MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

ENERGY EFFICIENCY AND DELAY PERFORMANCE ANALYSIS OF COOPERATIVE MIMO WITH COOPERATIVE AF RELAY IN WIRELESS SENSOR NETWORK

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Energy Efficiency and Delay Performance Analysis of Cooperative Mimo with Cooperative AF Relay in Wireless Sensor Network

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CERTIFICATE OF APPROVAL

The thesis titled "**Energy Efficiency and Delay Performance Analysis of Cooperative MIMO with Cooperative AF Relay in Wireless Sensor Network**" submitted by Fateha Noor, Student No. 142609 of Academic Year 2014-15 has been found as satisfactory and accepted as partial fulfilment for the Degree of MASTER OF SCIENCE in ELECTRICAL AND ELECTRONIC ENGINEERING on 25 October, 2018.

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Declaration

I hereby declare that this dissertation entitled **Energy Efficiency and Delay Performance Analysis of Cooperative MIMO with Cooperative AF Relay in Wireless Sensor Network** was carried out by me for the degree of Master of Science in Electrical and Electronic Engineering, M.Sc.(Engg.) in EEE, under the guidance and supervision of Prof. Dr. Mohammad Rakibul Islam, Islamic University of Technology, Gazipur, Dhaka, Bangladesh.

The findings put forth in this work are based on my research and understanding of the original works and they are not published anywhere in the form of books, monographs or articles. The other books, articles and websites, which I have made use of are acknowledged at the respective place in this thesis.

For the present thesis, which I am submitting to the University, no degree or diploma or distinction has been conferred on me before, either in this or in any other University.

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Abstract

An efficient design of a Wireless Sensor Network (WSN) has recently drawn increasing attention from research community. In a WSN sensors are often powered by non-rechargeable and non-replaceable batteries. Hence, it is essential to apply energy-efficient techniques to improve the lifetime of this network. Cooperative communication is such a proven method that uses spatial diversity to achieve significant gain and eventually increases network lifetime prominently. This thesis work has explored the benefits of two existing cooperative communication protocols- Cooperative Relaying and Cooperative Multiple-Input-Multiple-Output (C-MIMO). Cooperative Relaying is an effective method for WSN which reduces total energy consumption by exploiting the spatial diversity made available through cooperating nodes that relay signals for each other. Cooperative MIMO is another major breakthrough in the field of WSN. C-MIMO is a special type of MIMO technique where multi-antenna structure of MIMO is formed via cooperation in a network of single antenna nodes. Selective approach of C-MIMO is considered in this work. At first a network with cooperative Amplify-and-Forward (AF) relay terminal is designed and its total energy consumption equation is developed. It is shown that this network performs better in energy consumption than the traditional relay networks and the optimum relay location is also determined. Then the dual hop network is advanced into a multi-hop scenario. It is seen that with increasing hop numbers while traditional relay network consumes less energy, cooperative relay with single antenna based source and destination incurs more energy. To solve this problem a combination of these two approaches is proposed, i.e. selective cooperative MIMO network with cooperative AF relay. An experimental framework is developed for the total energy consumption of our proposed network. Both dual-hop and multi-hop network are considered while satisfying an average bit error rate (BER) requirement at the destination over Rayleigh fading channels. Energy and delay characteristics of proposed network model are observed via simulations. Simulation results show that our proposed model outperforms selective C-MIMO by 17%, traditional C-MIMO by 24% and SISO model by 48% in total energy consumption per bit after certain distance (~400m). The impacts of transmission distance between source and destination, relay number and relay position on total energy consumption per bit are evaluated and discussed. Delay difference (DD) is also calculated between SISO and proposed model and positive DD is observed after 68m which indicates proposed model's delay efficiency over SISO model. Finally it is observed that for larger scale WSNs (>600m) selective C-MIMO with equispaced multi-hop (hop=4) cooperative AF relay performs more efficiently than three-hop (~9.4%) or dual-hop (~35%) C-MIMO networks.

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I am also thankful to the people whom I did not mention, but have a valuable contribution to this research

To our beloved Prophet Muhammad (peace be upon him)

“Be Content with that which Allah has given you and you will be the richest of people"

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Chapter 1

Introduction

In this chapter, first an overview of my thesis is presented that includes the significance of the study and possible advancement in detail. Next, some basic information of C-MIMO is demonstrated like its uses in WSN and how it affects transmission energy and delay issues. Besides, cooperative relay is also discussed and the discussion is advanced by combining it with C-MIMO. After that, my thesis objectives and contributions are presented. The chapter ends with a short description of the organization of this thesis.

