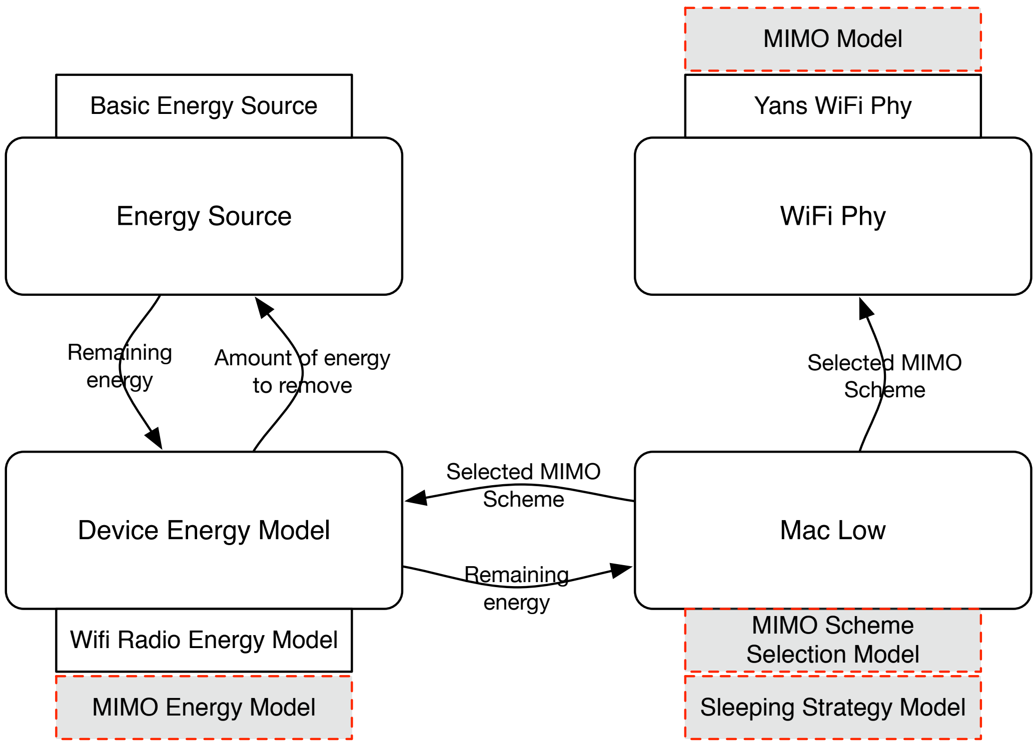


Figure 5.4: Wireless MIMO framework in ns-3.

- *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 energy 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, transmission, 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 3.2.

- *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 of transmitting the packets to the channel, using the link model of the selected MIMO scheme.

5.5 MAC-LEAP Simulation Results

In this section, we evaluate the performance of MAC-LEAP using the different policies described in Section 3.3 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

Table 5.1: 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

setting are listed in Table 5.2. We use the circuitry power consumption employed in [74, 75, 76, 77] 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 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 5.4, 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 meters, 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) [46, 68], and the E-Basic protocol presented in [53]. 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:

$$\text{Thr} = \frac{\text{Packet}_{recv} \times N}{T} \tag{5.1}$$

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.

5.5.1 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.

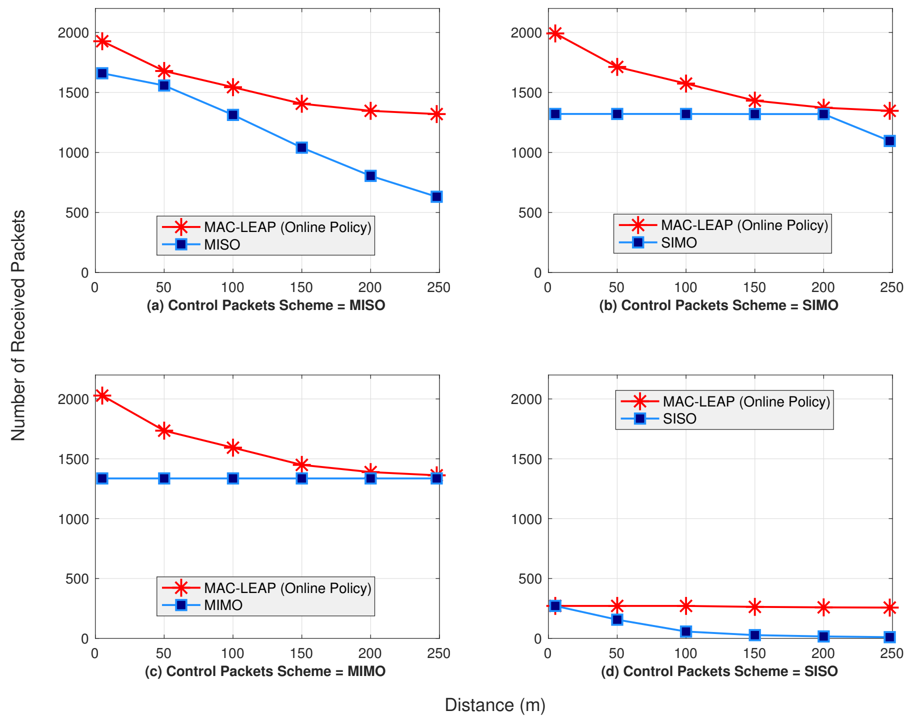
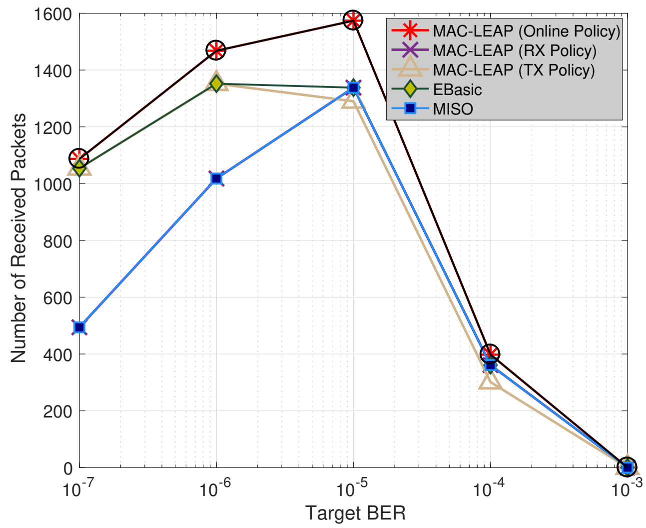
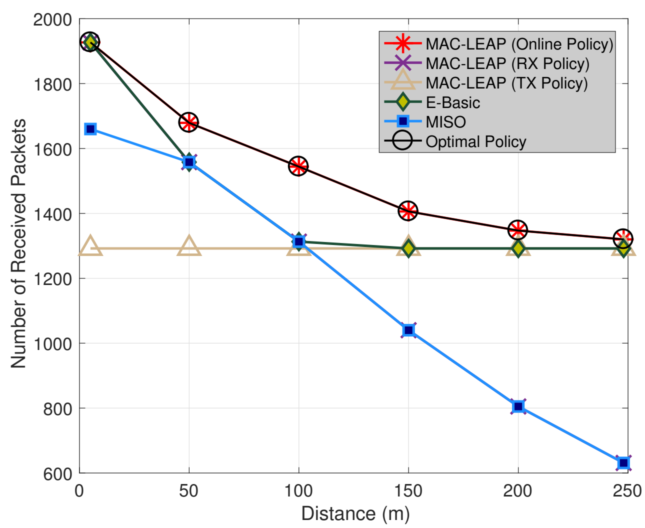


Figure 5.5: Number of received packets versus distance for four different fixed schemes used for sending control packets in a single communication link: (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO (Target BER= 10^{-5}).



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



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

Figure 5.6: Number of received packets versus (a) target BER and (b) distance in a single communication link with two nodes.

In Fig. 5.5, 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. 5.5(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.

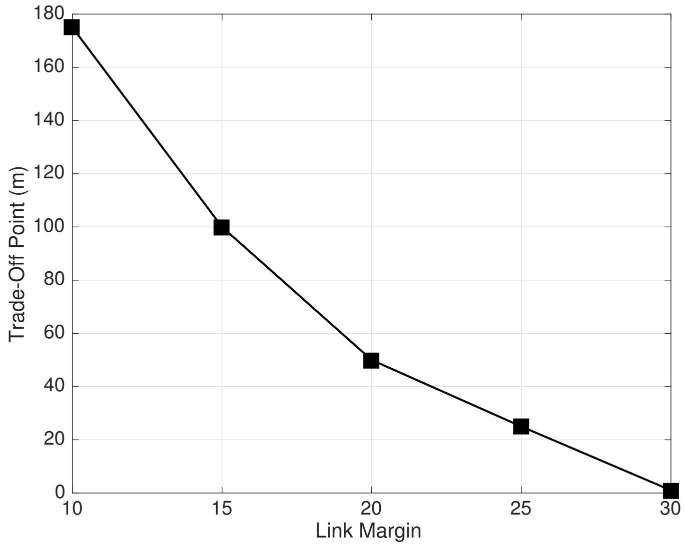
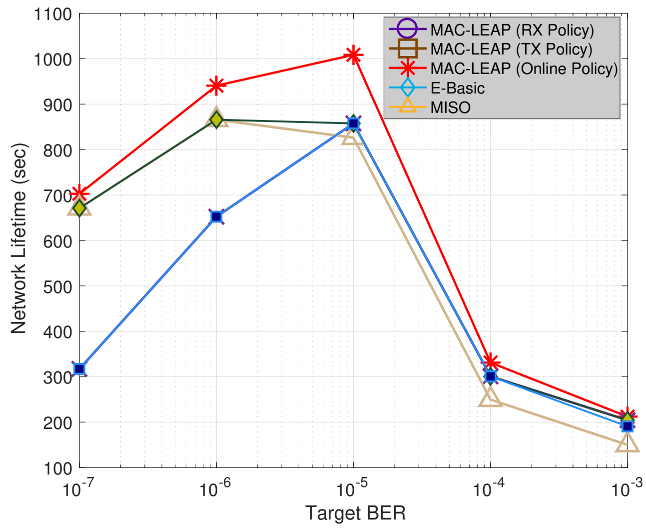
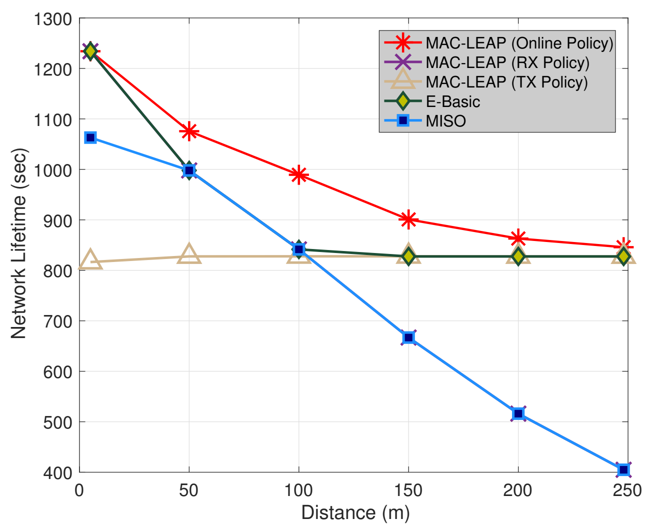


Figure 5.7: Trade-off point between TX and RX policies versus link margin in a single communication link with two nodes.

Fig. 5.6(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.



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



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

Figure 5.8: Network lifetime versus (a) target BER and (b) distance in a single communication link with two nodes.

As illustrated in Fig. 5.6(b), the total number of packets delivered by MAC-LEAP (Online Policy) in a single communication link is very close to 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. 5.7.

When considering the network lifetime, which is shown in Fig. 5.8, 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. 5.6(b), the drop in Fig. 5.8(b) is due to the high transmit power consumption required when transmitting data over long distances. The network lifetime shown in Fig. 5.8(a) follows as for the results described in Fig. 5.6(a).

5.5.2 Binary Tree Network with Single-hop Communication

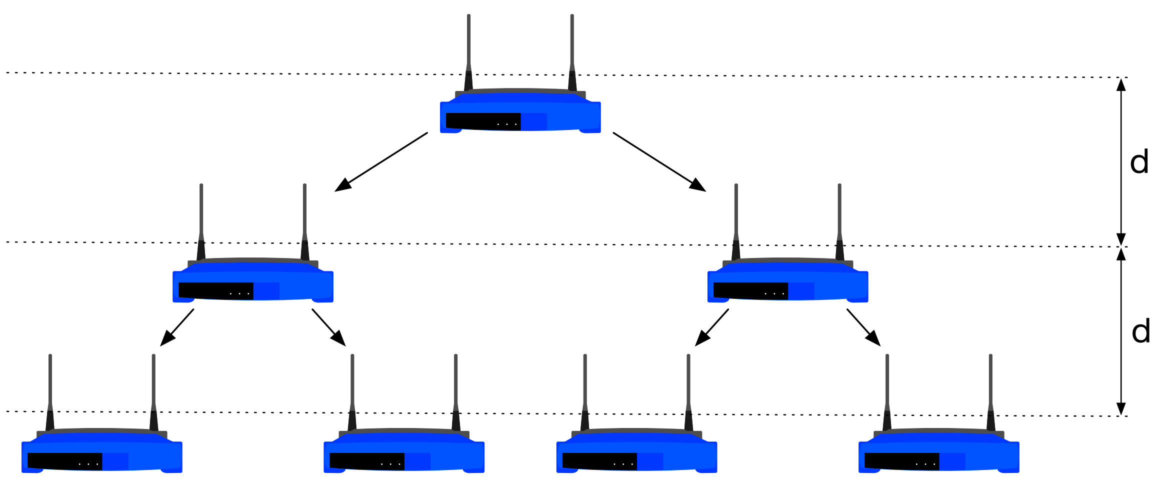
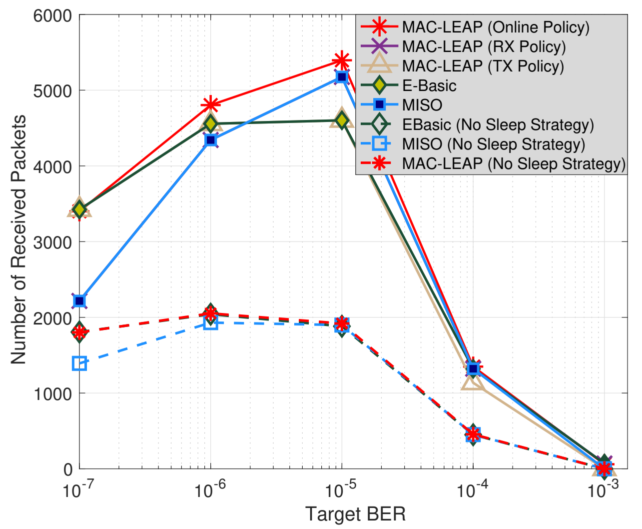
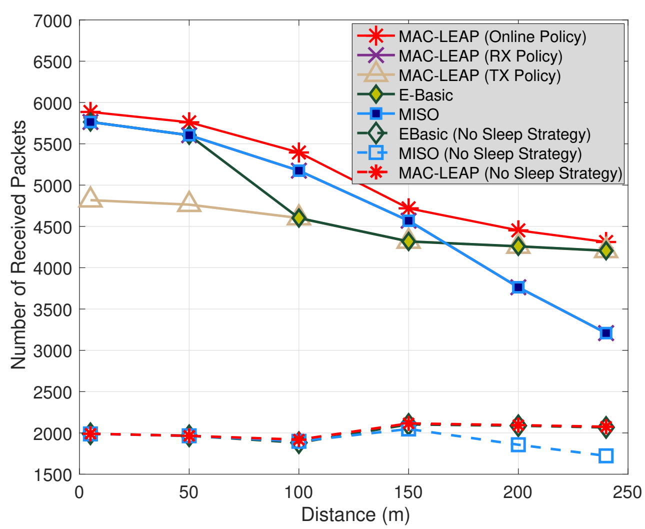


Figure 5.9: Binary Tree network topology with height of every level equal to distance d.

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. 5.9. All nodes may transmit or receive the 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.



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

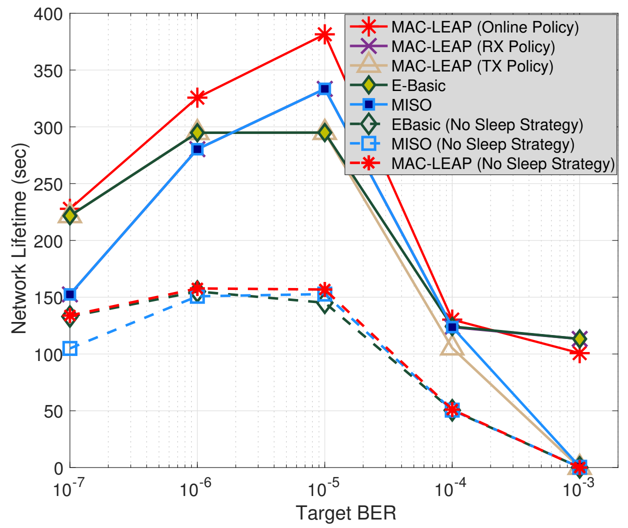


(b) Number of received packets versus distance (Target BER=10^{-5}).

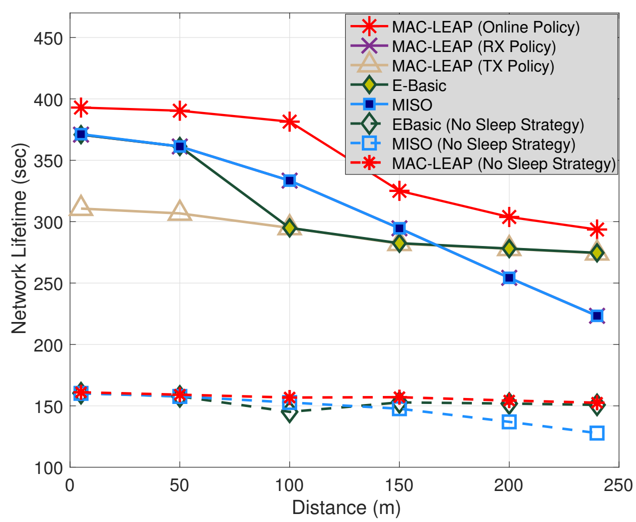
Figure 5.10: Number of received packets versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having equal initial energy of 5 J.

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. 5.10(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. 5.10(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 lower than 150 m and target BER less than 10^{-4}.



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



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

Figure 5.11: Network lifetime versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having equal initial energy of 5J.