1.1 Background

Wireless sensor network has become one of the most emerging technologies in the past few years. Due to advancement in Micro-Electro-Mechanical Systems (MEMS) technology, low power and low cost WSNs can be deployed in many real life applications, including environmental monitoring, home automation, traffic control, precision agriculture and health care [1–3]. The tiny wireless sensor nodes are able to sense, process and communicate with each other [3], [4]. Since the battery capacity in each node is limited and the goal is to maximise the lifetime of the network, there are strict energy consumption constraints in WSNs. MIMO techniques can be used in WSN to improve signal to noise ratio (SNR) at the receiver and to mitigate co-channel interference (CCI) along with beam forming techniques [22]. However, MIMO systems also have a higher circuit complexity, which consumes energy. In long distance transmission, circuit energy consumption is typically much lower than transmission energy consumption. In short distance transmission, however, circuit energy consumption can be comparable with transmission energy consumption. Thus, to evaluate the performance of MIMO techniques in energy limited WSNs, one must take into account of both circuit and transmission energy consumption. However, due to limited physical size, limited energy availability, and the need to maintain a minimum distance among the antennas (to avoid fading), true/ co-located MIMO structure is not feasible to realize the advantages of this method [26]. Thus, the concept of cooperative (virtual/distributive) MIMO was explored for energy and physically constrained WSN nodes in [43] using Alamouti coding [45]. In cooperative MIMO, multiple single-antenna nodes can be grouped as one entity, and each node shares its antenna with others in the group to function cooperatively as one MIMO system. It is a proven energy efficient technique by several researchers. Another energy efficient technique for WSN is cooperative relaying. Cooperative relay exploits the spatial diversity in multiuser wireless networks to improve the performance in terms of energy efficiency and signal to noise ratio (SNR) [25], [15]. C-MIMO and cooperative relaying can be combined for better performance in energy efficiency and other performance metrics.

1.2 Wireless Sensor Network

WSN is a wireless network where small, low cost electro-mechanical devices communicate wirelessly and have the capabilities of sensing, processing, and storing data [3], [4]. These tiny devices are called sensors. By sensing it is meant that sensors collect data from the environment they are being placed into. A simple wireless sensor network is shown in Fig. 1.1. In a particular environment, there are numerous sensor nodes that can sense and process data. A robust network is also required to comprehensively communicate elements to provide sensor networks and continue functioning. The size of sensors is typically small but the functions inside the sensor are complex.

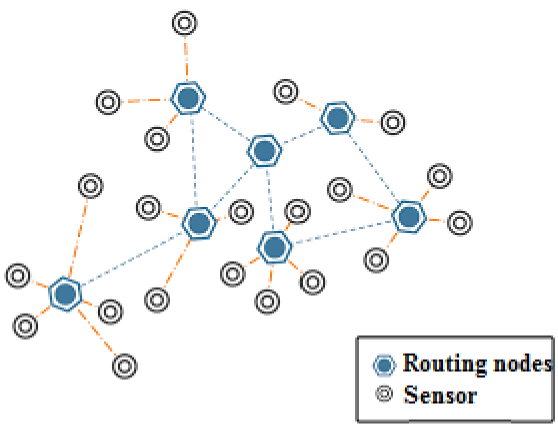


Fig 1.1: Wireless sensor network.

Recent hardware advancements allow more signal processing functionality to be integrated into a single sensor chip. RF transceiver, A/D and D/A converters, base band processors, and other application interfaces are integrated into a single device to be used as a smart wireless node. Such wireless nodes typically operate with small batteries for which replacement, when possible, is very difficult and expensive. Thus, in many scenarios, the wireless nodes must operate without battery replacement for many years. These batteries have limited capacity to store charge and the goal is to maximize the network lifetime by considering all the strict energy consumption constraints in WSNs.

With respect to WSNs, wireless data communication efficacy of sensors has two major issues. The first challenge is to maintain long distance communications between the sensor nodes and the remote base station without excessive energy use. The second is confronting delays during the data collection process. Those two problems need to be simultaneously resolved since they adversely affect one another and constitute conflicting objectives.

Several studies have been proposed in the literature aiming to propose solutions to these problems. Some of these are cluster head node based algorithm, data aggregation based algorithm, distributed antenna based algorithm etc. Among these cluster head method is commonly used. This particular algorithm aims at minimizing the delays in the data collection by reducing the number of sensor nodes and establishing cluster head. This reduction would also minimize the distance between cluster head nodes and the base station. In the distributed antenna based algorithm a wireless sensor network typically consists of a large number of sensor nodes distributed over a certain region. Monitoring node (MN) monitors its surrounding area, gathers application-specific information, and transmits the collected data to a data gathering node (DGN) or a gateway. The transmitted data is then presented to the system by the gateway connection. Energy issues are more critical in the case of MNs rather than in the case of DGNs since MNs are remotely deployed and it is not easy to frequently change the energy sources. Therefore, the MNs have been the principal design issue for energy limited wireless sensor network design. One prospective solution is the use of MIMO [43], [44] for energy efficient design with a targeted probability of bit error at the receiver.

1.3 Cooperative Amplify and forward (AF) Relay

Relaying is considered one of the promising techniques of reducing energy consumption [19]. The main idea in relaying is that a source communicates with its destination through single or multiple intermediate terminals, which are known as relays. As an application, the multi-hop configuration can be used for downlink cellular transmission in which a base station (BS), which acts as a source, communicates with a mobile station, which acts as a destination, through relay stations (RSs). These RSs involve different protocol layers in forwarding the data and are, hence, categorized as layers 1 (L1), 2 (L2), and 3 (L3) RSs. Among these types of RSs, the L1 RS is considered the simplest as it employs an amplify-and-forward (AF) relaying protocol at the physical layer. In the AF protocol, a relay simply amplifies the source signal and forwards it to the next terminal without decoding. This is in contrast with L2 and L3 RSs, where decoding and encoding are performed at the relays [27]. Considering that the AF protocol is relatively less complex and requires minimum hardware, L1 RSs are expected to be included in future cellular systems, e.g., in Long-Term Evolution Advanced (LTE-A) [27]. If multiple AF relay nodes works together in a cooperative mode, it’s called cooperative AF relay. Figure 1.2 shows a simplified structure of cooperative AF relay.