As shown in Fig. 5.11, 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. 5.12 between MAC-LEAP and the fixed schemes,

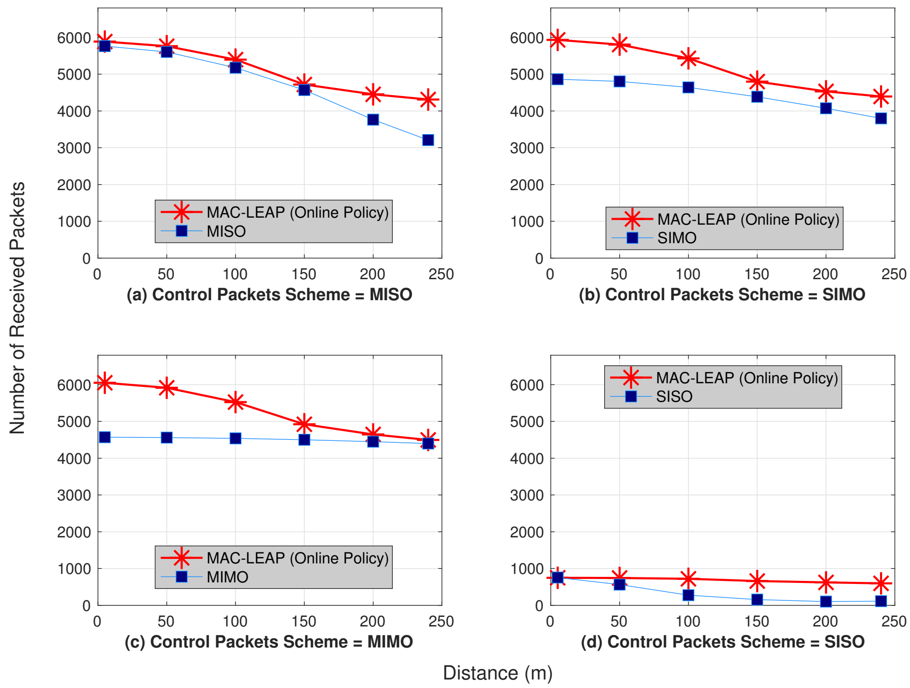
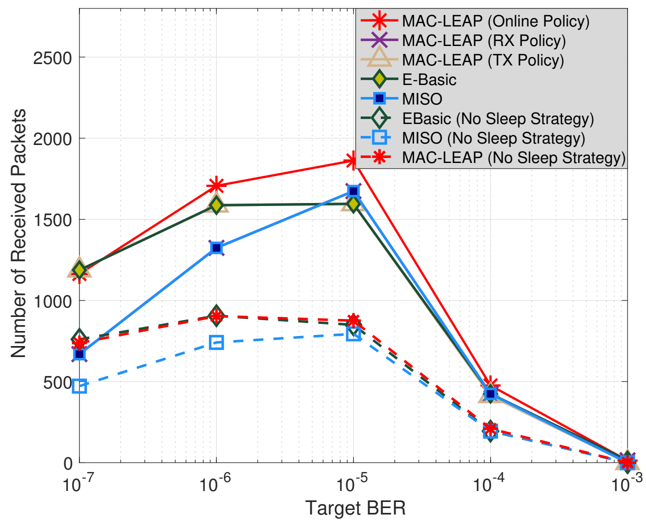


Figure 5.12: Number of received packets versus distance with four different fixed schemes used for control packets (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO in a Binary Tree network (target BER= 10^{-5}) with nodes having equal initial energy of 5J.

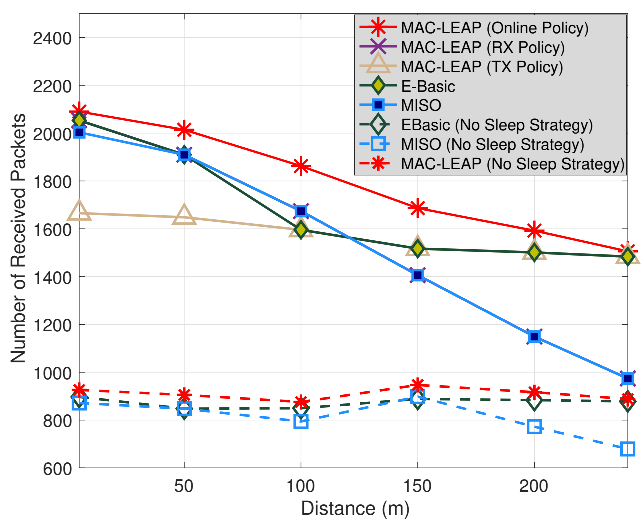
MAC-LEAP achieves a higher number of received packets compared to others. The maximum gain over all distances in terms of number of received packets for MAC-LEAP is 34%, 32%, 22%, and more than 400%, when compared to MISO, MIMO, SIMO, and SISO, respectively.

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. 5.13, the number of received 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) with sleep strategy, in terms of number of received packets is about 18% more packets than E-Basic (with sleep strategy) over all distances and target BERs. Moreover, according to Fig. 5.13(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.



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

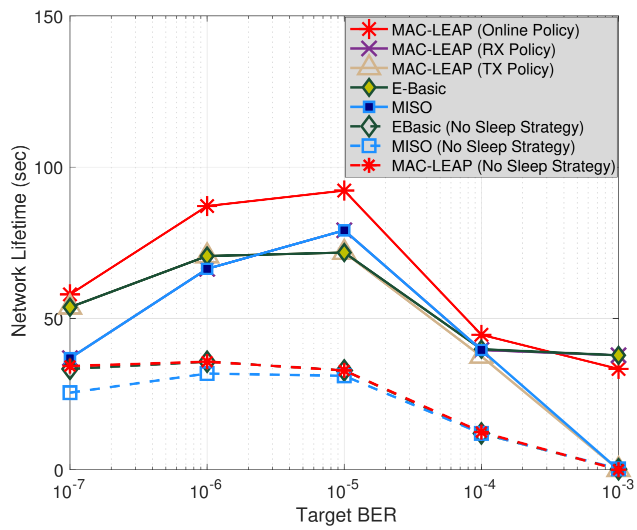


(b) Number of received packets versus distance (Target BER=10^{-5}).

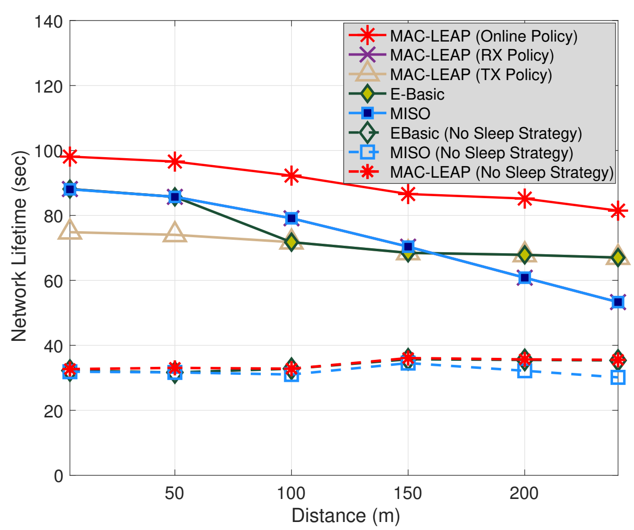
Figure 5.13: Number of received packets versus (a) target BER and (b) distance in a Binary Tree network with 9 nodes having uniform initial energy distribution in [1, 5] J.

As shown in Fig. 5.14, the maximum improvement in terms of the network lifetime of MAC-LEAP

(Online policy) with sleep strategy is 29% and 52%compared to E-Basic (with sleep strategy) and MISO (with sleep strategy), respectively. Moreover, MAC-LEAP improves the number of received packets by at most 18% and 73% compared to E-Basic (with sleep strategy) and MISO (with sleep strategy), respectively.



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



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

Figure 5.14: 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.

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. 5.15. The maximum gain in terms of number of packets for MAC-LEAP is 63%, 32%, 20%, and 200% compared to MISO, MIMO, SIMO, and SISO, respectively.

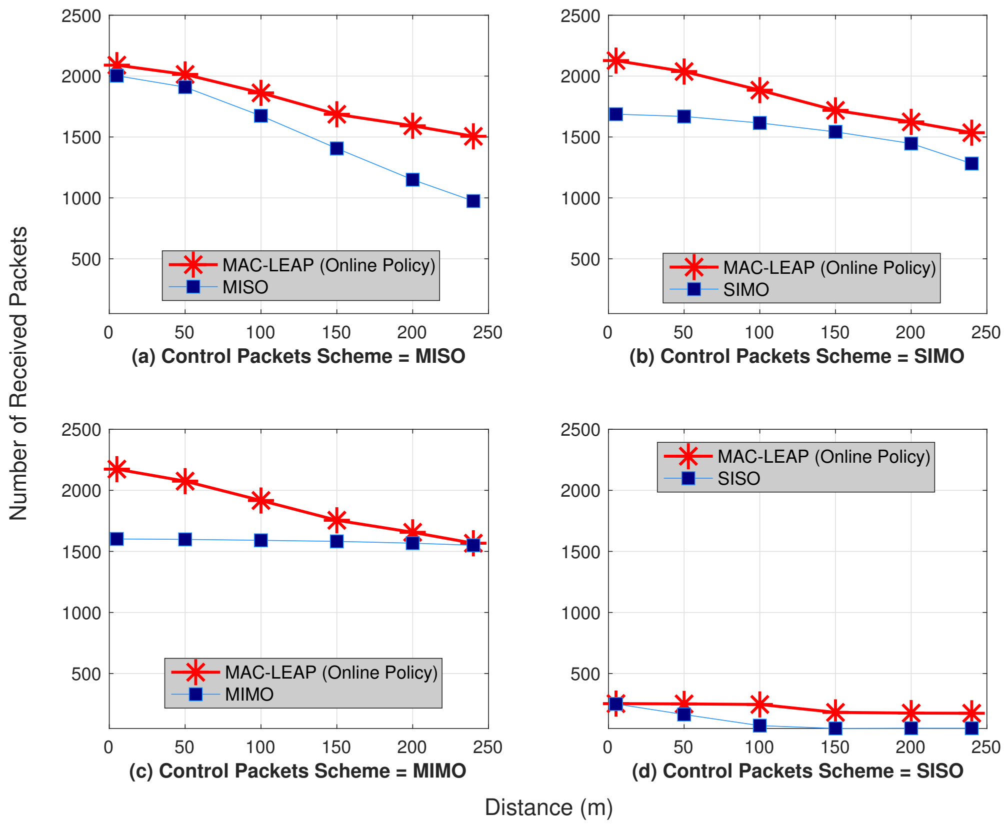


Figure 5.15: Number of received packets versus distance with four different fixed schemes used for control packets: (a) MISO, (b) SIMO, (c) MIMO, and (d) SISO in a Binary Tree network (target BER= 10^{-5}) with uniform energy distribution.

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

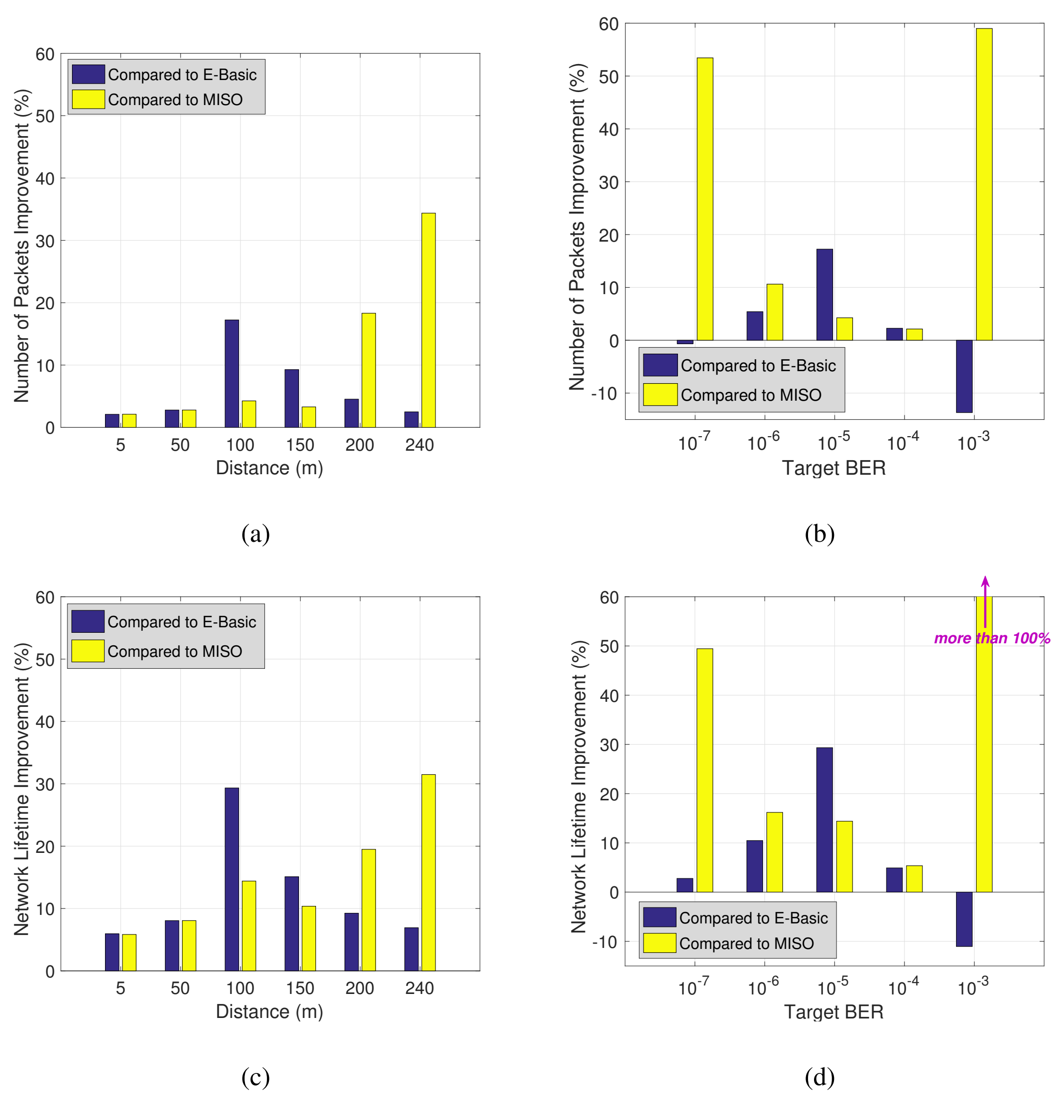
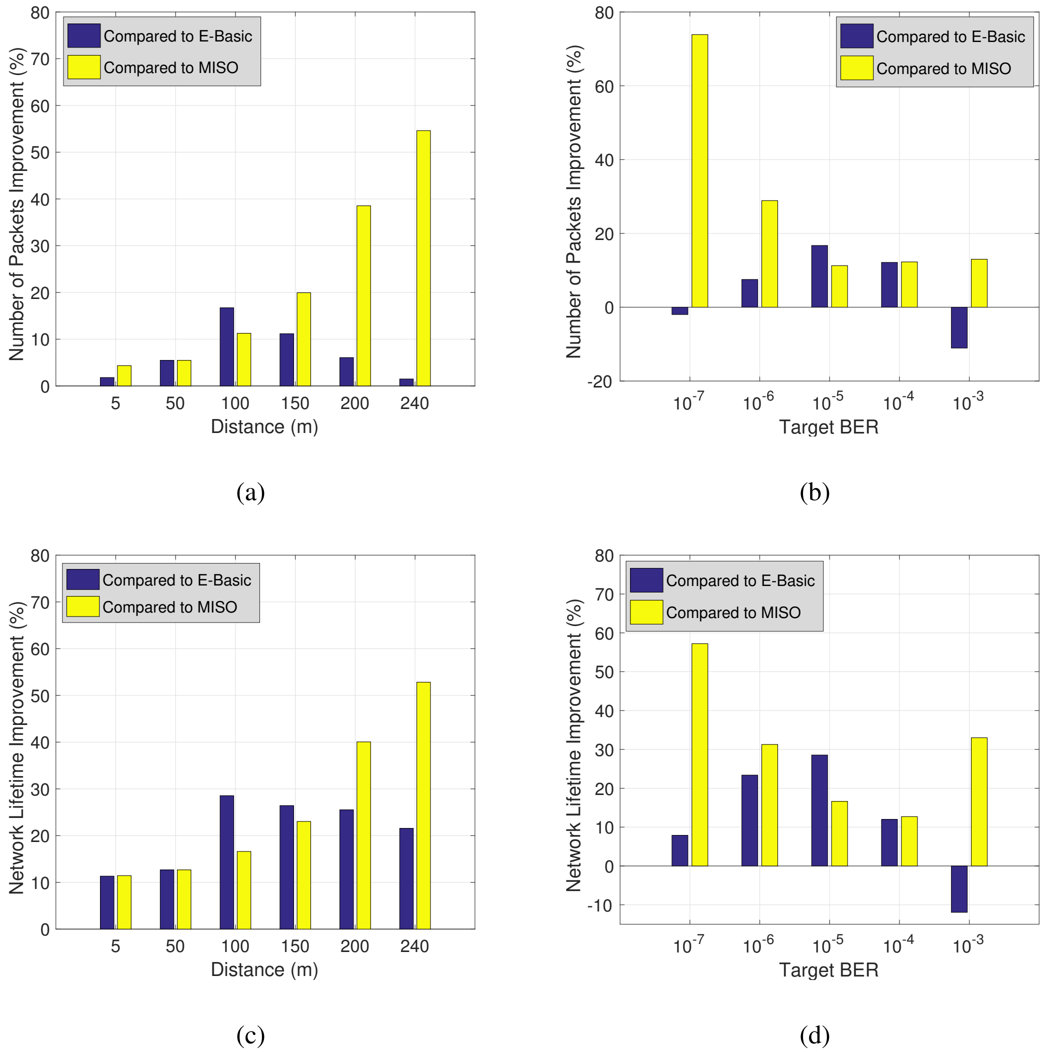


Figure 5.16: Improvement of MAC-LEAP compared with E-Basic (with sleep strategy) and MISO (with sleep strategy) in terms of number of received packets (a) vs. distance, and (b) vs. target BER, and in terms of the network lifetime (c) vs. distance, and (d) vs. target BER, in a Binary Tree network with 9 nodes having the same initial energy of 5 J.

Fig. 5.16 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 34% and 59% compared to MISO for various distances (Fig. 5.16(a)) and various target BERs (Fig. 5.16(b)). Moreover, MAC-LEAP increases the number of received packets up to 17% compared to E-Basic for both various distances and target BERs (according to Fig. 5.16(a) and Fig. 5.16(b)). Network lifetime is improved by 31% for various distances and by 118% for different target BERs compared to MISO as shown in Fig. 5.16(c) and Fig. 5.16(d). Moreover, MAC-LEAP increases the network lifetime by a maximum of 29% for various distances and target BERs compared to E-Basic when the sleep strategy is employed.



(a) (b) (c) (d)

Figure 5.17: 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.

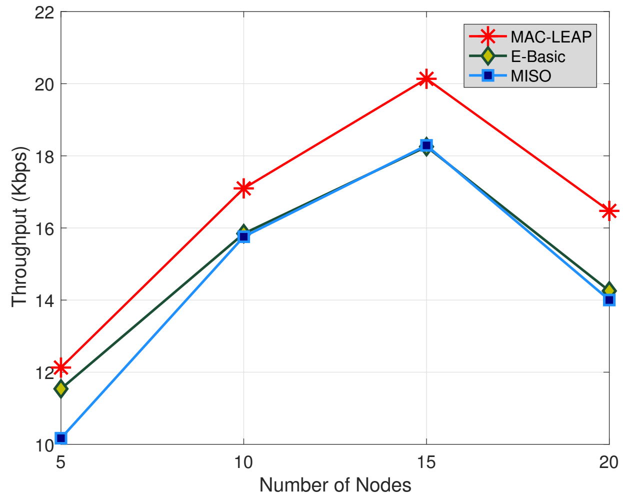
According to Fig. 5.17(a) and Fig. 5.17(b), MAC-LEAP improves the number of received packets compared to MISO by a maximum of 54% for various distances and by a maximum of 73% when the target BER is changing in the Binary Tree network with uniform initial energy distribution. It also increases the number of packets by a maximum of 17% (vs. distance and vs. target BER) compared to E-Basic with sleep strategy. As shown in Fig. 5.17(c) and Fig. 5.17(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.