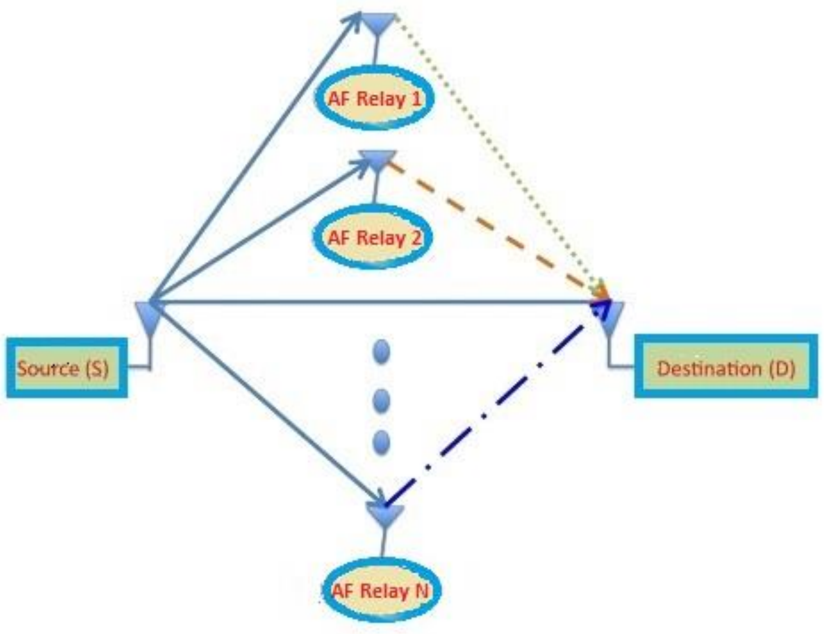


Fig 1.2: Cooperative AF relay system

Cooperative relay exploits the spatial diversity in multiuser wireless networks to improve the performance in terms of energy efficiency and signal to noise ratio (SNR) [17]. In wireless sensor networks (WSNs), a single or multiple motes can serve as relays between the source and destination, thus forming additional transmission paths or spatial diversity. In such a cooperative relay model, a major concern is the optimal power allocation scheme (i.e., power allocation to the source and relay nodes) to achieve minimum energy cost at a desired quality of service (QoS) objective. However, it is an effective approach to save power when the transmit power dominates the power cost. Second, the cooperative relay scheme further adopts signal selection compared to the relay only scheme, thus requires less transmit power at the relay node to achieve the same PER objective [24].

1.4 Cooperative MIMO

Multi-antenna systems have been studied intensively in recent years due to their potential to dramatically increase the channel capacity in fading channels [20]. It has been shown that multi-input–multi-output (MIMO) systems can support higher data rates under the same transmit power budget and bit-error-rate performance requirements as a single-input single-output (SISO) system. An alternative view is that for the same throughput requirement, MIMO systems require less transmission energy than SISO systems. MIMO techniques are capable of providing high system performance without additional transmission power and bandwidth. However, due to the small form factor and limited energy of sensor nodes, it is often not realistic to equip each sensor with multiple antennas to implement MIMO. Instead, a cluster of single-antenna sensor nodes can cooperate to form a virtual antenna array (VAA) [42] to achieve virtual MIMO or cooperative MIMO (C-MIMO) communication. The basic idea of C-MIMO was first proposed by S. Cui in [43]. Later this idea has been improved in [44] by Jayaweera considering channel estimation (training overhead) in the DGN side and is further modified in [48] by Y. Gai and in [58] by M. Rakibul. Fig 1.3 shows a basis C-MIMO structure. Cooperative MIMO systems are distributed in nature because multiple nodes are placed at different physical locations to cooperate with each other. With proper timing and frequency synchronization between constituent nodes of the VAA, cooperative MIMO can realize the advantages of true MIMO techniques for WSNs. That is, performance of cooperative MIMO channels is equal to that of real MIMO channels but for a small SNR loss [49].