5.5.3 Random Network with Multi-hop Communication

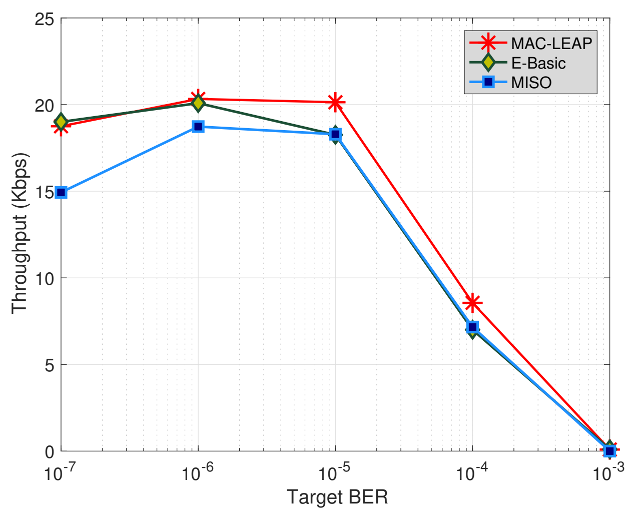
In this section we analyze the performance of MAC-LEAP in a random network when all nodes have the same initial energy of 5 J, and when the nodes' initial energies follow a uniform distribution in $[1, 5]$ J. We present the results for different numbers of nodes uniformly distributed in a 700 m by 700 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.

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. (5.1)) when the number of nodes and the target BER in the network are changing.



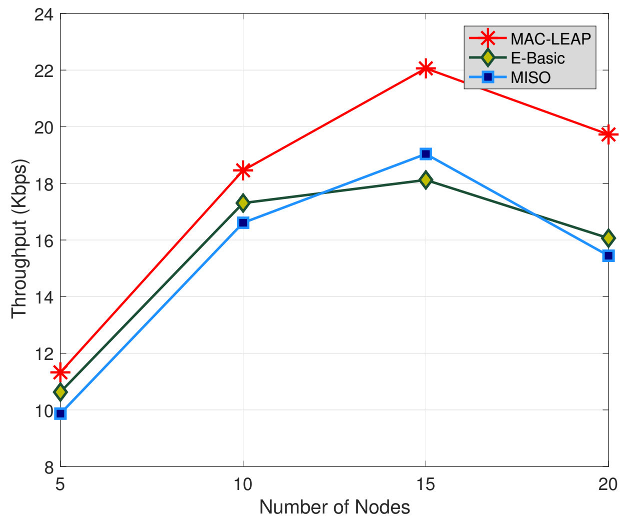
(a) Average network throughput versus number of nodes (Target BER = 10^{-5}).



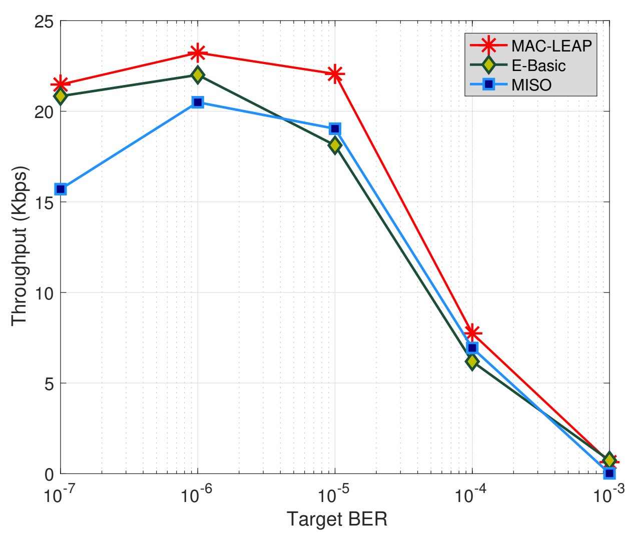
(b) Average network throughput versus target BER (Number of Nodes=15).

Figure 5.18: 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.

In Fig. 5.18, the average network throughput is shown when the sleep strategy is not employed in MAC-LEAP, E-Basic, and MISO. As the number of node grows in the network, more data packets are transferred in the network. According to Fig. 5.18(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.



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



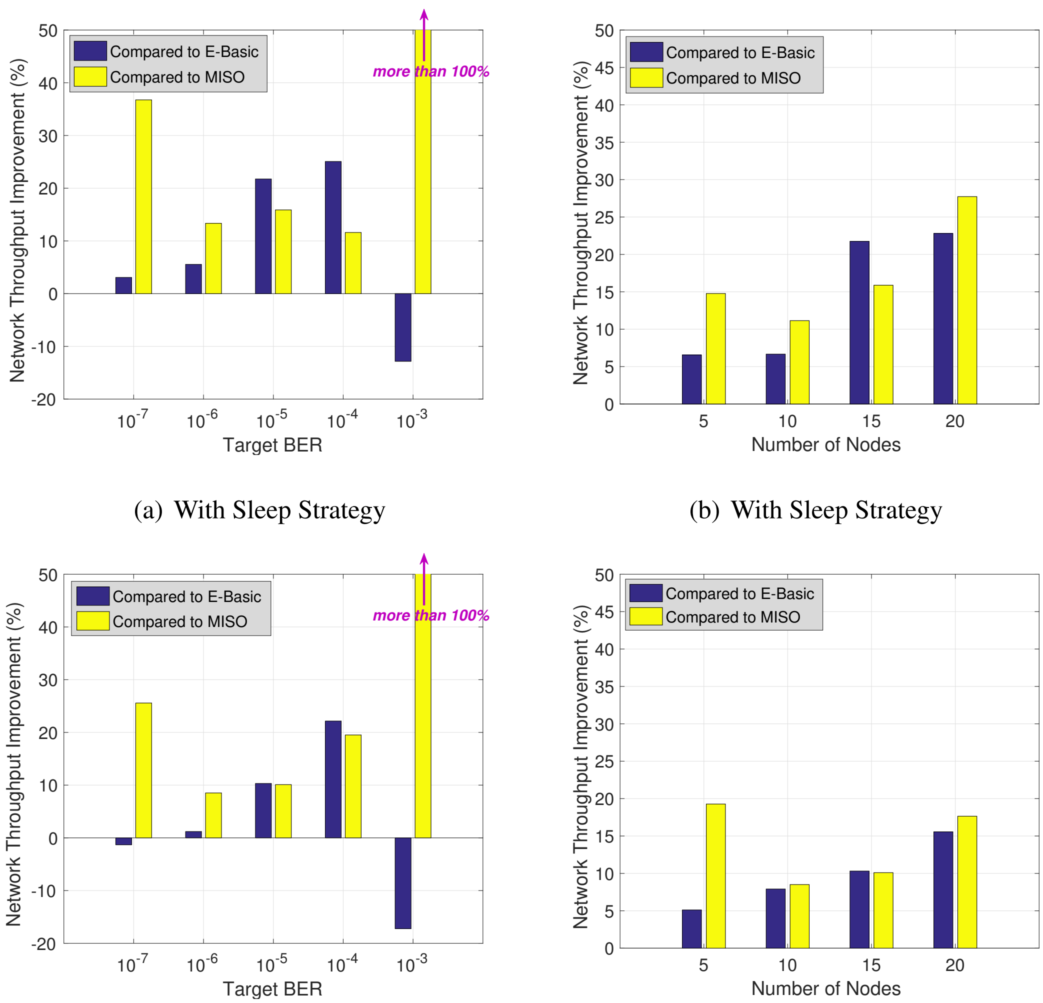
(b) Average network throughput versus target BER (Number of Nodes=15).

Figure 5.19: 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.

Fig. 5.18(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 the number of nodes increases, the number of RTS/CTS transmission/reception is also increased. With small amount of nodes (e.g. from 10 nodes to 15 nodes) the number of packets and thus the network throughput grows dramatically. After increasing the nodes from 15 to 20, due to higher energy consumption of the received/transmitted RTS/CTS packets, the nodes loose their energy faster in the network with 20 nodes compared to 15 nodes. Thus, the throughput drops when the number of nodes grows from 15 to 20.

As shown in Fig. 5.19, when the sleep strategy is employed in the nodes, the network throughput is higher than the network without sleep strategy (Fig. 5.18). MAC-LEAP greatly increases the network throughput compared to E-Basic and MISO as shown in Fig. 5.19(a) and Fig. 5.19(b).



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

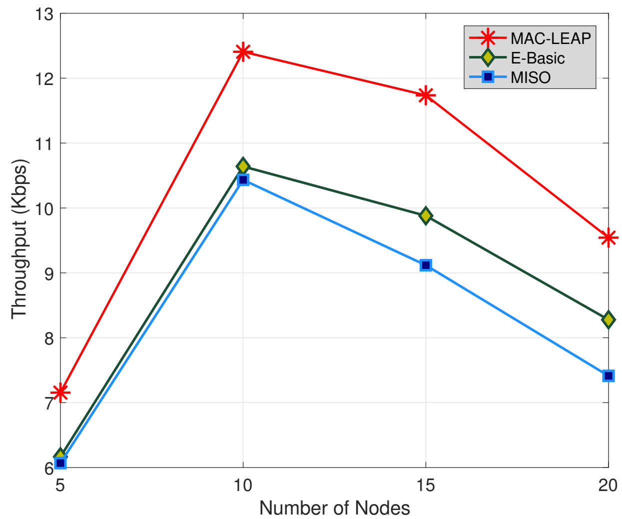
(c) Without Sleep Strategy (d) Without Sleep Strategy

Figure 5.20: 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.

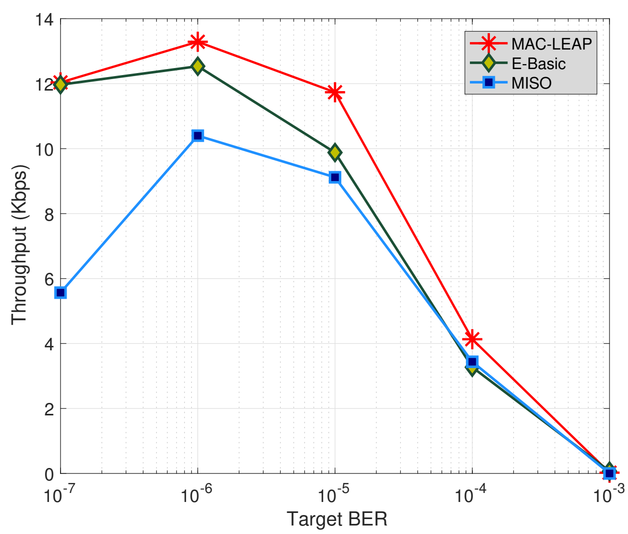
Fig. 5.20 shows the improvement percentage of MAC-LEAP compared to E-Basic and MISO in terms of network throughput with/without sleep strategy when all nodes in the network have 5 J of initial energy. For various target BER, MAC-LEAP increases the network throughput by at most more than 100% (with and without sleep strategy) compared to MISO, and by maximum of 26% (with sleep strategy) and 23% (without sleep strategy) compared to E-Basic, respectively (Figs. 5.20(a) and 5.20(c)). Moreover, for various number of nodes in the network the maximum network improvement by MAC-LEAP is 22% (with sleep strategy) and 16% (without sleep strategy) compared to E-Basic, and 28% (with sleep strategy) and 19% (without sleep strategy) compared to MISO, respectively (Figs. 5.20(b) and 5.20(d)).

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. We compare MAC-LEAP with E-Basic and MISO with/without sleep strategy. We evaluate network throughput in terms of number of nodes and target BER.



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

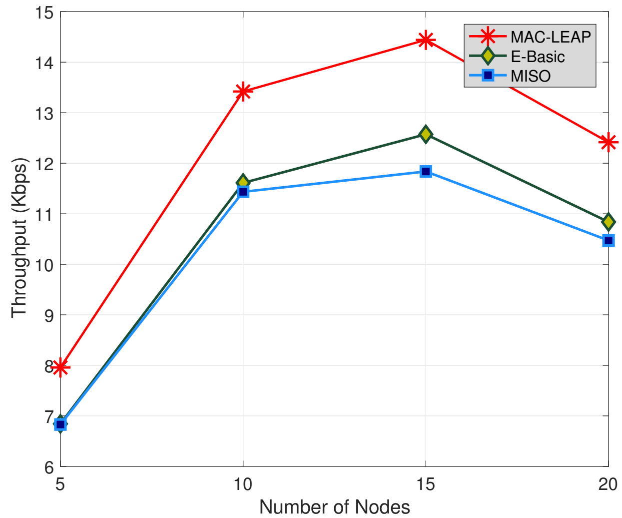


(b) Average network throughput versus target BER (Number of Nodes=15).

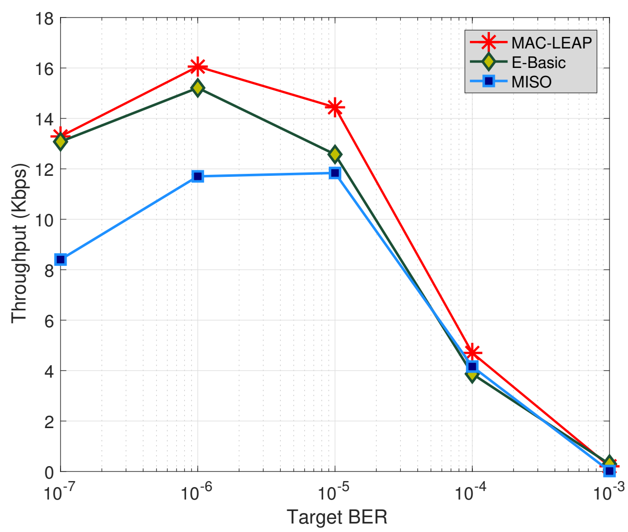
Figure 5.21: Network throughput in the random network with nodes having the uniform initial energy distribution of [1,5] J and without employing the sleep strategy.

Average network throughput when the nodes have uniform initial energy distribution of [1,5]J is shown in Figs. 5.21 and 5.22. In Fig. 5.22 all nodes in MAC-LEAP, E-Basic, and MISO employ sleep strategy to save more energy and send more packets. In Fig. 5.21, however, the results for

MAC-LEAP, E-Basic, and MISO protocols are represented when the nodes don't employ the sleep strategy.



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

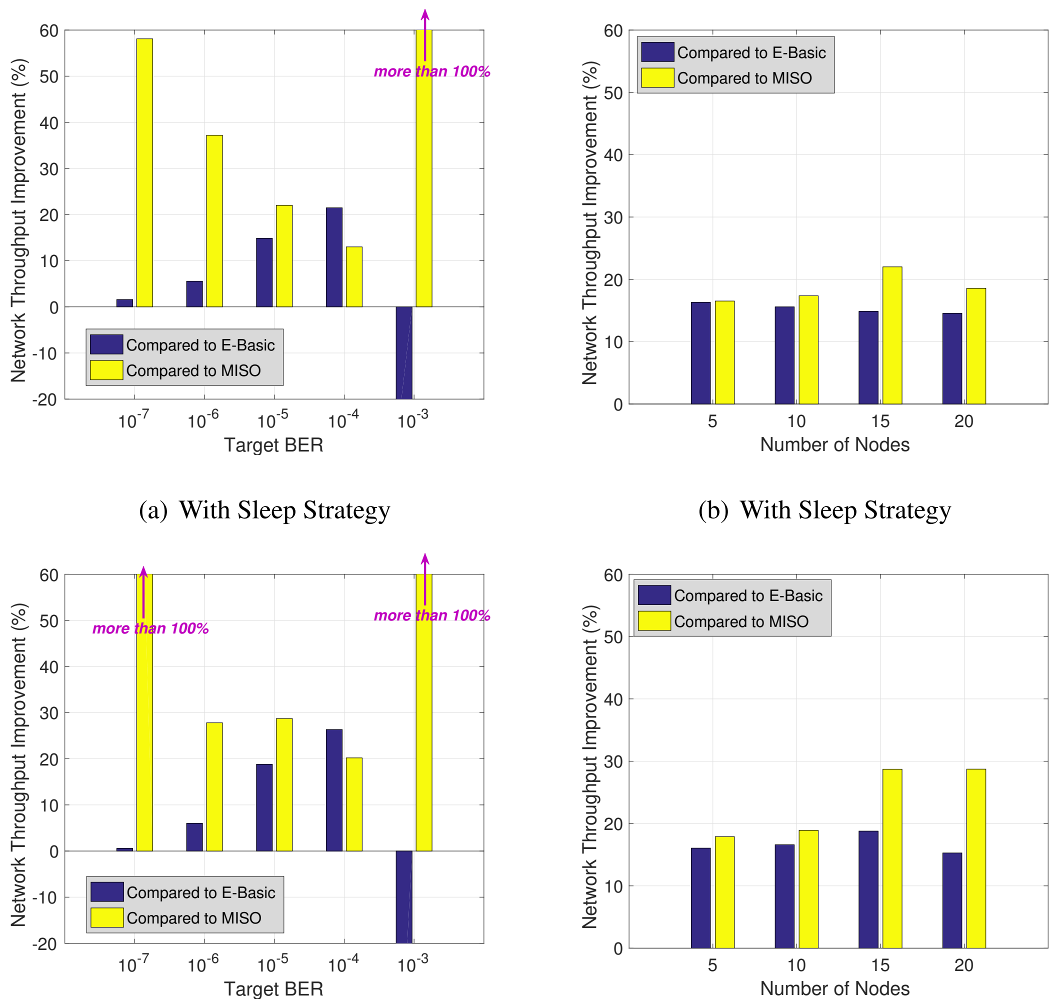


(b) Average network throughput versus target BER (Number of Nodes=15).

Figure 5.22: Network throughput in the random network with nodes having the uniform initial energy distribution of [1,5] J and employing the sleep strategy.

As shown in Fig. 5.21(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. 5.21(b), the average network throughput decreases as the BER increases since more packets are lost in high target BERs. MAC-LEAP improves the network throughput for various target BERs by an maximum of more than 100% and 27% compared to MISO and E-Basic, respectively.

By employing the sleep strategy in the nodes, MAC-LEAP increases the network throughput (shown in Fig. 5.22) compared to Fig. 5.21 when no sleep strategy is employed. Moreover, MAC-LEAP gains better average network throughput compared to both E-Basic and MISO in various target BER and number of nodes in the network.



(a) With Sleep Strategy

(b) With Sleep Strategy

(c) Without Sleep Strategy

(d) Without Sleep Strategy

Figure 5.23: 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 Uniform initial energy distribution in $[1, 5]$ J.

Fig. 5.23 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 achieves higher network throughput by maximum of 21% and more than 100% for various target BER, and by maximum of 22% and 17% 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 27% and more than 100% (vs. target BER) and 19% and 29% (vs. number of nodes) compared to E-Basic and MISO, respectively.

5.5.4 Target BER Analysis

In the designed wireless network, we set the target BER at the transmitter side. At the receiver side the channel BER is estimated based on the received Signal-to-Noise Ratio (SNR) and using the probability of error formula in Eq. (3.12).