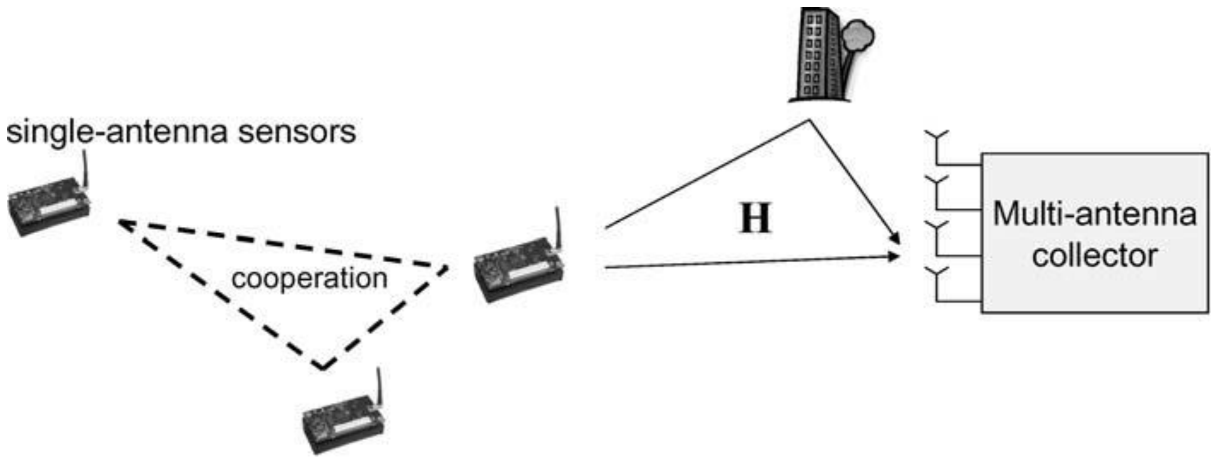


Fig 1.3: The cooperative MIMO technique

The cooperative MIMO technique yields higher capacities and lower bit-error rates (BER) for fixed individual sensor powers. This capability can be exploited in a combination of ways. First, higher data rates (spectral efficiency) can be obtained using the sensor array, without increasing BER. Second, if the data rate and BER are to remain fixed, we can lower the individual sensor powers by adding more sensors. Thus, various combinations of increased power efficiency and higher data rates can be traded off using the cooperative MIMO approach. Cooperative MIMO can provide gains in terms of savings in the required transmit power in order to achieve a certain performance requirement because of the spatial diversity it adds to the system. However, if one takes into account the extra processing and receiving power consumption at the relay and destination nodes required for cooperation, then there is obviously a tradeoff between the gains in the transmit power and the losses due to the receive and processing powers when applying cooperation. Hence, there is a tradeoff between the gains promised by cooperation, and this extra overhead in terms of the energy efficiency of the system should be taken into consideration in the design of the network.

1.5 Combination of C-MIMO and Cooperative Relay

Many efforts have been made to enable cooperative relay transmission to cope with channel degradation, with the assumption that Tx and Rx have single antenna [19], [27], [24]. One question to raise is: is it beneficial to adopt cooperative relay to facilitate transmission in a C-MIMO based wireless sensor network?

The introduction of cooperative relay transmission into a network where terminals are equipped with multiple antennas/sensors could bring in benefits far beyond that of simply combining the two techniques together. It would not only allow joint exploitation of multiplexing gain of C-MIMO and cooperative diversity gain of relay transmission, but would also help mitigate many issues presenting in conventional relay transmissions. First, with the support of relay nodes, transmissions on C-MIMO links with harsh conditions or temporary breakages can possibly be bridged through relay links over source-relay-destination paths. Without being impacted by a poor link for a continuous time period, traffic can be scheduled more efficiently to avoid a significant transmission delay and extra consumption of precious network resources. Second, with a careful relay selection, the channel quality of a relay link would be generally better thus allow for a higher rate, which reduces the cost of using relay transmission. Third, taking advantage of multi-packet transmission/reception capability enabled by C-MIMO technique, a relay node which has multiple antennas can overhear the transmission from a source while receiving its own packets, which avoids the need for the source to forward the packet explicitly to the relay node as in conventional cooperative transmission. Meanwhile, a relay node can simultaneously forward packet for others while transmitting its own packets.

1.6 Applications of C-MIMO and Cooperative Relay

Numerous application of C-MIMO have been reported, including in :

- WSNs - Reduce total energy consumption [43], [53].
- MANETs - Improve throughput and reduce delay [54].
- WLANs - Boost capacity [55].
- MIMO CRNs (cognitive radio network) s - improve network throughput and reduce the delay [56].
- Cellular Systems – significantly improve capacity and coverage [28].

Diverse application of cooperative relays are also seen in below fields :

- WSNs – Achieve promising gains in throughput, energy efficiency and delivery ratio of packet retransmissions [33-35].
- MANETs – Improve connectivity and energy efficiency, reduce collision resolution and routing problems [36].

- WLANs- Improve network throughput, reduce delay [37-38].
- Vehicular Communications- Lower packet error rate [39].
- CRNs - Increase packet delivery rate, reduce delay [40], [41].

1.7 Objectives

From above discussion various usage of C-MIMO and cooperative relays are seen. Both techniques perform significant improvement, specially in energy efficiency, delay efficiency and network throughput. Their working principles are also same in WSNs except C-MIMO is based on cooperative communication among simple sensor nodes where cooperative relay consists of multiple relay nodes. Relay node does additional task of either amplification, compression or decoding which simple sensor node does not. This issue results variation in total energy consumption and throughput gain. My research aimed at combining cooperative MIMO with cooperative relay in WSN. This merging approach should satisfy the following criteria:

- To introduce an energy efficient and robust technique that will improve a wireless sensor network's performance compared to traditional C-MIMO.
- It will address an energy efficient method which can be used in various environments such as cellular systems, extreme remote areas etc.
- The proposed method should also be delay efficient than traditional C-MIMO so that it can lead to smaller end-to-end delay.
- To propose a network model firstly for single relay and extend this scenario to multiple relays network.
- The comparative performance should be evaluated against exiting C-MIMO and SISO method using proper benchmark dataset.