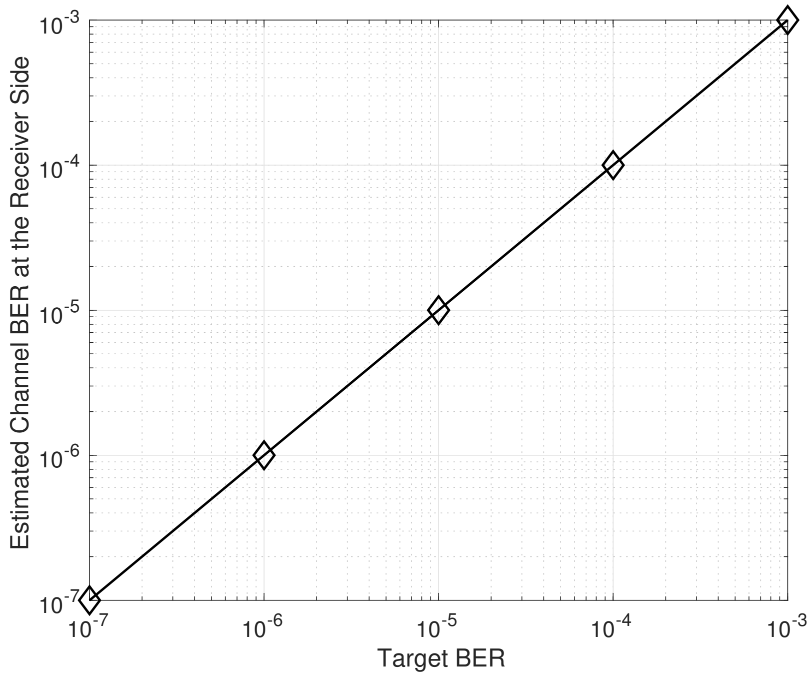


Figure 5.24: Target BER and channel BER comparison.

We assumed that we only have channel noise and interference, and we don't have any system loss. The noise interference is very small (negligible), and thus, as shown in Fig. 5.24, the estimated channel BER is the same as the target BER.

5.6 MAC-LEAP in the JumboNet Application

In this section, we evaluate MAC-LEAP in a real animal tracking application. We evaluate this protocol in an elephant tracking application called JumboNet for three different scenarios: when the nodes have limited energy; when the nodes have unlimited energy; and when the nodes have energy harvesting. Based on the results, we show that by using MAC-LEAP, the network outperforms the traditional JumboNet application in terms of packet delivery ratio, energy consumption per packet, and delay per packet.

5.6.1 Introduction: Animal Tracking Wireless Networks

Animal tracking is a popular wireless networking research area that enables the monitoring and tracking of the behavior and some characteristics of the animals such as heart rate [90], location [91], body temperature [92], or activity [93]. This information is useful for scientific and conservation purposes. Among these characteristics, ttracking the locations of the animals may provide safety for both humans and the animals.

In traditional animal tracking systems, the animals are tagged with a collar with a basic Very High Frequency (VHF) transmitter [94]. The researchers drive through an area carrying a receiver antenna in order to find the animals. As soon as an animal is found, they measure the required characteristics and store a location in the database. It is obvious that these systems cannot monitor the animal behavior in real time, and depend on the weather conditions since during the snowy and rainy days, it may be harder for the humans to come outside every minutes to store the information. Moreover, it is very hard to track some species such as wild animals or the ones that avoid human contact. Wireless networks along with the Global Positioning System (GPS) and satellite tracking is a solution to this problem.

To find the animal's location, a wireless device is attached to the animals. The required information such as the location is collected using GPS and can be transmitted either through satellite [95, 96, 97] or locally through routing algorithms [91] to a base station for further processing. The satellite-based tracking systems are very expensive since they require the transmission of data from the satellite transmitters mounted on the animals to the satellite database which results in the regular update of the database, [98]. Moreover, these applications use non-rechargeable batteries that not only provide limited energy for the device but also require battery replacement once in a while.

In order to prevent the battery replacement issues and satellite expenses, some other applications use solar power to recharge their batteries and also use GPS and routing algorithms for data delivery. In [91] the authors proposed the ZebraNet system, which is designed for tracking zebras. Each zebra has a collar that is embedded with GPS to find the zebra location. The gathered data is transmitted by a peer-to-peer routing protocol to the base station (mounted in a car or a plane) on a daily/weekly basis. The authors in [99] and [98] proposed animal tracking applications for tracking turtles and reindeers. In [13], the authors proposed JumboNet, which is an elephant tracking application. They track the elephants in a real-time manner. All of the aforementioned applications use GPS for finding the animals' locations and their devices are equipped with solar panels or kinetic energy harvesters for recharging for recharging the batteries [13, 98] .

In many of the animal tracking applications, critical parameters such as energy efficiency and delay should be taken into account. In terms of delay constraints networks, the data should be transmitted in a real-time manner, and thus the routing algorithm should be efficient in order to deliver the data to the base station as soon as possible. The energy efficiency of the network is also very important. Although the aforementioned animal tracking applications use solar or kinetic energy harvesters to recharge the batteries, they still may have problems providing the energy when the animal is mostly in the shade or dark places or when the animal is still and doesn't move. Due to this shortcoming, in this section we employ MAC-LEAP protocol for an animal tracking application. Moreover, in order to reduce the latency for delivering the data to the base station as much as possible, a delay tolerant routing protocol is employed along with MAC-LEAP for speeding the data delivery process. We test the proposed protocol in the JumboNet application and compare its performance with a network with the traditional JumboNet implementation.

5.6.2 MAC-LEAP in JumboNet

In this section, we describe the implementation of the MAC-LEAP protocol in the JumboNet application [13]. JumboNet is an elephant tracking application in which the real-time locations of the elephants are monitored in order to prevent danger to both elephants and humans and improve their co-existence. Each elephant has a single antenna wireless collar that measures the location of the elephant using GPS. In order to prolong the device lifetime, each collar is also equipped with an energy harvester to provide the required energy for communication. Since the amount of harvested energy may be limited depending on the environment, energy efficient communication protocols can be helpful to reduce the energy consumption. As described in Section 5.3, MAC-LEAP is a protocol that provides energy balance among the nodes in a MIMO-based network and improves the network energy efficiency.

We assumed that every node in the network is equipped with two antennas and it can either use one or both antennas for communications. The communication pattern between each pair of nodes, depending on the number of antennas they are using, is MIMO, SIMO, MISO, or SISO.

We assume that all the control packets including the RTS and CTS packets are transferred using SISO scheme in MAC-LEAP. After the RTS/CTS handshake between two nodes, the nodes transfer the data using the selected MIMO scheme. Moreover, since JumboNet is a real-time animal tracking application, the data should reach the destination (sink) in a certain amount of time. Thus, we assume that the number of sinks can be more than one and all of the sinks are connected with the others. In case of having multiple sinks, the nodes can send the data messages to any of the sinks.

Moreover, it is assumed that the original JumboNet (without MAC-LEAP) uses a CSMA/CA protocol and all nodes have a single antenna for transferring all the data and non-data packets.

5.6.3 Routing Protocol in MAC-LEAP

In this section we describe the Epidemic routing protocol that MAC-LEAP uses in the JumboNet network. Epidemic routing is a routing protocol that is suitable for networks with limited connectivity among the nodes where there is no direct connection between the source and the destination at the time of data generation. Epidemic routing is a store-and-forward protocol, where all the generated and received data are first stored in a buffer and then disseminated to any other node as soon as it is within transmission range. The protocol relies on mutual packet exchange between mobile nodes, and considers that one of the nodes will eventually reach the destination [100].

The packet transmission between nodes using epidemic routing is shown in Fig. 5.25. According to this packet exchange mechanism, two nodes first use a "Beacon" message to determine if they are in communication range. When this happens, one of the nodes (A in Fig. 5.25) starts by sending a summary vector (SV_A) of the messages it has in its buffer to the other node (B in Fig. 5.25). After receiving this vector, B checks its available messages in the buffer and sends to A both the packets that are missing to A and its summary vector (SV_B), which is used by node A to determine the packets that node B is missing. Finally, A sends the missing packets to B.

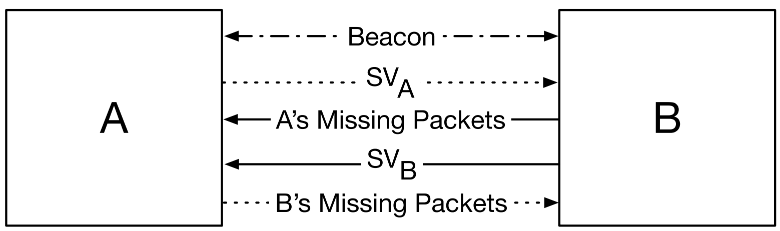


Figure 5.25: Packet transmission between two nodes in epidemic routing.

In sparse MANETs and DTNs, epidemic routing has been shown to outperform traditional routing protocols, in terms of packet delivery ratio and average packet delay [101].

5.6.4 Performance Evaluation

In this section we evaluate the performance of MAC-LEAP in JumboNet with the Epidemic routing and various packet sizes using the ns-3 network simulator. In what follows, we refer to the traditional JumboNet protocol simply as "JumboNet", and we consider three scenarios: a first one where the nodes have an unlimited energy buffer, a second scenario in which the nodes have a limited amount of energy, and a third case where the nodes can harvest energy from the environment. As explained in [13], our simulation is done based on the movements patterns of the elephants. We assume

Table 5.2: WiFi Radio Parameters for Evaluating MAC-LEAP in JumboNet Application

Channel Parameters

Parameter	Value
G_tG_r	5 dBi
M_l	10dB
N_f	10 dB
f_c	5.15 GHz
R_b	1Mbps
k	2
Tx range	250 m

Circuitry Power Consumption

Parameter	Value
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

that each elephant herd has a herd leader that sends the location information every hour. Multiple sinks are also located close to the herds to exchange the data from the herd leaders, as shown in Fig. 5.26. For all the results of this section, we consider a network with 24 elephants, an epidemic routing beacon interval and packet generation rate of 60 minutes, and a total simulation time of 10 days. The WiFi radio parameters are listed in Table 5.2.

5.6.5 Unlimited Energy Buffer

In the first experiment, we assume all nodes have unlimited amount of energy in their buffer. In Figure 5.6.5, we compare packet delivery ratio (PDR) versus different number of sinks for the JumboNet network with MAC-LEAP protocol (referred to as MAC-LEAP in all figures), and the original JumboNet protocol (referred to as JumboNet in all figures). With more sinks around the nodes, more packets can be delivered. Since the amount of energy in the nodes is unlimited, the PDR for MAC-LEAP and JumboNet are almost the same.

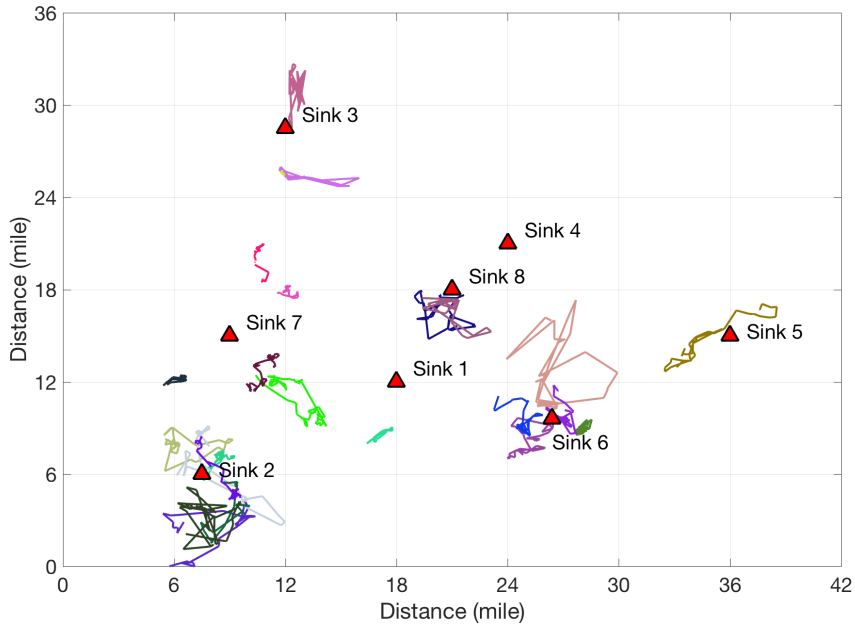


Figure 5.26: Location of the sinks and the pattern movements of the herd leaders

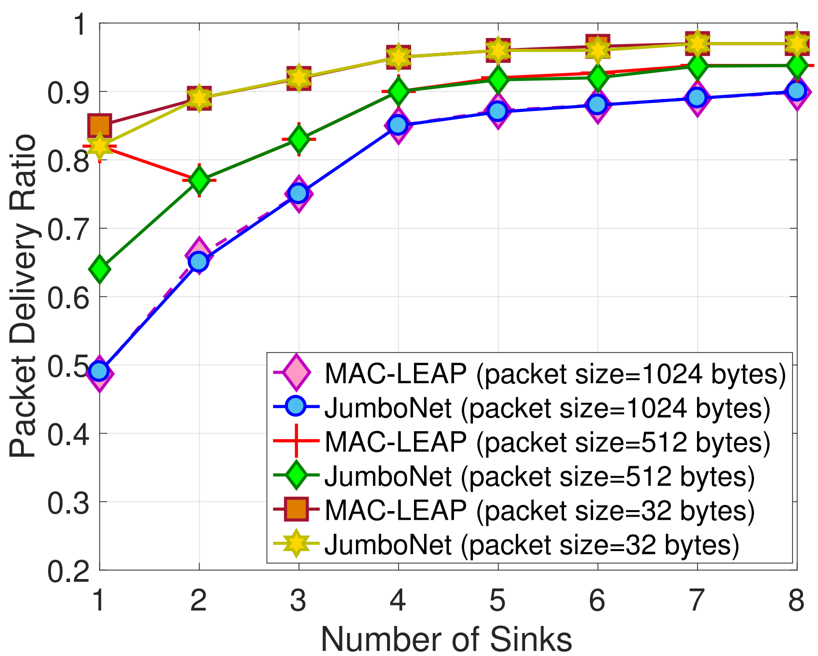


Figure 5.27: Packet Delivery Ratio (PDR) versus number of sinks with unlimited initial energy.

Moreover, the amount of delay per packet for various number of sinks has the same behavior for both MAC-LEAP and JumboNet, as shown in Fig. 5.6.5. We define delay as the time between the generation of the packet and when it is successfully delivered at the destination. Since the nodes' energy is unlimited, as the number of sinks increases, the nodes can reach a sink sooner without running out of energy. Thus, the amount of delay per packet decreases.

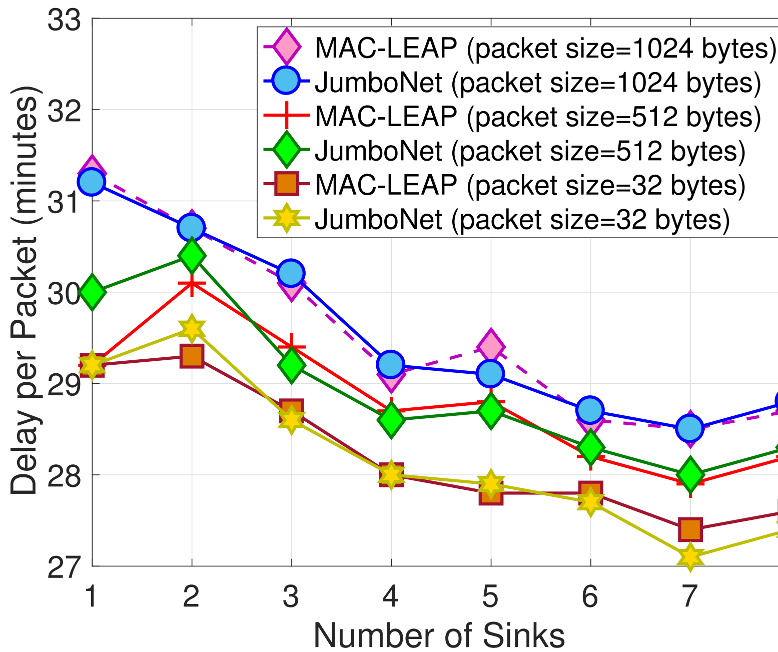


Figure 5.28: Average packet delay versus number of sinks with unlimited initial energy.

Since the nodes in the JumboNet network each have a single antenna, the communication between each pair of nodes is SISO and the amount of transmit power is fixed and equal to the power to reach a distance of 250 m. According to Eq. (3.5), SISO consumes a lot of transmit energy especially for larger distances compared to MIMO, MISO, and SIMO. In MAC-LEAP, however, the Online policy chooses the most energy efficient MIMO scheme for every packet transmission based on certain parameters including the nodes' communication distance and their remaining energy.

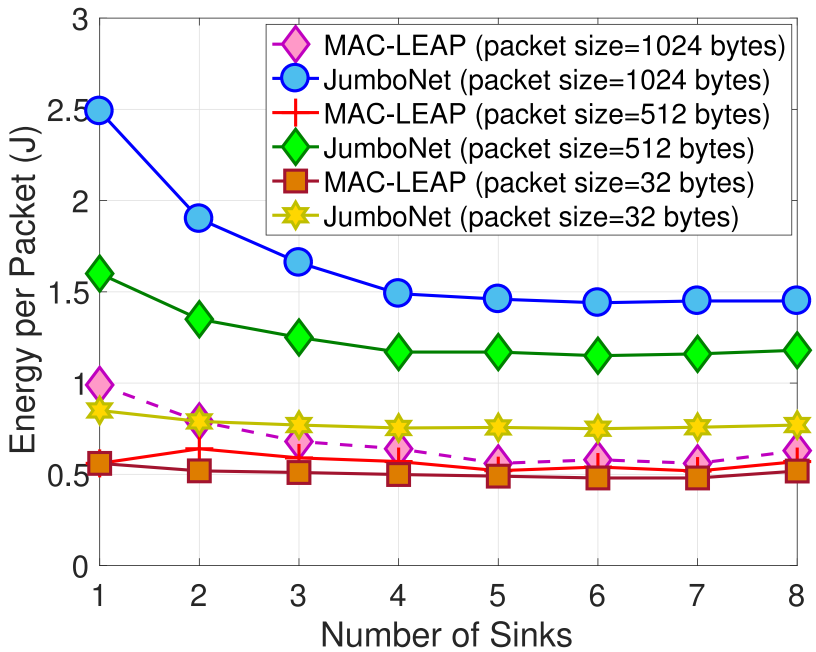


Figure 5.29: Average energy consumption per packet versus number of sinks with unlimited initial energy.

Since MAC-LEAP chooses the most energy efficient MIMO communication scheme based on the transmission distance, the amount of energy consumption per packet is much less than JumboNet. Fig. 5.6.5 shows that the energy consumption per packet in MAC-LEAP is much less than the one in JumboNet. Moreover, the energy consumption per packet is lower with a higher number of sinks because with more sinks around the nodes, each node may have a sink closer to itself. Thus, the distance between a node and one of the sinks is smaller, which results in having lower energy consumption during sending a packet.

5.6.6 Limited Energy Buffer

In this scenario, we assume that each node has a limited amount of energy (10 J) and their batteries are non-rechargeable. Fig. 5.6.6 shows the comparison of PDR versus number of sinks. MAC-LEAP consumes much less energy compared to JumboNet since it adapts the transmit power according to the transmission distance and the remaining energy of the nodes. Thus, the lifetime of the nodes is much longer in MAC-LEAP and more packets are successfully delivered to the sinks. Moreover, with more sinks available in the network, more packets can be delivered.