1.8 Contribution

In this thesis work we have proposed a combined network model comprised of C-MIMO and cooperative relay using MATLAB. The main contributions of this thesis are summarised as follows :

- The introduction of an analytical framework for the total energy consumption of a cooperative amplify-and-forward (AF) dual hop C-MIMO network employing *M*-ary quadrature amplitude modulation (MQAM) while satisfying an average bit error rate (BER) requirement at the destination over Rayleigh fading channels.
- Based on this framework, we then establish the conditions under which a dual-hop relay network is always more energy efficient when compared with a reference single-hop C-MIMO and SISO network.
- Moreover, dual hop network is extended to multi hop scenario and the impact of the relay's location is analysed for both cases.
- Since a realistic power consumption model is considered, it is shown that there exists an optimal number of relays for the linear multi-hop relay network that achieves maximum energy efficiency (EE) under specified BER.

1.9 Organization

The rest of the thesis will be organized as follows: in Chapter 2, the literature review of existing methods and their performance as well as limitations are discussed for the wireless sensor network. In Chapter 3, our proposed methodology is presented in detail. There, we discuss about the overall idea of our proposed method and step by step implementation process are discussed. In Chapter 4, experimental set up, experimental results and performance analysis of my proposed idea with various promising methods are discussed. Finally, in Chapter 5, my thesis contributions are concluded and the future scopes are shown for further development of the proposed method.

Chapter 2

Literature Review

A substantial amount of methods have been developed to increase the network performance of wireless sensor network. A detailed review of the existing methods can be found at this section. In this chapter we have discussed five major methods for WSN from energy and delay perspectives. Those are 1) Simple relaying, 2) Cooperative relaying, 3) Cooperative MIMO, 4) Selective cooperative MIMO and 5) C-MIMO with cooperative relay approach. Besides, some survey papers are also discussed here.

2.1 Relaying in WSN

Over the past two decades Wireless Sensor Networks (WSNs) and their applications have been the topic of many studies. WSN is a network responsible for collecting, processing and distributing wireless data to the intended database storage centre with the help of tiny sensor nodes. In [1] and [2] the sensing tasks and the potential sensor networks applications are explored by Akyildiz and Yick. They explained the factors that influence the design of sensor network such as fault tolerance, scalability, production costs, operating environment, sensor network topology, hardware constraints, transmission media and power consumption in their papers. If we consider the study of sensor node functioning [3], we realize that sensor nodes are extremely prone to dying out due to their limited battery capacity. Besides, these sensors are usually installed at remote sites, so despite the recent advances in the WSN technology, its applications still face significant challenges [4]. Out of these, energy conservation and consumption and confronting delays in data transfer process rise as two major concerns. To ensure and incorporate energy efficiency in WSN, the usage of relay node is unavoidable.

The idea of deploying relay nodes in sensor network was first introduced by Cheng et al. in 2001 [5], which was based on flat architectures. They have proposed to use relay nodes for maintaining connectivity, by using minimum-per-node transmission power. For the network model, the authors have considered only the biomedical class of sensor networks, where sensor locations are usually pre-determined & fixed. In [6], Dasgupta et al. have focused on maximizing the lifetime of sensor networks by studying topology-aware nodes' placement problem and the nodes' role-assignment problem in sensor networks. But instead of considering that the nodes' positions are fixed (as in [5]), they have allowed node mobility and provided an integer solution to the optimization problem. In [7] Falck et al. have focused on balanced data gathering against sufficient coverage of the monitored area in a sensor networks. The have considered a multi-hop network model consisting of sensor nodes and relay nodes and a base station. The relay nodes are less-energy constrained compared to the sensor nodes. Data are to be gathered at the base station and the location of sensor nodes and the base station are pre-determined. The objective was to achieve balanced data gathering against sufficient coverage of the monitored area. In [8] Coleri and Varaiya have focused on achieving a desired network lifetime using minimum total energy in a sensor network that contains relay nodes. In their model, the sensor nodes may also take part in routing. They have attempted to achieve the goal of maximizing the network lifetime by determining the optimal locations along with the optimal energy provisioning of the relay nodes within the networks. For the placement problem, they have proposed an NLP formulation and an approximation algorithm.

The deployment of relay nodes in hierarchical architecture was first proposed in 2003, in two different publications, [9] and [10]. In [9], Gupta and Younis focused on the issue of load-balancing and proposed an algorithm for load-balanced-clustering of hierarchical sensor networks .They have called the relay nodes gateway nodes. In [10] authors have called the relay nodes as aggregation nodes (AN), and have attempted to maximize the topological network lifetime of sensor networks. Their approach has focused on arranging the base stations (BS) and optimizing inter-AN relaying. In [11], Tang, Hao and Sen focused on the issue of scalability as well as the extended lifetime of sensor networks using relay nodes and have proposed formulation for solving the problem. In [12], Patel et al. addressed the placement problem of sensor nodes, relay nodes and base station in sensor networks and formulated a solution to achieve minimal number of sensor nodes, minimal total cost and energy consumption as well as maximal energy utilization and lifetime of the network. In [13], Hou et al. focused on prolonging the lifetime of sensor networks with energy provisioning and deploying relay nodes within the networks. And in [14], Liu, Wan, and Jia have addressed the issue of fault tolerance in sensor networks, using a minimal number of relay nodes. Their approach was based on different assumptions regarding the functionality of sensor nodes and the requirement of connectivity among the nodes. A survey on "Relays in WSN" is briefly discussed in [15]. The last research paper studied in this category is [16]. In this paper a WSN connectivity is proposed by deploying powerful relay node in sensor network, and it was shown that how the relay node placement (RNP) affects the performance of the network seriously.

All the papers above used relay node just as a forwarding terminal which receives data packet and forwards it to the receiver or another relay. It does not modify the received signal or act jointly with the other relay nodes.

2.2 Cooperative relay

Energy becomes the scarcest resource of WSN nodes, which determines the lifetime of the network. As such, the power minimization problem (i.e., saving as much energy as possible) has become a hot research topic for WSNs. The main idea of cooperative relay communication is originated from the concept of three terminal (S, R, D) communications which firstly proposed by the van der Meulen (in 1971) [17]. He studied the upper and lower bounds of the channel capacity, and proved relay technology can improve spectral efficiency and link performance. Later in 1979, Cover and EI Gammal obtained ground-breaking achievements which were based on that, they derived the upper and lower bounds of this channel capacity under several "classical" and general cases [16]. It established foundation for the theory of cooperative communication. MIMO systems and space-time coding technologies have been emerged until the end of the 1990s.

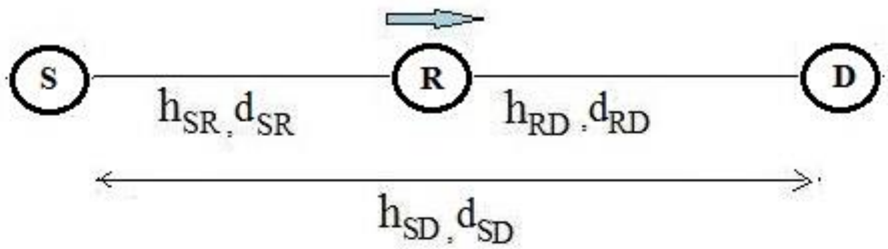
A novel technique has been proposed by Laneman and Wornell in [18] to enhance the throughput and energy efficiency of wireless communication named as "Cooperative Relay" scheme. In this paper the terminals acting as relays do not have data to transmit. They only forward copied versions of data to destination to achieve the spatial diversity, thus increasing performance of the original transmission (i.e. source-destination transmission). The same authors published another paper [19] regarding the same topic. This time they develop and analyse repetition-based and distributed space-time code-based (DSTC-based) [12] cooperative relay techniques. Their technique exploits space diversity available through cooperating terminals' relaying signals for one another and the performance characterizations reveal that large power or energy savings result from the use of these protocols. With space-time encoding at the relays discussed in [20], a spatial diversity gain that is proportional to the number of relays can be achieved. Hence, for a given QoS requirement (e.g., a target received SNR or bit error rate), the total transmit power decreases with the number of relays, thus achieving energy efficiency.

Many cooperative strategies have been proposed in the literature based on different relaying techniques, such as the amplify-and-forward [19],[21]; decode-and-forward(DF) [5], [22], [19]; selective relaying (SR) [19]; compress-and-forward(CF) [21]; coded cooperation(CC) [23]etc. Among these relays, AF-relays and DF-relays are the most popular one due to their simplicity and intuitive designs. Therefore, AF will be considered in this thesis. AF protocol is referred as non-regenerative, which has firstly proposed by the J.N. Laneman [19].

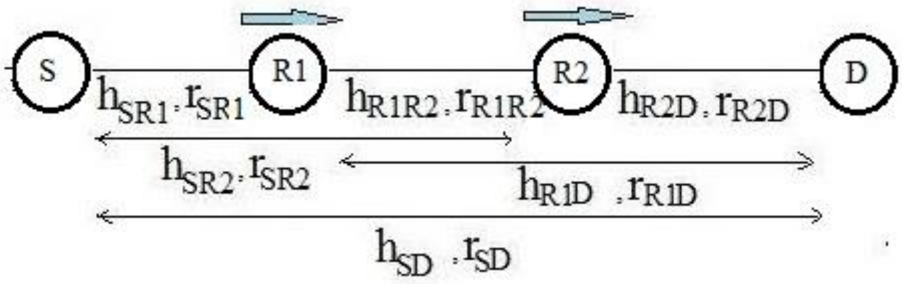
Liqui Shi and Abraham showed in [24] that cooperative relay scheme provides up to 200% and 90% power savings over the direct transmission and relay only schemes, respectively, with the most gain attained at low PER objectives. There is also an optimal number of relay nodes exists for a given S-D distance and PER objective in a two-hop multiple relays scenario. This optimal number of relay nodes increases as the distance between the source and destination nodes increases. Along with the reduction in power consumption, we observe from [25] that cooperative relay also increases SNR performance in WSN. Many issues in cooperative communications still need to be addressed. Simple network models are considered and strict synchronization among distributed users are often assumed, which are difficult to achieve in practice. A major challenge lies in the design of asynchronous cooperation strategies, e.g. [26]. Therefore, relays should be adopted only if the source-relay channel is sufficiently reliable. This observation leads to the selective relaying (SR) [19] cooperation scheme where relays are selected to retransmit the source message only if the quality of the transmission over the interuser channel meets a certain criterion.