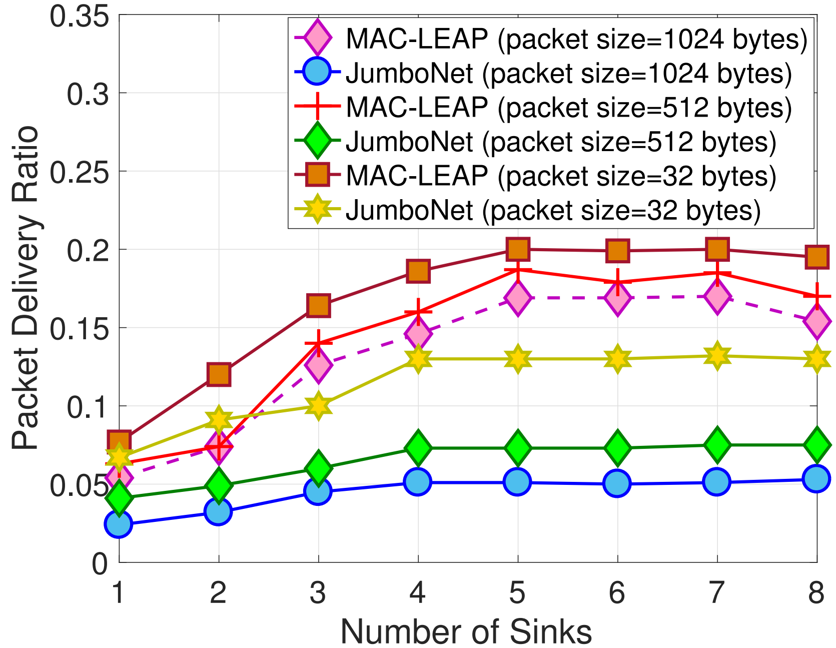


Figure 5.30: Packet Delivery Ratio (PDR) versus number of sinks with limited initial energy.

Fig. 5.6.6 shows the amount of delay per packet when the number of sinks in the area is changing. For all the different packet sizes, MAC-LEAP requires lower delay per packet compared to the JumboNet protocol.

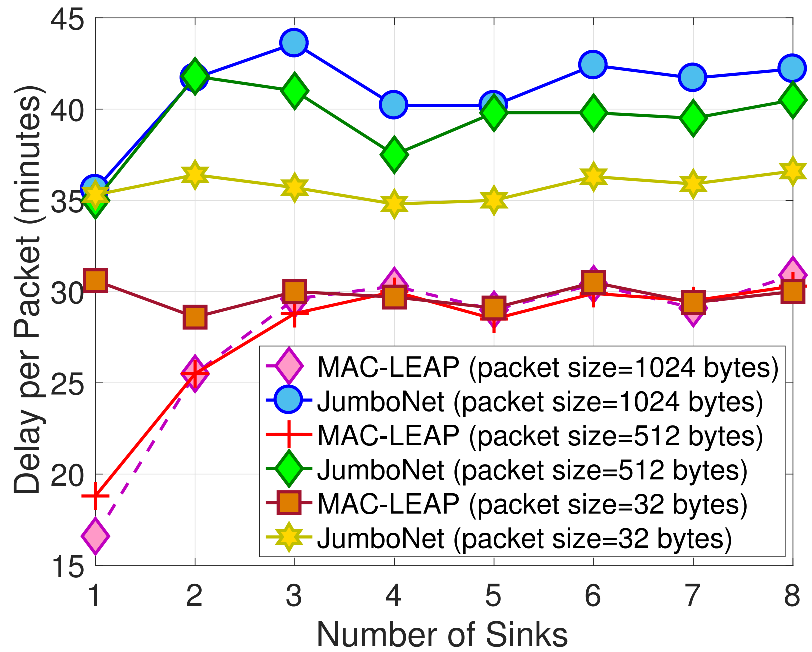


Figure 5.31: Average packet delay versus number of sinks with limited initial energy.

With a limited amount of energy, MAC-LEAP consumes less energy and thus provides higher lifetime for the nodes compared to JumboNet. As shown in Fig. 5.6.5, the energy consumption per packet in MAC-LEAP is much less than the one in the JumboNet network. Moreover, as the packet size increases, the amount of energy consumption gets higher.

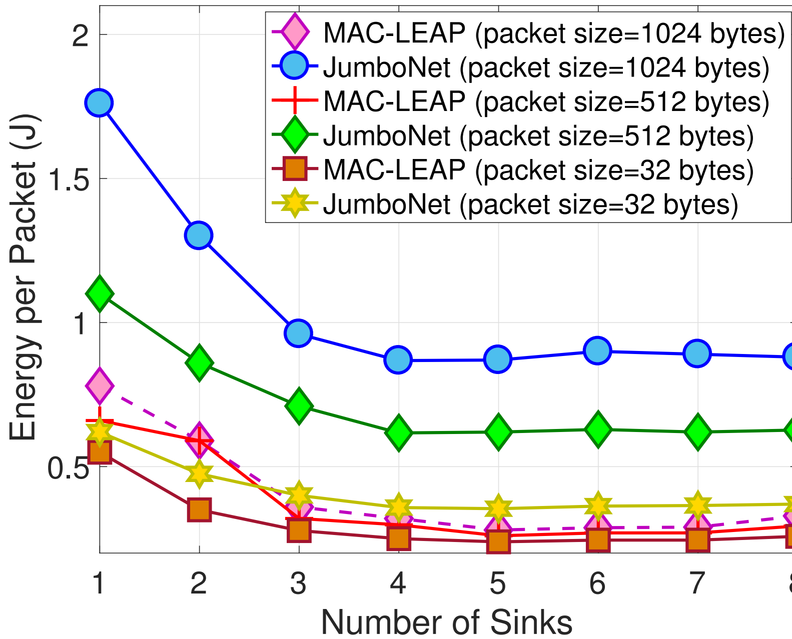


Figure 5.32: Average energy consumption per packet versus number of sinks with limited initial energy.

5.6.7 Limited Energy Buffer with Energy Harvesting

In this section, we assume each node has 2 J of initial energy and is equipped with a solar energy harvester. The harvested energy over time is shown in Fig. 5.33, where each sample is taken every 5 minutes for a total of four days. Unlike the unlimited energy buffer scenario where we assumed that the nodes always have enough energy in their buffer (Section 5.6.5) , the energy coming from the solar harvester is added to the buffer gradually during the day.

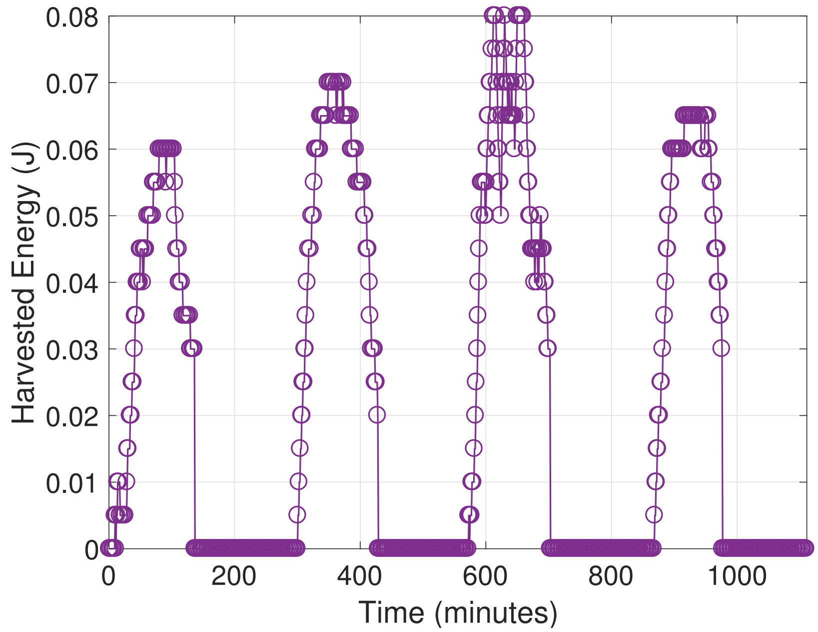


Figure 5.33: Sampled solar harvested energy every 5 minutes for four days.

As shown in Fig. 5.6.7, PDR increases as the number of sinks increases with different packet sizes. With larger packet sizes, the PDR is lower. With packet size of 1 Kbytes, MAC-LEAP has a 10% improvement over JumboNet. With packet sizes of 512 and 32 bytes, the improvement is smaller since energy conservation is higher with larger packet sizes. Moreover, PDR of MAC-LEAP is higher than JumboNet since it uses the online policy to select the most energy efficient MIMO scheme for data transmission.

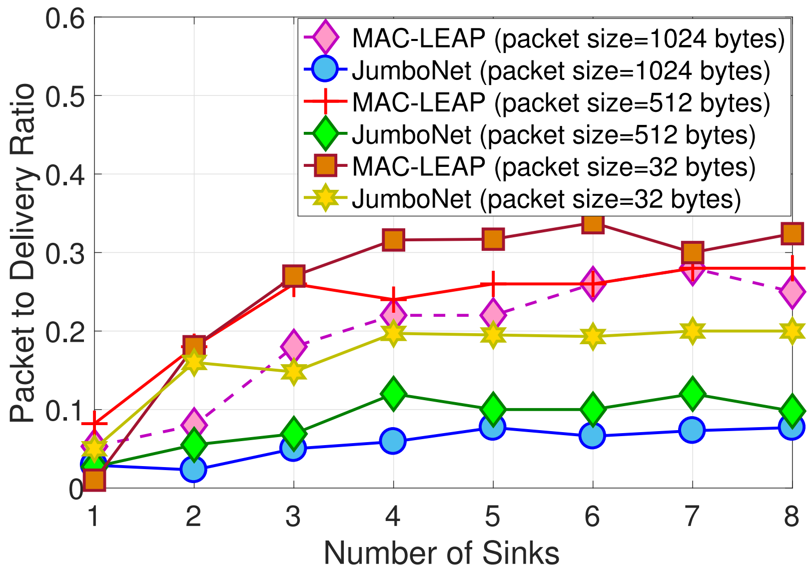


Figure 5.34: Packet Delivery Ratio (PDR) versus number of sinks with energy harvesting.

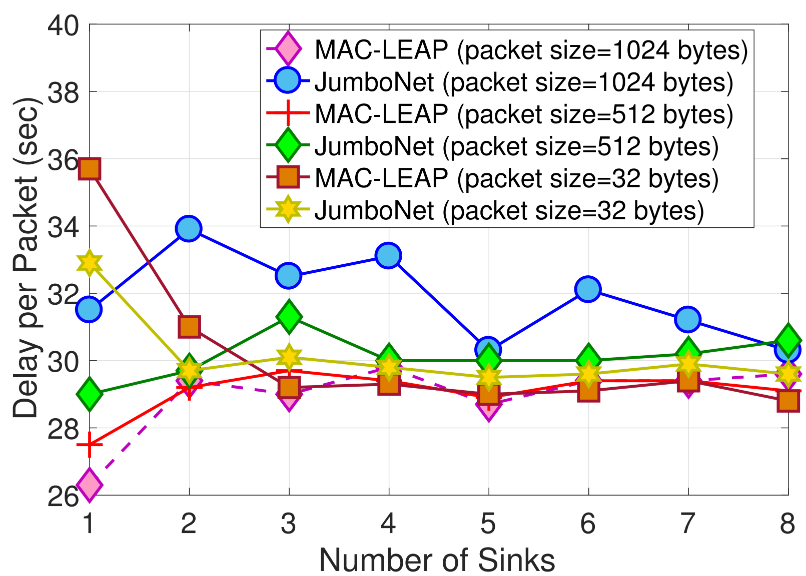


Figure 5.35: Average packet delay versus number of sinks with energy harvesting.

In Fig. 5.6.7, we plot the average packet delay as the number of sinks increases. Delay per packet in JumboNet is on average 3 minutes higher than MAC-LEAP when the packet size is 1 Kbytes. Moreover, for 512 and 32 bytes packet sizes, the MAC-LEAP delay is 1 minutes less than JumboNet.

5.7 Conclusions

In this chapter, we proposed Multi-Antenna, Cross Layer, Energy Adaptive Protocol (MAC-LEAP), 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 RTS and CTS packets to provide collision avoidance. We also introduced a MIMO-based framework for wireless communication into Network Simulator 3 (ns-3). Using this framework, we evaluated MAC-LEAP through extensive simulations.

Moreover, we also evaluated MAC-LEAP in a real animal tracking application called JumboNet. We tested the protocol in three scenarios: a network with limited energy buffer; a network with unlimited energy buffer; and a network where the nodes utilize energy harvesting. According to the simulation results, MAC-LEAP outperforms the traditional JumboNet network in terms of packet delivery ratio, transmission delay, and energy consumption for different packet sizes.

In order to make the network more scalable and also to make the routing more energy efficient, we need to change the architecture of the network to a cluster-based network in which nodes may either have one or two antennas. Every cluster has a cluster-head (CH) that is connected to several normal nodes. Cluster-based networks are more energy efficient since they reduce the communication range of the nodes and thus they use less transmission power to communicate inside the clusters. Most of the nodes (except the cluster heads) are not responsible for the energy-intensive tasks such as data aggregation or forwarding. Moreover, it is possible to balance the energy consumption even more by using cluster head rotation methods.

Some of the cluster-based networks also use MIMO in order to provide energy balance and reduce the nodes' energy consumption. In a traditional MIMO cluster-based network, the nodes cooperate with each other in order to receive the data faster. This method is known as cooperative MIMO (also virtual MIMO). In our work, however, we intend to employ single-user MIMO in a cluster-based network to both avoid the complexity and the nodes cooperation mechanisms of virtual MIMO. In the next chapter, we describe our work exploring the benefits in terms of energy efficiency and scalability of this type of network.

Chapter-6

Cluster-based Energy Harvesting MIMO Wireless Networks

6.1 Introduction

In order to have a scalable network, the wireless nodes may form groups called clusters that are connected to each other through Cluster-Heads (CH). A cluster-based wireless network has two or more tiers. In the lowest tier are the normal wireless nodes that communicate with the CHs. In the upper tiers are the CHs, which communicate with each other and are responsible for more complicated tasks compared to the normal nodes. Clustering has various advantages. Due to the layered architecture, communication bandwidth and redundant message exchanges among the nodes are reduced, since the normal nodes only communicate with their assigned CHs and are not affected by the overhead caused by changes at the CH level.

In cluster-based wireless networks, it is important to balance energy consumption inside the cluster in order to avoid the CHs from running out of energy. There are many cluster-based networks that provide energy efficiency for single antenna wireless networks [57, 102, 103, 104, 105, 106] and cooperative MIMO wireless networks [107, 108, 109, 110, 111, 112]. For multi-antenna wireless networks, however, the number of cluster-based algorithms is limited.

In a cluster-based network using MIMO, the nodes are equipped with more than one antenna. In such a network, CHs can have a single antenna or multiple antennas. Assuming all the nodes (CHs and normal nodes) have a single antenna, the communication between the normal nodes and the CH is more efficient for smaller distances and thus with small clusters. If the CH has multiple antennas, the inter-cluster communication is either MISO, SIMO, or MIMO depending on the number of antennas of the normal nodes. In the case where the CH has multiple antennas, the communication is more energy efficient for larger distances and larger cluster sizes.

There are various benefits of using MIMO in a cluster-based network:

- If a message is broadcast by a multi-antenna CH to the nodes inside a cluster, the total energy consumption is less than the situation in which the CH has a single antenna, since in the former case, the transmission energy consumption of the CH is much higher when it sends the data to the nodes that are located far away from the CH.

- Assuming the coverage area is a circle with the CH in the center, MIMO provides better coverage than SISO communication. Having a multi-antenna CH, we have clusters with larger diameter since the data sent by this CH can be received by farther nodes. With a single antenna CH, however, the coverage is worse and thus the size of the cluster in terms of diameter is smaller. Moreover, MIMO consumes less transmission energy for larger communication distances compared to SISO. Thus, with lower transmission energy consumption, MIMO achieves better coverage than SISO.

- In most cluster-based networks, CH rotation is done when the CH battery level becomes low. Although CH rotation provides better lifetime and energy efficiency for the network, the cluster should be reformed and all the nodes inside the cluster should disconnect with the previous CH and connect to the new one. Since MIMO consumes less transmission energy than SISO, the CH's battery will drain more slowly compared to SISO communication in the cluster. Moreover, the CH rotation inside a cluster with SISO communication should be performed more frequently than a cluster-based network with MIMO communication. Thus, by having the same energy efficiency, we can achieve fewer CH rotations and re-clustering operations in a MIMO based network.

In this chapter, we propose an energy efficient MIMO protocol called Cluster-based energy Harvesting MIMO (or CH-MIMO) for cluster-based multi-antenna wireless networks. We assume that all nodes have more than one antenna and use the most energy efficient number of antenna for communication that provides the highest energy efficiency. CH-MIMO is evaluated in two types of networks. In the first type, the nodes' energy source is limited and they have non-rechargeable batteries. When their batteries run out of energy, they die. In the second type of network, the nodes are powered by harvested solar energy and thus they have unlimited energy source. Moreover, we evaluate the performance of CH-MIMO in a network with fixed nodes and in a network with mobile nodes.

6.2 CH-MIMO: Cluster-based Energy Harvesting Multi-Antenna Protocol

CH-MIMO is designed for a cluster-based network in which the nodes have multiple antennas for communication. We assume N nodes are randomly located in a square-shaped area. Each group of nodes form a cluster by finding the closest Cluster-Head (CH) and connecting to it. CH-MIMO is designed based on rounds. At each round, several actions are taken: (a) CH selection, (b) packet transmission from normal nodes to the CHs, and (c) forwarding the received packets from the CH to the sink. In this work, we utilize the LEACH protocol for the selection of CHs and the formation of clusters, but CH-MIMO can work with any cluster formation algorithm.

6.2.1 Cluster-Head Selection Algorithm

At the beginning of each round, certain nodes are chosen to be CHs according to the CH selection algorithm in LEACH [57]. Each node decides to be a CH or not based on two factors: the suggested percentage of CHs in the network, and the number of times that this node was a CH in the previous rounds. Based on these factors, a threshold *T(n)* is defined in Eq. 6.1:

$$T(n) = \begin{cases} \frac{P}{1-P\times(r \bmod \frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \tag{6.1}$$

where P is the suggested percentage of CHs in the network ($0 \leq P \leq 1$), r is the current round number, and G is the set of nodes that have not been a CH in the previous $\frac{1}{P}$ rounds. For making a decision to be a CH or not, a node chooses a random number between 0 and 1. If the number is less than T(n), the node will be a CH for the current round. Thus, each node will be a CH once every $\frac{1}{P}$ rounds. A node might be a CH in the last round and then again when all nodes are eligible to be a CH in the next set of 1/P rounds. This algorithm provides fairness in terms of CH selection among the nodes. Due to this CH rotation, the algorithm prevents the CHs from running out of energy while other nodes have lots of energy in their buffers.

6.2.2 Cluster Formation

Once the CH nodes are chosen, they send an advertisement message in which their location is included, to other nodes in order to inform them that they are CHs. The advertisement messages are sent using a CSMA MAC protocol in order to avoid collisions. Although the CHs use the same transmit power to propagate the advertisement messages, unlike LEACH, in CH-MIMO, all CHs send these messages by Multiple Input Multiple Output (2x2 MIMO).

After the CH selection phase, the nodes choose the CH they want to join depending on the received signal strength of the advertisement messages, such that each node connects to the closest CH in terms of communication distance, which requires less energy to communicate. When a node joins a cluster, it informs the CH by sending a small message using the CSMA MAC protocol.

In Fig. 6.1, an example of the proposed cluster-based network with CH-MIMO with 50 nodes is shown. In this figure, the nodes have 1 J of initial energy and the network is running for 300 rounds. Based on the cluster formation algorithm, the nodes are connected to the closest CH according to their euclidean distance (which minimizes communication energy). In the first round, all nodes have enough energy for communication. As the number of rounds increases, the nodes' remaining energy decreases. As shown in Fig. 6.1, in the 150^{th} round, two nodes are dead. The percentage of dead nodes grows while the number of clusters decreases as the algorithm reaches round 200. Finally, almost all nodes die in round 250 and no more packets are transmitted.

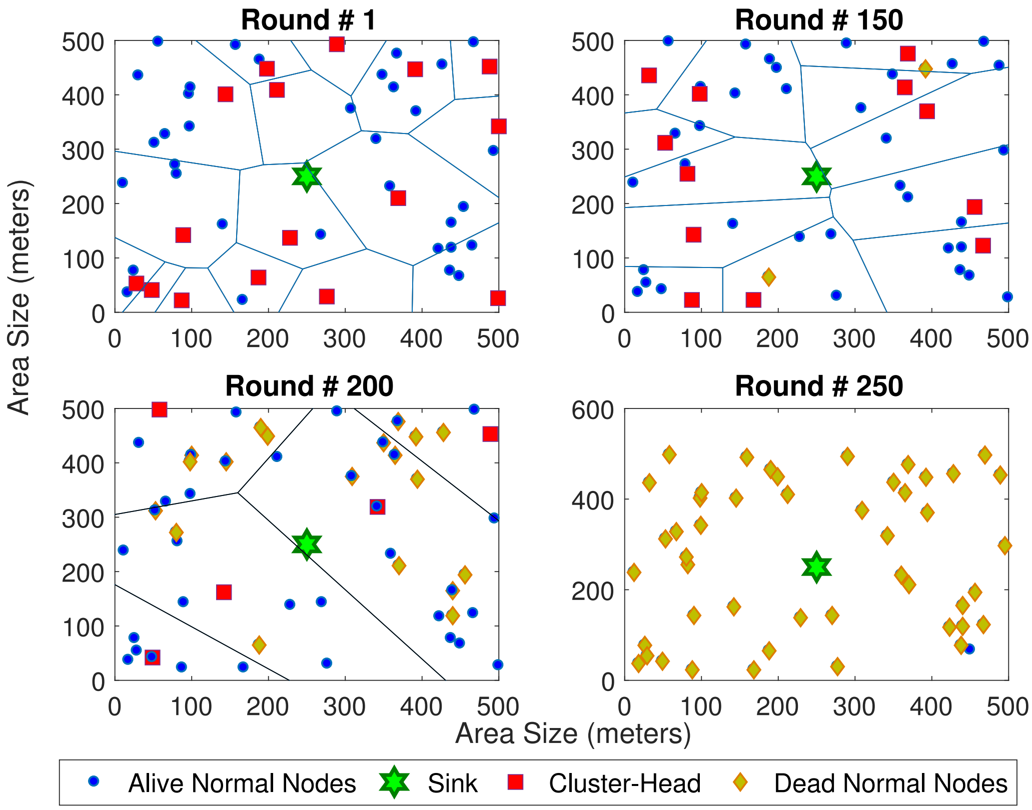


Figure 6.1: Cluster-based network.

6.2.3 Data Transmission

The data transmission process from a node to the sink has three steps; in the first step the number of antennas of the normal node and the CH are selected using the *Online Policy*, in the second step, the nodes send data to the CH, and in the last step, the CH forwards the data to the sink.

Multi-Antenna Selection Policy

It is assumed that all nodes (both CHs and non-CHs) are equipped with multiple antennas. For each node-CH pair, the communication can be MIMO, MISO, SIMO, and SISO, each of which may be more energy efficient than the others depending on various parameters. In order to select the most energy efficient MIMO scheme (out of these four schemes), we employ an *Online Policy* algorithm, which calculates the number of packets for MIMO, MISO, SIMO, and SISO and chooses the multi-antenna scheme for data transmission that maximizes the total number of received packets in the network.

As the name suggests, the *Online Policy* works online and chooses the best MIMO scheme to be used for the communication, on a per-packet basis, on-the-fly. In the *Online Policy*, for a specific Bit-Error-Rate (p_b) and at a fixed transmitter-receiver distance, we compute the number of received packets for all the four antenna modes, and we select different schemes interchangeably. In particular, at time t, depending on the remaining energy at the transmitter and the receiver, we choose the scheme M_{tx}^txM_{rx}^t that provides the highest number of received packets, according to Eq. 3.8. 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., $B_{tx}^{t+1} = B_{tx}^t - E_{\mathrm{pkt}}^{tx}(M_{tx}^t, M_{rx}^t)$ and $B_{rx}^{t+1} = B_{rx}^t - E_{\mathrm{pkt}}^{rx}(M_{tx}^t, M_{rx}^t)$). Moreover, the control packets (advertisement message, RTS, and CTS packets) are exchanged by a fixed multi-antenna scheme (e.g., MISO).

Intra-Cluster Communication

Since there is a chance for packet collision in CSMA/CA when the RTS packets are exchanged at the same time from two nodes to a single destination, we used TDMA to completely avoid the packet collision issue. For each cluster, the CH node assigns a time slot to each node inside the cluster based on a TDMA scheme. Each node is allowed to send data to the CH only in its assigned slot. Once the TDMA slots are selected, a message is broadcast to all nodes inside the cluster informing them of the assigned TDMA time slots. At each TDMA slot, several data packets are sent to the CH. The information regarding the remaining energy and the location of the node and the CH should be updated before data transmission in order to choose the most energy efficient multi-antenna scheme for data exchange. Before each data packet transmission between a node and the CH, the node sends its location information and also its remaining energy through an RTS packet to the CH. The CH calculates the communication distance and the most energy efficient MIMO communication scheme using the *Online Policy* for data transmission. Then, the CH sends this information back to the node using a CTS packet. Reading the energy efficient MIMO scheme for data transmission from the CTS packet, the node sends the data packet to the CH by the chosen MIMO scheme.

Inter-Cluster Communication

We assumed that the sink has unlimited energy. Thus, when a CH sends a packet to the sink, it is best to use the multi-antenna scheme which provides the highest energy efficiency for the CH. The sink is always the receiver and CH is the sender in the CH-Sink communication. Since the packet is transmitted from the CH to the sink, the CH chooses the antenna mode that has the lowest energy consumption, thus resulting in the highest number of sent packets for the CH. By calculating the transmitted number of packets ($L_{tx}^t(M_{tx}M_{rx})$ in Eq. 3.7) for four multi-antenna schemes, the multi-antenna mode which results in the highest number of sent packets is chosen for CH-Sink data transmission. Moreover, since the CH is the transmitter, B_{tx}^t equals to the remaining energy of the CH in Eq. 3.7 and the communication distance is the distance between the CH and the sink. Thus, the multi-antenna mode may be changed depending on the CH-sink distance and the CH's remaining energy.

6.3 Performance Evaluation

In this section, we evaluate the performance of CH-MIMO under various settings in MATLAB. We assume a Rayleigh fading channel with an average path loss that falls off with the square of distance (d^2). We have 50 nodes that are randomly located in a 500 m x 500 m area. The initial parameters for the simulation setting, the circuitry power consumption, and the channel parameters are listed in Table 6.1. Moreover, the results are averaged over 10 iterations over channel realization and the nodes' location. The channel realization and the nodes' locations are fixed in each iteration.

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 pre-determined fixed MIMO scheme, while for sending the DATA packets, depending on the policy selected by the *Online Policy*, 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 for control packets to be one. The transmitter, however, uses

Table 6.1: Simulation parameters for cluster-based networks.

General Parameters	
Number of Nodes	50
P	0.2
Data Packet Size	16 Kbyte
Control Packet Size	20 bytes
Number of Rounds	300
Initial Energy	30 J
Target Bit-Error-Rate	10^{-5}
Multi-Antenna Scheme for Control Packets	MISO
Length of a TDMA Slot	30 packets

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, since the nodes does not have the updated location information of each other before the RTS/CTS transmission, the transmission mode and the transmit power for RTS and CTS should be fixed. We assume that the nodes send the control packets (RTS, CTS, and ACK) with the highest transmit power (with maximum distance equal to the area size) and with MISO in order to be received by the CH/normal node even if they are located at the longest distance of each other.

We considered two scenarios; in the first one the nodes are not mobile and have limited energy source (e.g., non-rechargeable batteries). In the second scenario, the nodes are mobile and are powered by solar energy. In both of these scenarios, we evaluate the number of packets received by the sink, the percentage of dead nodes over time, the network lifetime, which is defined as the time when more than 90% of the nodes die, and the nodes' total energy consumption rate.

6.3.1 CH-MIMO With Fixed Nodes and Non-Rechargeable Batteries

In this section, we have a cluster-based network with 50 fixed nodes, each of which has 1 J of initial energy. The nodes are equipped with two antennas and a non-rechargeable battery. We evaluate CH-MIMO in terms of number of received packets, the percentage of dead nodes, and the total energy consumption. We compare CH-MIMO with LEACH in which all nodes communicate with each other with a fixed MISO scheme for both data and non-data packets and doesn't exchange

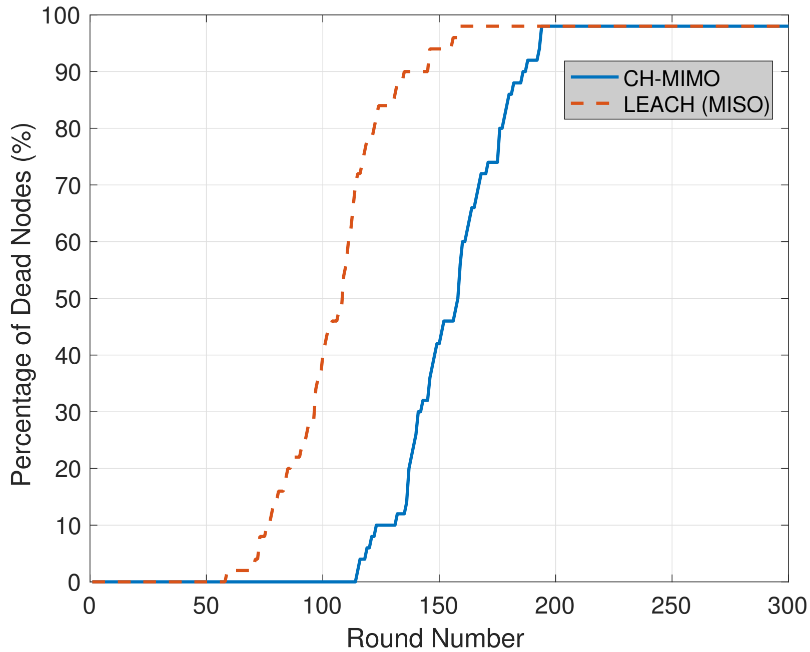


Figure 6.2: Percentage of dead nodes versus round number (without mobility and without energy harvesting).

RTS/CTS packets.

As shown in Fig. 6.2, the number of dead nodes increases as time goes on and the round number increases. By employing the *Online Policy* as the energy efficient multi-antenna selection algorithm, CH-MIMO outperforms the traditional LEACH protocol with fixed MISO scheme by 37% in terms of percentage of dead nodes. Moreover, in terms of the network lifetime (the time when more than 90% of the nodes die), CH-MIMO improves the network lifetime by 50% since 90% of the nodes die at round 91 and 135 in LEACH (MISO) and CH-MIMO, respectively.

According to Fig. 6.3, due to the high energy efficiency of the *Online Policy*, the total remaining energy of the nodes in CH-MIMO is much higher than the traditional approach. Due to higher remaining energy of the nodes, more packets are received by the sink by using CH-MIMO (Fig. 6.4).

During the first rounds, all nodes have enough energy for communication. Thus the number of packets increases linearly by round number. At round 150 and 200, the last packet is transmitted in the network when LEACH (MISO) and CH-MIMO are employed, respectively. After the last packet transmission, the number of packets remains fixed since the nodes run out of energy.

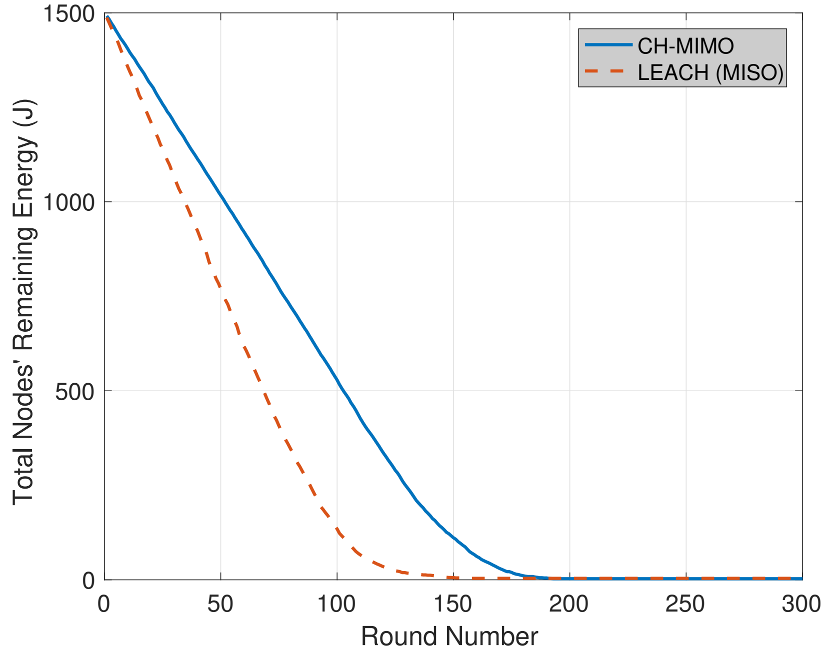


Figure 6.3: Total remaining energy versus round number (without mobility and without energy harvesting).

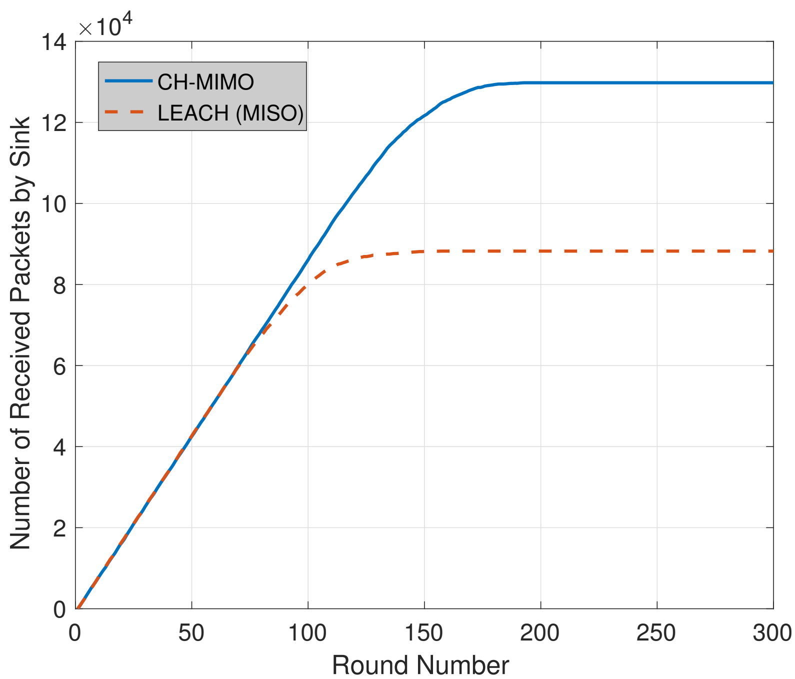


Figure 6.4: Number of received packets by the sink versus round number (without mobility and without energy harvesting).

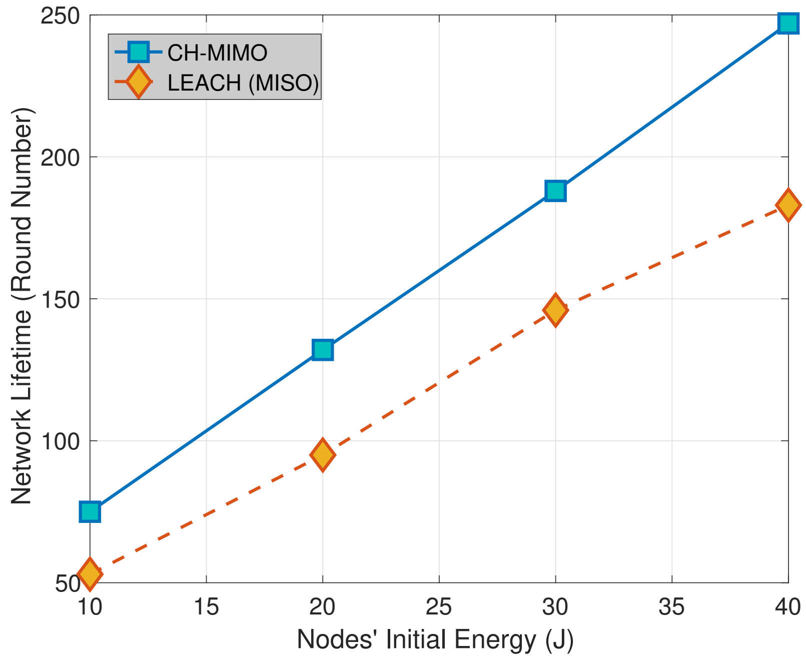


Figure 6.5: Network lifetime versus nodes' initial energy (without mobility and without energy harvesting).

We also measure the network lifetime, which is defined as the time (round number) when more than 90% of the nodes die. In Fig. 6.5, the network lifetime for CH-MIMO and LEACH (MISO) is shown when the initial energy of the nodes increases from 10 J to 40 J. CH-MIMO improves the network lifetime by an average of 36% for various initial energy values compared to LEACH (MISO). Due to employing the *Online Policy* in CH-MIMO, the nodes dynamically adjust their number of antenna before data communication. Thus, the node's energy consumption rate is much lower in CH-MIMO than LEACH (MISO), which results in prolonging the network lifetime.