We advance our study on AF cooperative relay. For less complexity and less hardware requirement AF cooperative relays are widely used in cellular systems [27], [29]. In [27] relays in cellular system is broadly discussed. For downlink cellular transmission there is a base station (BS), which acts as a source, communicates with a mobile station, which acts as a destination, through relay stations (RSs). In the AF protocol, a relay simply amplifies the source signal and forwards it to the next terminal without decoding. This is in contrast with L2 and L3 RSs, where decoding and encoding are performed at the relays [27]. Considering that the AF protocol is relatively less complex and requires minimum hardware, L1 RSs are expected to be included in future cellular systems, e.g., in Long-Term Evolution Advanced (LTE-A) [27]. According to [24] & [29] AF cooperative relay is an effective approach to save power when the transmit power dominates the power cost.

In [30], Sunil Pattepu and S. Mukherjee compared different cooperative relay systems. They took into account three cooperative communication scheme: a) one assisted relay for both AF and DF relay, b) cooperative communication with two assisted relays for both DF, AF relay, c) cooperative communication with hybrid relay scheme such as relay1 (R1) with Decode-and-Forward scheme, relay2 (R2) with Amplify-and-Forward scheme and relay1 (R1) with Amplify- and-Forward scheme, relay2 (R2) with Decode-and-Forward scheme. Their proposed relay assisted networks are shown in the next page.



(a)



(b)

Fig. 2.2: Cooperative communication with (a) one assisted relay and (b) two assisted relays

Their comparison shows that for one assisted relay scheme AF relay is better. For two assisted relay scheme DF relay is better than hybrid relay for shorter distances and AF relays are not energy efficient than other relay schemes. They also compared delay and outage probability behaviour of these schemes.

Chin-Liang Wang in [31] presented a cooperative multi-hop transmission scheme for two-way amplify-and-forward (AF) relay networks. Based on a symbol error probability (SEP) analysis and using geographic information, they derived the maximum one-hop distance for a networking node under a given SEP and developed a next-hopping-node selection scheme. With these results, they proposed a routing protocol based on a greedy algorithm to realize the transmission scheme, where a routing path consisting of a number of independent two-way AF relaying procedures is built to connect the two sources. As compared to the previous related works, their proposed approach removes the utilization limitation and improves the routing efficiency. Computer simulation results also showed that it provides a higher probability of successfully building a routing path with close effective throughput for most cases of interest.

In 2018 Fabien H´eliot and Rahim Tafazolli published a paper [32] regarding cooperative MIMO-AF system. Their proposed system model is shown in Fig. 2.2(c).

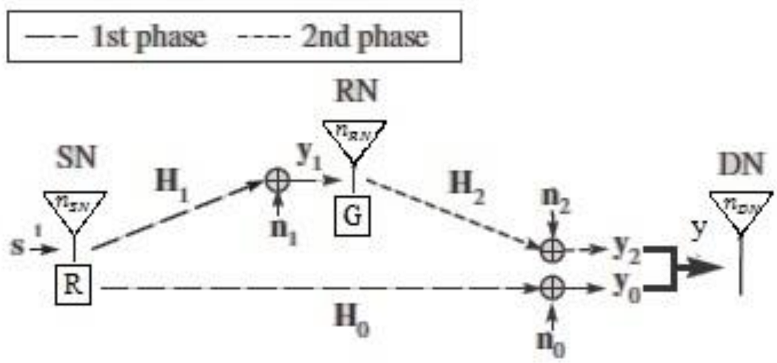


Fig. 2.2(c): Cooperative MIMO-AF system model

In this paper, authors proposed a breakthrough approach for maximizing the energy efficiency (EE) of cooperative MIMO-AF systems, where they derived both EE-optimal sensor node (SN) and relay node (RN) precoding matrices. In this work derivation of SN and RN precoding matrices to maximize the EE is an entirely new proposition. In addition, they also formally proved the optimality of their SN and RN precoders by relying on pseudo-convexity arguments and provide a closed form expression for the EE-optimal SN precoding matrix. Authors assumed, as in most existing works on MIMO-AF precoding, that full channel state information (CSI), i.e. transmit and receive CSI, is available at both the SN and

RN. They proved here the pseudo-convexity/ convexity of the main optimization problem, provide an EE-optimal relay precoding matrix (instead of suboptimal), and consider power constraints for designing the source and relay precoders.

Various applications of cooperative relay in practical fields are also studied. This method is vastly used in WSNs [33-35], MANETs [36], WLANs [37], [38], vehicular communication [39], CRNs [40], [41] and many more.

2.3 C-MIMO in WSN

In our thesis work we consider cooperative communication in wireless sensor network and study accordingly. MIMO stands for multiple-input-multiple-output which is primarily a multi-antenna system. It has been shown in [20] that multi-input–multi-output (MIMO) systems can support higher data rates under the same transmit power budget and bit-error-rate performance requirements as a single-input single-output (SISO) system. However, application of multi-antenna techniques to sensor networks has been a very interesting research topic among the researchers over the decades. When this multi-antenna system is modified for cooperative communication it is called Cooperative MIMO. Cooperative MIMO (C-MIMO), sometimes referred to as distributed, virtual, or networked MIMO, is one type of cooperative communications, whereby several nodes, each equipped with one or more antennas, cooperate to emulate a multi-antenna node, also known as a virtual antenna array (VAA). During the late 1990s, Dohler and Said introduced VAAs [42], a MIMO-based cooperative scheme. In their model, a source node first broadcasts its data to a group of spatially adjacent nodes. These nodes then cooperate to form a VAA that forwards the signal to the next VAA. The process continues until the last VAA sends the signal to a sink. Each element in the VAA is referred to as a cooperating node/sensor node.