6.3.2 CH-MIMO With Mobile Nodes and Energy Harvesting

In this section, the nodes are equipped with solar panels and rechargeable batteries that are recharged using solar power. It is assumed that each round is 20 seconds and the initial energy of all nodes is 0.1 J. Fig. 6.6 shows the amount of harvested solar energy over time. We use the solar harvested energy dataset gathered in Edmonton, Canada [1]. Each node receives a factor of the harvested energy from the solar panel every round to recharge their batteries. In this scenario, we

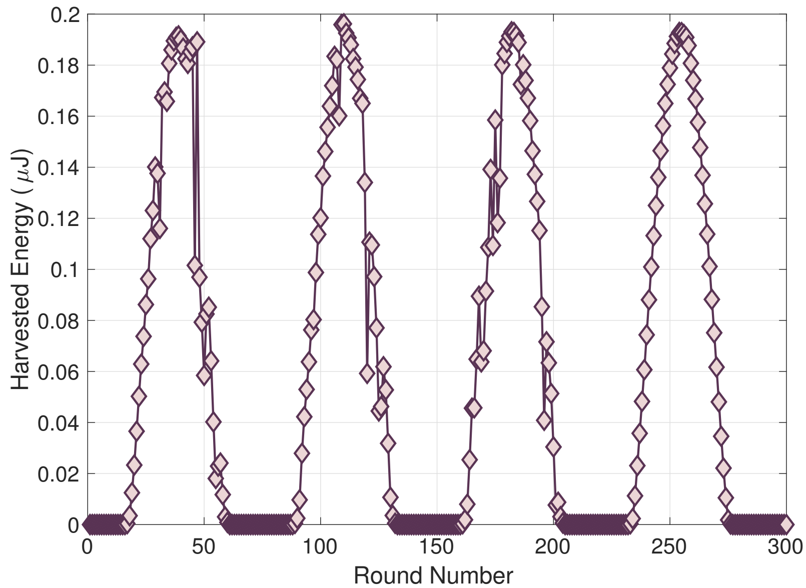


Figure 6.6: Harvested solar energy versus time (data from [1]).

assume that the nodes are mobile, each with a different velocity that follows a random walk model with Gaussian steps.

At every round (represents 20 seconds), each node receives a factor of the harvested energy. We apply the factor (harvested factor) at the energy source since we assume that the nodes are located in different geographical locations and do not have the same weather conditions. Some nodes may be in direct sun light while others are in the shade. The harvested factor for each node changes over time as the node may move from sun light into the shade. Moreover, this factor is different at every node and follows a uniform distribution of U[0,1].

In Fig. 6.7, the number of received packets for various fixed multi-antenna schemes is shown. By using SISO in LEACH and also in exchanging the control packets in CH-MIMO, the number of packets is less compared to MISO, SIMO, and MIMO since the energy consumption of SISO is very high. The number of packet's improvement of CH-MIMO is %23, %273, %116, and %87 compared to LEACH when the fixed multi-antenna scheme is SISO, MISO, SIMO, and MIMO, respectively. Due to the highest improvement with MISO fixed multi-antenna scheme in terms of number of packets, we use MISO as the default fixed scheme for all the simulation results.

In Fig. 6.8, total remaining energy of the nodes versus round number is shown for CH-MIMO and

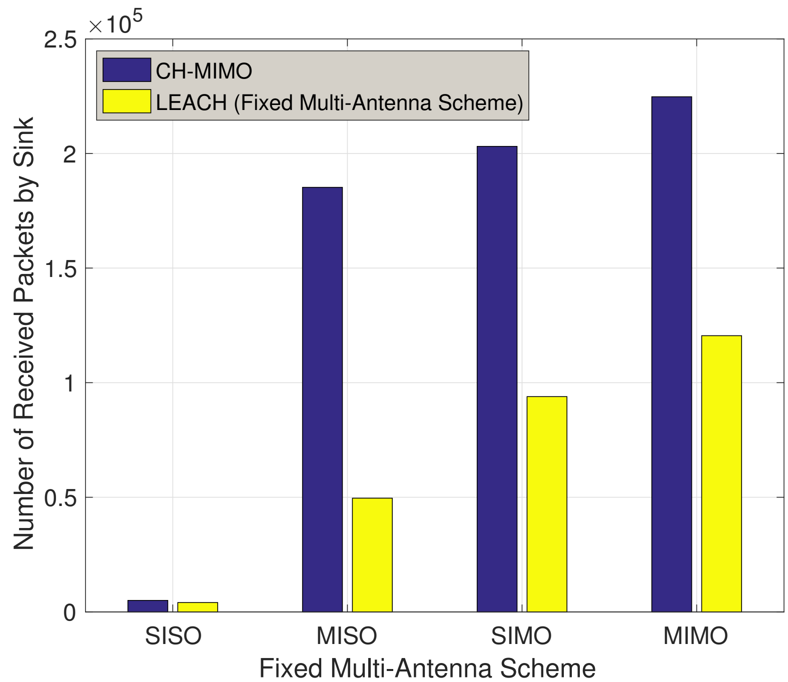


Figure 6.7: Number of received packets versus multi-antenna fixed scheme (with mobility and energy harvesting).

LEACH (MISO). Since the energy source is solar harvested energy, the nodes' batteries are charged during the day and discharged at night. The nodes have lower energy consumption by using CH-MIMO, which results in an average of 80% improvement in terms of total remaining energy compared to LEACH (MISO).

Due to the high energy that is saved using CH-MIMO, as shown in Fig. 6.9, more packets are received by the sink compared to LEACH (MISO). When the batteries are completely discharged at night, no new packets are sent/received until the batteries are recharged during the day.

By increasing the number of nodes in the network, more packets are received by sink as shown in Fig. 6.10. Moreover, CH-MIMO improves the number of packets by an average of 61% as the number of nodes changes in the network.

The data packet size also impacts the energy consumption of the nodes. By sending larger packets, the nodes' batteries are discharged faster and thus fewer packets are sent/received. As shown in Fig. 6.11, the number of received packets decreases as the size of the packets increases.

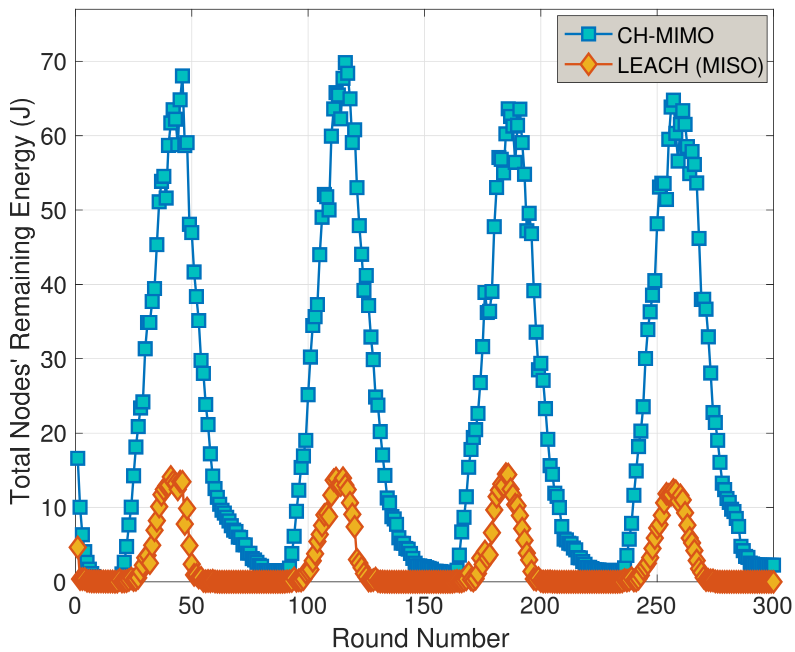


Figure 6.8: Total remaining energy of all nodes versus round number (with mobility and energy harvesting).

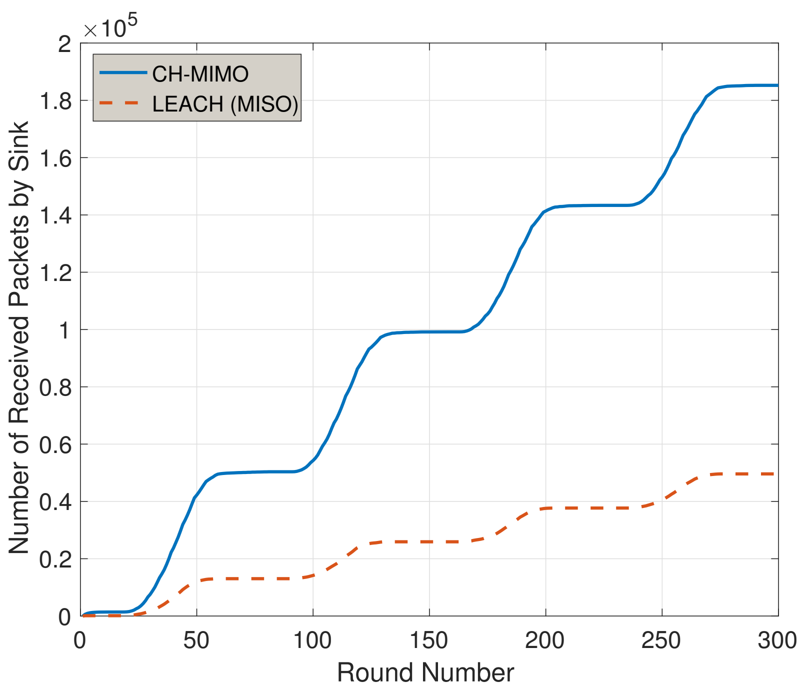


Figure 6.9: Number of received packets versus round number (with mobility and energy harvesting).

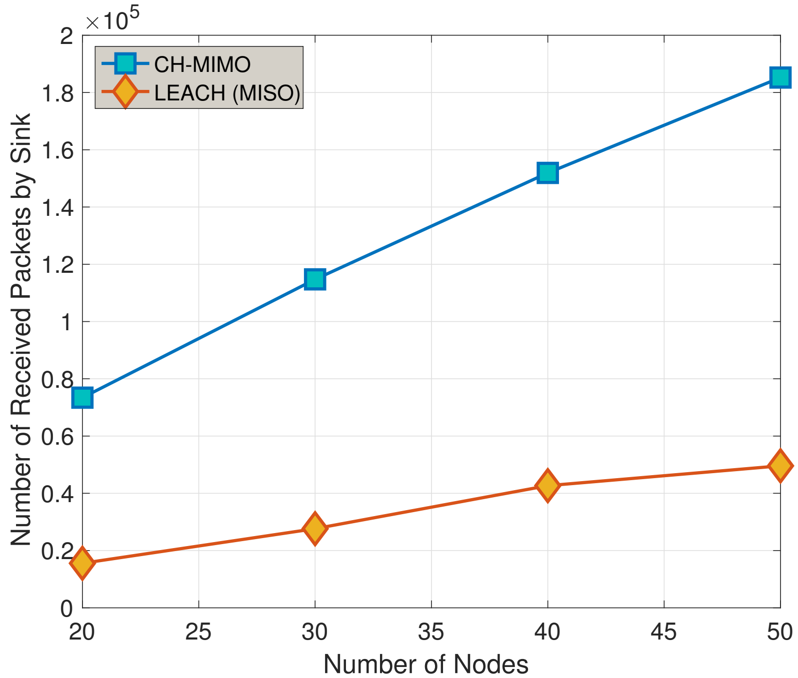


Figure 6.10: Number of received packets versus number of nodes (with mobility and energy harvesting).

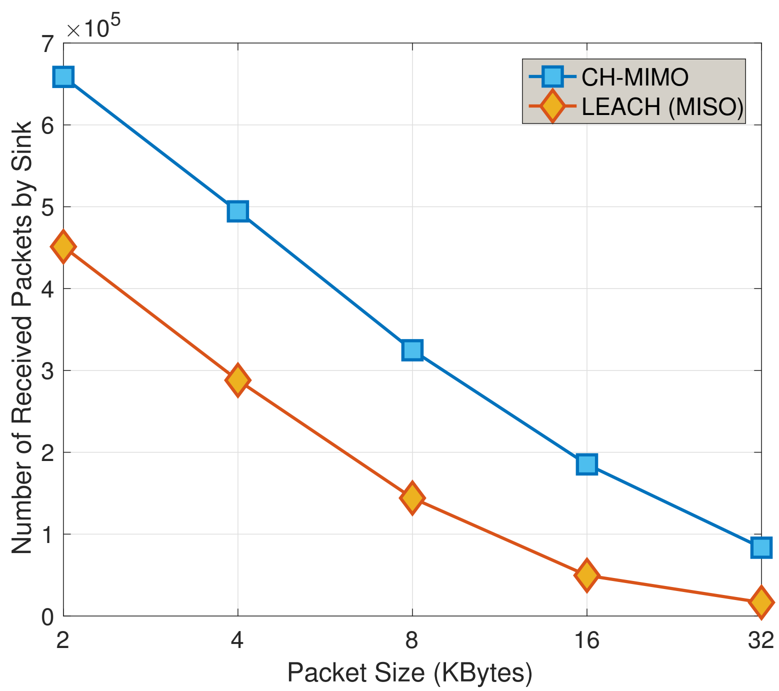


Figure 6.11: Number of received packets versus packet size (with mobility and energy harvesting).

6.4 Conclusions

In this chapter, CH-MIMO, a MIMO protocol for cluster-based networks is proposed to make the network more scalable and more reliable in terms of communication and energy efficiency. CH-MIMO adapts the number of antennas in both the normal nodes and CHs to maximize the energy efficiency. Moreover, this protocol employs LEACH's CH rotation algorithm to avoid draining the energy of the CH nodes. I evaluated CH-MIMO in various scenarios; with fixed nodes and limited energy, and with mobile nodes and energy harvesting. According to the simulation results, CH-MIMO outperforms the traditional protocol in terms of number of received packets, percentage of dead nodes, the total remaining energy, the network lifetime, and the energy consumption per packet.

Chapter-7

Conclusions and Future Work

7.1 Conclusions

In this thesis, I explore energy balancing techniques in wireless networks through the use of MIMO communication. The contributions of this research are summarized below.

- I modeled the problem of dynamically adjusting the number of antennas based on nodes' energy levels such that the nodes' communication is based on MIMO, MISO, SIMO, or SISO on a per-packet basis. The selection of the optimal multi-antenna scheme is done based on various parameters such as the nodes' distance, remaining energy, and the target Bit-Error-Rate.

- I introduced a simulation framework for MIMO wireless networks for the ns-3 simulator. In the framework, the wireless nodes can select their number of antennas, and the transmission power and receiver energy consumption are calculated accordingly. Moreover, an energy prediction model for energy harvesting is implemented for the ns-3 simulator in which the energy harvesting is based on real solar data. I implemented two well known energy prediction models: WCMA and EWMA.

- I extended the MIMO energy model for the case of energy harvesting. I consider a point-to-point MIMO wireless communication link in which there are two nodes equipped with energy harvesters and rechargeable batteries. I modeled the system using a finite MDP with unknown transmission probabilities and found an optimal transmission policy using Q-learning. I considered four transmitter-receiver antenna pairs in the MIMO system, each of which may result in different energy consumption for the nodes. Based on the energy consumption and the harvested energy arrival, I employed Q-learning to find the most energy efficient transmission policy and maximize the total throughput during a specific time that the system is running.

- I extended the network to more than two nodes and proposed an energy balancing protocol called MAC-LEAP: Multi-Antenna, Cross Layer, Energy Adaptive Protocol for both single-hop and multi-hop MIMO wireless networks. This 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 RTS and CTS packets to provide collision avoidance.

- I evaluated MAC-LEAP in a real animal tracking application called JumboNet. I tested the protocol for three scenarios: a network with limited energy buffer; a network with unlimited energy buffer; and a network where the nodes utilize energy harvesters. According to the simulation results, MAC-LEAP outperforms the traditional JumboNet network in terms of packet delivery ratio, transmission delay, and energy consumption for different packet sizes.

- I proposed Cluster-based MIMO (CMIMO), a scalable version of MAC-LEAP for multi-antenna cluster-based wireless networks. CMIMO adapt the number of antennas in both the normal nodes and CHs to maximize the energy efficiency. We evaluated CMIMO when the nodes have non-rechargeable batteries, when the nodes have energy harvesting, and when the nodes are mobile. According to the simulation results, CMIMO outperforms the traditional protocol in terms of number of received packets, percentage of dead nodes, the total remaining energy, the network lifetime, and the energy consumption per packet.

7.2 Future Work

In order to improve the performance of MIMO wireless networks, several directions can be pursued as future research.

- The Online Policy in MAC-LEAP adjusts the number of antennas only based on the the transmitter and the receiver parameters. However, in a network with more than two nodes, the remaining energy of every transmitter node depends not only on the receiver node's parameters but also on other networks conditions such as the transmitter's number of neighbors, the remaining energy and distance of each neighbor, and the velocity and mobility status of the neighbors. In order to further improve the antenna selection algorithm in the network, more research can be applied to consider all the network parameters in the number of antenna adjustment algorithm.
- The optimal number of antennas for achieving maximum number of packets is found for a network with two nodes using the Optimal Policy described in section 3.3.1. Due to extensive network variation and parameters, finding the optimal number of antennas for all nodes is challenging in a network with more than two nodes. Further research can be applied in this area.
- The cluster-based CMIMO protocol is designed for single-hop communication in which the CHs directly send their data to the Sink. This protocol can be extended for multi-hop communication. In order to improve the energy efficiency of the cluster-head tier, a routing protocol can be used among the CHs to find the most energy efficient path to the Sink.

Bibliography

[1] "Solar Harvested Energy Dataset." [Online]. Available: http://www.nrel.gov/midc/usep_milford/

[2] I. A. Ieropoulos, J. Greenman, C. Melhuish, and J. Hart, "Comparative study of three types of microbial fuel cell," *Enzyme and microbial technology*, vol. 37, no. 2, pp. 238–245, 2005.

[3] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Transactions on Embedded Computing Systems (TECS)*, vol. 6, no. 4, p. 32, 2007.

[4] J. M. Rabaey, M. J. Ammer, J. L. Da Silva, D. Patel, and S. Roundy, "Picoradio supports ad hoc ultra-low power wireless networking," *Computer*, vol. 33, no. 7, pp. 42–48, 2000.

[5] S. J. Roundy, "Energy scavenging for wireless sensor nodes with a focus on vibration to electricity conversion," Ph.D. dissertation, University of California, Berkeley, 2003.

[6] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, 2011.

[7] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Signal processing magazine*, vol. 19, no. 2, pp. 40–50, 2002.

[8] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive computing*, vol. 4, no. 1, pp. 18–27, 2005.

[9] H. Ayatollahi, C. Tapparello, and W. Heinzelman, "Transmitter-receiver energy efficiency: A trade-off in mimo wireless sensor networks," in *Wireless Communications and Networking Conference (WCNC), 2015 IEEE*. IEEE, 2015, pp. 1476–1481.

[10] ——, "MAC-LEAP: Multi-antenna, cross layer, energy adaptive protocol," in *Transaction on Mobile Computing (TMC)*, Submitted.

[11] C. Tapparello, H. Ayatollahi, and W. Heinzelman, "Energy harvesting framework for network simulator 3 (ns-3)," in *Proceedings of the 2nd International Workshop on Energy Neutral Sensing Systems*. ACM, 2014, pp. 37–42.

[12] H. Ayatollahi, C. Tapparello, and W. Heinzelman, "Reinforcement learning in mimo wireless networks with energy harvesting," in *IEEE International Conference on Communication (ICC)*, 2017.

[13] M. Wijesundara, C. Tapparello, A. Gamage, Y. Gokulan, L. Gittelson, T. Howard, and W. Heinzelman, "Design of a kinetic energy harvester for elephant mounted wireless sensor nodes of jumbonet," in *Global Communications Conference (GLOBECOM), 2016 IEEE*. IEEE, 2016, pp. 1–7.

[14] N. Adam, C. Tapparello, M. Wijesundara, and W. Heinzelman, "Jumbonet elephant tracking using delay-tolerant routing with multiple sinks," in *Submitted*.

[15] H. Ayatollahi, C. Tapparello, M. Wijesundara, and W. Heinzelman, "Energy conservation in animal tracking," in *International Conference on Computing, Networking and Communications (ICNC)*, 2018.

[16] Z. Wang, E. Bulut, and B. K. Szymanski, "Energy efficient collision aware multipath routing for wireless sensor networks," in *Communications, 2009. ICC'09. IEEE International Conference on*. IEEE, 2009, pp. 1–5.

[17] H. Li, Y. Liu, W. Chen, W. Jia, B. Li, and J. Xiong, "Coca: Constructing optimal clustering architecture to maximize sensor network lifetime," *Computer Communications*, vol. 36, no. 3, pp. 256–268, 2013.

[18] D. Kumar, T. C. Aseri, and R. Patel, "Eehc: Energy efficient heterogeneous clustered scheme for wireless sensor networks," *Computer Communications*, vol. 32, no. 4, pp. 662–667, 2009.

[19] A. Liu, J. Ren, X. Li, Z. Chen, and X. S. Shen, "Design principles and improvement of cost function based energy aware routing algorithms for wireless sensor networks," *Computer Networks*, vol. 56, no. 7, pp. 1951–1967, 2012.

[20] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados, "Energy-efficient routing protocols in wireless sensor networks: A survey," *IEEE Communications surveys & tutorials*, vol. 15, no. 2, pp. 551–591, 2013.

[21] Y. Ming Lu and V. WS Wong, "An energy-efficient multipath routing protocol for wireless sensor networks," *International Journal of Communication Systems*, vol. 20, no. 7, pp. 747–766, 2007.

[22] F. Ingelrest, G. Barrenetxea, G. Schaefer, M. Vetterli, O. Couach, and M. Parlange, "Sensorscope: Application-specific sensor network for environmental monitoring," *ACM Transactions on Sensor Networks (TOSN)*, vol. 6, no. 2, p. 17, 2010.

[23] T. Wang, "Water quality monitoring system based on wsn," 2012.

[24] E. Sardini and M. Serpelloni, "Self-powered wireless sensor for air temperature and velocity measurements with energy harvesting capability," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 5, pp. 1838–1844, 2011.

[25] K. Chottirapong, S. Manatrinon, P. Dangsakul, and N. Kwankeow, "Design of energy harvesting thermoelectric generator with wireless sensors in organic fertilizer plant," in *Information and Communication Technology for Embedded Systems (IC-ICTES), 2015 6th International Conference of*. IEEE, 2015, pp. 1–6.

[26] F. Touati, A. Galli, D. Crescini, P. Crescini, and A. B. Mnaouer, “Feasibility of air quality monitoring systems based on environmental energy harvesting,” in *Instrumentation and Measurement Technology Conference (I2MTC), 2015 IEEE International*. IEEE, 2015, pp. 266–271.

[27] S. W. Arms, C. Townsend, D. Churchill, J. Galbreath, and S. Mundell, “Power management for energy harvesting wireless sensors,” in *Proc. SPIE*, vol. 5763, 2005, pp. 267–275.

[28] W. Ye, J. Heidemann, and D. Estrin, “An energy-efficient mac protocol for wireless sensor networks,” in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 3. IEEE, 2002, pp. 1567–1576.

[29] T. Van Dam and K. Langendoen, “An adaptive energy-efficient mac protocol for wireless sensor networks,” in *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM, 2003, pp. 171–180.

[30] J. Polastre, J. Hill, and D. Culler, “Versatile low power media access for wireless sensor networks,” in *Proceedings of the 2nd international conference on Embedded networked sensor systems*. ACM, 2004, pp. 95–107.

[31] M. Buettner, G. V. Yee, E. Anderson, and R. Han, “X-mac: a short preamble mac protocol for duty-cycled wireless sensor networks,” in *Proceedings of the 4th international conference on Embedded networked sensor systems*. ACM, 2006, pp. 307–320.

[32] S. Lin, F. Miao, J. Zhang, G. Zhou, L. Gu, T. He, J. A. Stankovic, S. Son, and G. J. Pappas, “Atpc: Adaptive transmission power control for wireless sensor networks,” *ACM Transactions on Sensor Networks (TOSN)*, vol. 12, no. 1, p. 6, 2016.

[33] L. H. Correia, D. F. Macedo, A. L. dos Santos, A. A. Loureiro, and J. M. S. Nogueira, “Transmission power control techniques for wireless sensor networks,” *Computer Networks*, vol. 51, no. 17, pp. 4765–4779, 2007.

[34] X. Chu and H. Sethu, “Cooperative topology control with adaptation for improved lifetime in wireless ad hoc networks,” in *INFOCOM, 2012 Proceedings IEEE*. IEEE, 2012, pp. 262–270.

[35] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of mimo and cooperative mimo techniques in sensor networks," *IEEE Journal on selected areas in communications*, vol. 22, no. 6, pp. 1089–1098, 2004.

[36] S. K. Jayaweera, "Virtual mimo-based cooperative communication for energy-constrained wireless sensor networks," *IEEE Transactions on wireless communications*, vol. 5, no. 5, pp. 984–989, 2006.

[37] X. Chen, X. Wang, and X. Chen, "Energy-efficient optimization for wireless information and power transfer in large-scale mimo systems employing energy beamforming," *Wireless Communications Letters, IEEE*, vol. 2, no. 6, pp. 667–670, 2013.

[38] H. H. Yang, G. Geraci, and T. Q. Quek, "Energy-efficient design of mimo heterogeneous networks with wireless backhaul," *IEEE Transactions on Wireless Communications*, vol. 15, no. 7, pp. 4914–4927, 2016.

[39] V. K. Sachan, R. Maheshwari, and S. A. Imam, "Energy efficient wireless sensor networks using co-operative mimo: A technical review," *Energy*, vol. 135, no. 11, 2016.

[40] J. Li, X. Jiang, and I.-T. Lu, "Energy balance routing algorithm based on virtual mimo scheme for wireless sensor networks," *Journal of Sensors*, vol. 2014, 2014.

[41] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell labs technical journal*, vol. 1, no. 2, pp. 41–59, 1996.

[42] L. Zheng and D. N. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," *Information Theory, IEEE Transactions on*, vol. 49, no. 5, pp. 1073–1096, 2003.

[43] M. Yuksel and E. Erkip, "Multiple-antenna cooperative wireless systems: A diversity–multiplexing tradeoff perspective," *Information Theory, IEEE Transactions on*, vol. 53, no. 10, pp. 3371–3393, 2007.

[44] T. ElBatt, "On the scheduling, multiplexing and diversity trade-off in mimo ad hoc networks: A unified framework," *Ad Hoc Networks*, vol. 11, no. 2, pp. 639–653, 2013.

[45] 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.

[46] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[47] M. Park, S.-H. Choi, and S. M. Nettles, "Cross-layer mac design for wireless networks using mimo," in *Global Telecommunications Conference, 2005. GLOBECOM'05. IEEE*, vol. 5. IEEE, 2005, pp. 5–pp.

[48] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang, "Medium access control in ad hoc networks with mimo links: optimization considerations and algorithms," *Mobile Computing, IEEE Transactions on*, vol. 3, no. 4, pp. 350–365, 2004.

[49] H. Badis and A. Rachedi, "Performance evaluation of mimo-based mac/phy cross-layer design in multi-hop ad hoc networks," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2015 IEEE 11th International Conference on*. IEEE, 2015, pp. 542–548.

[50] J. Mundarath, P. Ramanathan, and B. D. Van Veen, "Nullhoc: a mac protocol for adaptive antenna array based wireless ad hoc networks in multipath environments," in *Global Telecommunications Conference, 2004. GLOBECOM'04. IEEE*, vol. 5. IEEE, 2004, pp. 2765–2769.

[51] H. Kim, C.-B. Chae, G. De Veciana, and R. W. Heath Jr, "A cross-layer approach to energy efficiency for adaptive mimo systems exploiting spare capacity," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 8, pp. 4264–4275, 2009.

[52] D. Gong, M. Zhao, and Y. Yang, "A multi-channel cooperative mimo mac protocol for wireless sensor networks," in *Mobile Adhoc and Sensor Systems (MASS), 2010 IEEE 7th International Conference on*. IEEE, 2010, pp. 11–20.

[53] M. Z. Siam, M. Krunz, S. Cui, and A. Muqattash, "Energy-efficient protocols for wireless networks with adaptive mimo capabilities," *Wireless networks*, vol. 16, no. 1, pp. 199–212, 2010.

[54] M. Younis, M. Youssef, and K. Arisha, "Energy-aware routing in cluster-based sensor networks," in *Modeling, Analysis and Simulation of Computer and Telecommunications Systems, 2002. MASCOTS 2002. Proceedings. 10th IEEE International Symposium on*. IEEE, 2002, pp. 129–136.

[55] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad hoc networks*, vol. 3, no. 3, pp. 325–349, 2005.

[56] Y. T. Hou, Y. Shi, H. D. Sherali, and S. F. Midkiff, "On energy provisioning and relay node placement for wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 2579–2590, 2005.

[57] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System sciences, 2000. Proceedings of the 33rd annual Hawaii international conference on*. IEEE, 2000, pp. 10–pp.

[58] O. Younis and S. Fahmy, "Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Transactions on mobile computing*, vol. 3, no. 4, pp. 366–379, 2004.

[59] C.-H. Lin and M. Gerla, "A distributed control scheme in multi-hop packet radio networks for voice/data traffic support," in *Communications, 1995. ICC'95 Seattle,'Gateway to Globalization', 1995 IEEE International Conference on*, vol. 2. IEEE, 1995, pp. 1238–1242.

[60] P. Ding, J. Holliday, and A. Celik, "Distributed energy-efficient hierarchical clustering for wireless sensor networks," *Distributed computing in sensor systems*, pp. 466–467, 2005.

[61] S. Bandyopadhyay and E. J. Coyle, "Minimizing communication costs in hierarchically-clustered networks of wireless sensors," *Computer Networks*, vol. 44, no. 1, pp. 1–16, 2004.

[62] V. Mhatre and C. Rosenberg, "Design guidelines for wireless sensor networks: communication, clustering and aggregation," *Ad hoc networks*, vol. 2, no. 1, pp. 45–63, 2004.

[63] A. Manjeshwar and D. P. Agrawal, "Teen: a routing protocol for enhanced efficiency in wireless sensor networks," in *null*. IEEE, 2001, p. 30189a.

[64] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge University Press, 2003.

[65] L. Dai and Q. Zhou, "Energy efficiency of MIMO transmission strategies in wireless sensor networks," in *Proc. of CCCT*, Austin, TX, USA, Aug. 2004.

[66] 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.

[67] M. Sadek, A. Tarighat, and A. H. Sayed, "Active antenna selection in multiuser mimo communications," vol. 55, no. 4, pp. 1498–1510, Apr. 2007.

[68] S. K. Jayaweera, "Energy analysis of MIMO techniques in wireless sensor networks," in *Proc. of CISS*, Princeton, NJ, USA, Mar. 2004.

[69] J. G. Proakis, *Digital Communications*. McGraw-Hill, 2000.

[70] T. M. Duman and A. Ghrayeb, *Coding for MIMO Communication Systems*. Wiley, 2007.

[71] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 16, no. 8, pp. 1451–1458, 1998.

[72] J. Proakis, *Digital Communications*, ser. Electrical engineering series. McGraw-Hill, 2001. [Online]. Available: https://books.google.com/books?id=sbr8QwAACAAJ

[73] M. Atenas, S. Sendra, M. Garcia, and J. Lloret, "Iptv performance in ieee 802.11 n wlans," in *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*. IEEE, 2010, pp. 929–933.

[74] M. Steyaert, B. D. Muer, P. Leroux, M. Borremans, and K. Mertens, “Low-voltage low-power cmos-rf transceiver design,” vol. 50, pp. 281–287, Jan. 2002.

[75] T. H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*. Cambridge University Press, 1998.

[76] S. Willingham, M. Perrott, B. Setterberg, A. Grzegorek, and B. Mc-Farland, “An integrated 2.5GHz $\Sigma\Delta$ frequency synthesizer with 5μs settling and 2 Mb/s closed loop modulation,” in *Proc. of IEEE ISSCC 2000*, San Francisco, CA, USA, Feb. 2000.

[77] M. Steyaert, B. D. Muer, P. Leroux, M. Borremans, and K. Mertens, “Low-voltage low-power CMOS-RF transceiver design,” vol. 50, pp. 281–287, 1997.

[78] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, and K. Huang, “Energy harvesting wireless communications: A review of recent advances,” *IEEE J. on Sel. Areas Commun.*, vol. 33, no. 3, pp. 360–381, Mar. 2015.

[79] A. Sinha, “Optimal power allocation for a renewable energy source,” in *Proc. of IEEE NCC*, Feb. 2012, pp. 1–5.

[80] J. Lei, R. Yates, and L. Greenstein, “A generic model for optimizing single-hop transmission policy of replenishable sensors,” *IEEE Trans. on Wireless Commun.*, vol. 8, no. 2, pp. 547–551, 2009.

[81] J. Yang and S. Ulukus, “Optimal packet scheduling in an energy harvesting communication system,” *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 220–230, 2012.

[82] B. Devillers and D. Gündüz, “A general framework for the optimization of energy harvesting communication systems with battery imperfections,” *Journal of Communications and Networks*, vol. 14, no. 2, pp. 130–139, 2012.

[83] M. Gregori and M. Payaró, “Optimal power allocation for a wireless multi-antenna energy harvesting node with arbitrary input distribution,” in *Proc. of IEEE ICC*, Jun. 2012, pp. 5794–5798.

[84] P. Blasco, D. Gunduz, and M. Dohler, “A learning theoretic approach to energy harvesting communication system optimization,” *IEEE Trans. on Wireless Commun.*, vol. 12, no. 4, pp. 1872–1882, 2013.

[85] A. Ortiz, H. Al-Shatri, X. Li, T. Weber, and A. Klein, “Reinforcement learning for energy harvesting point-to-point communications,” in *Proc. of IEEE ICC*, May 2016, pp. 1–6.

[86] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, “Transmission with energy harvesting nodes in fading wireless channels: Optimal policies,” *IEEE J. Sel. Areas Commun.*, vol. 29, no. 8, pp. 1732–1743, 2011.

[87] R. S. Sutton and A. G. Barto, *Reinforcement learning: An introduction*. MIT press Cambridge, 1998, vol. 1, no. 1.

[88] M. A. Wiering, “Explorations in efficient reinforcement learning,” Ph.D. dissertation, University of Amsterdam, 1999.

[89] “Network Simulator 3 (ns-3).” [Online]. Available: https://www.nsnam.org

[90] V. A. Langman, “A radio-biotelemetry system for monitoring body temperature and activity levels in the zebra finch,” *The Auk*, pp. 375–383, 1973.

[91] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein, “Energy-efficient computing for wildlife tracking: Design tradeoffs and early experiences with zebranet,” *ACM SIGARCH Computer Architecture News*, vol. 30, no. 5, pp. 96–107, 2002.

[92] D. Chabot, “The use of heart rate telemetry in assessing the metabolic cost of disturbances,” in *Transactions of the North American Wildlife and Natural Resources Conference*, vol. 56, 1991, pp. 256–263.

[93] M. W. Hayward and G. J. Hayward, “Activity patterns of reintroduced lion panthera leo and spotted hyaena crocuta crocuta in the addo elephant national park, south africa,” *African journal of ecology*, vol. 45, no. 2, pp. 135–141, 2007.

[94] R. E. Kenward, *A manual for wildlife radio tagging*. Academic Press, 2000.

[95] A. Buerkert and E. Schlecht, "Performance of three gps collars to monitor goats? grazing itineraries on mountain pastures," *computers and electronics in agriculture*, vol. 65, no. 1, pp. 85–92, 2009.

[96] M. Taillade, "Trends in satellite-based animal tracking," *Biotelemetry XII. Litografia Felici, Pisa*, pp. 291–297, 1993.

[97] F. Papi, P. Luschi, E. Crosio, and G. Hughes, "Satellite tracking experiments on the navigational ability and migratory behaviour of the loggerhead turtle caretta caretta," *Marine Biology*, vol. 129, no. 2, pp. 215–220, 1997.

[98] Á. Gutiérrez, N. I. Dopico, C. González, S. Zazo, J. Jiménez-Leube, and I. Raos, "Cattle-powered node experience in a heterogeneous network for localization of herds," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 8, pp. 3176–3184, 2013.

[99] J. Sorber, A. Balasubramanian, M. D. Corner, J. R. Ennen, and C. Qualls, "Tula: Balancing energy for sensing and communication in a perpetual mobile system," *IEEE Transactions on Mobile Computing*, vol. 12, no. 4, pp. 804–816, 2013.

[100] A. Vahdat, D. Becker *et al.*, "Epidemic routing for partially connected ad hoc networks," 2000.

[101] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, "Performance modeling of epidemic routing," *Computer Networks*, vol. 51, no. 10, pp. 2867–2891, 2007.

[102] J.-S. Leu, T.-H. Chiang, M.-C. Yu, and K.-W. Su, "Energy efficient clustering scheme for prolonging the lifetime of wireless sensor network with isolated nodes," *IEEE communications letters*, vol. 19, no. 2, pp. 259–262, 2015.

[103] P. K. Batra and K. Kant, "Leach-mac: a new cluster head selection algorithm for wireless sensor networks," *Wireless Networks*, vol. 22, no. 1, pp. 49–60, 2016.

[104] A. Bouyer, A. Hatamlou, and M. Masdari, "A new approach for decreasing energy in wireless sensor networks with hybrid leach protocol and fuzzy c-means algorithm," *International Journal of Communication Networks and Distributed Systems*, vol. 14, no. 4, pp. 400–412, 2015.

[105] M. Ye, C. Li, G. Chen, and J. Wu, "Eecs: an energy efficient clustering scheme in wireless sensor networks," in *Performance, Computing, and Communications Conference, 2005. IPCCC 2005. 24th IEEE International*. IEEE, 2005, pp. 535–540.

[106] V. Gupta and M. Doja, "H-leach: Modified and efficient leach protocol for hybrid clustering scenario in wireless sensor networks," in *Next-Generation Networks*. Springer, 2018, pp. 399–408.

[107] G. Li and A. Hu, "Virtual mimo-based cooperative beamforming and jamming scheme for the clustered wireless sensor network security," in *Computer and Communications (ICCC), 2016 2nd IEEE International Conference on*. IEEE, 2016, pp. 2246–2250.

[108] Y. Qin, Q. Tang, Y. Liang, X. Yue, and X. Li, "An energy-efficient cooperative mimo scheme for wireless sensor networks based on clustering," in *Computational Science and Engineering (CSE), 2011 IEEE 14th International Conference on*. IEEE, 2011, pp. 471–474.

[109] Y. Yuan, M. Chen, and T. Kwon, "A novel cluster-based cooperative mimo scheme for multi-hop wireless sensor networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2006, no. 1, p. 072493, 2006.

[110] Q. Gao, Y. Zuo, J. Zhang, and X.-H. Peng, "Improving energy efficiency in a wireless sensor network by combining cooperative mimo with data aggregation," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 8, pp. 3956–3965, 2010.

[111] Y. Yuan, Z. He, and M. Chen, "Virtual mimo-based cross-layer design for wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 3, pp. 856–864, 2006.

[112] D. Gong, M. Zhao, and Y. Yang, "A multi-channel cooperative mimo mac protocol for clustered wireless sensor networks," *Journal of Parallel and Distributed Computing*, vol. 74, no. 11, pp. 3098–3114, 2014.