The basic idea of energy efficient C-MIMO was first proposed by S. Cui, A. Goldsmith in [43]. Later this idea has been improved in [44] by Jayaweera considering channel estimation (training overhead) in the DGN side and is further modified in [45] by Y. Gai and in [26] by M. Rakibul. In [43] the authors highlighted the energy efficiency of MIMO used in WSNs by cooperation among sensors using Alamouti coding [25]. They advance the joint energy-minimizing techniques proposed for SISO systems in [46] & [47]

for cooperative MIMO system. They revealed that the reduction in the transmission energy, obtained through diversity gain, comes at the price of higher circuit energy consumption. The higher the gain, the larger the number of cooperating sensor nodes, and thus the higher the circuit energy. For long transmission distances, transmission energy dominates the total energy consumption. In this case, a C-MIMO scheme should increase the size of sensor clusters (VAAs) to better exploit DIV. On the other hand, for short distances, circuit energy is the major contributor to the total energy consumption, so one should employ smaller number of sensors or even operate in a SISO mode. This finding raises two key issues for protocol design: when should sensor nodes cooperate, and how many of them should be used to form a VAA. To refine the results in [43] another author, Jayaweera, takes into account the training overhead required in any MIMO-based system in [44]. He develops a semi analytical approach that takes into account extra training energy overhead for a MIMO-based system in order to obtain a fair comparison with a SISO-based sensor network. His analysis and numerical results suggest that with judicious choice of parameters at the system design level, proposed virtual MIMO-based communication can provide significant energy and delay efficiencies in wireless sensor networks.

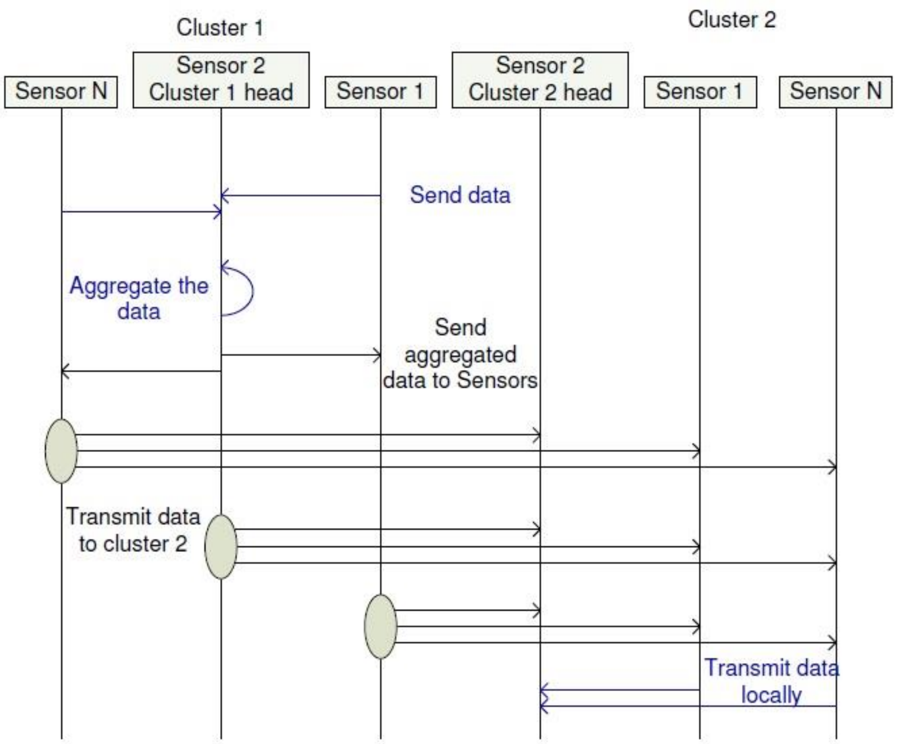


Fig 2.3: Data aggregation in cooperative communication.

The very first paper which considered data aggregation technique to minimize energy consumption in C-MIMO is [48] by Y. Gai and L. Zhang. According to them, data aggregation is the tool by which the correlated data size can be significantly reduced depending on the correlation factor. Their proposed method is briefly explained below with Figure 2.3. Here the sensors at cluster 1 send the information data to the cluster head of cluster 2. At the first step, the sensors at cluster 1 send the data to their cluster head. The cluster head then aggregates the data in the second step. After the aggregation, the cluster head send the aggregated data back to all the sensors in that cluster. This is the step three in cooperative communication. At this stage, all the sensors at cluster 1 have the same information data. At the fourth step, the sensors transmit the aggregated data to the cluster 3. After receiving the data at the receiving cluster, sensors at cluster 2 transmit the received data to their cluster head locally and complete the cooperative communication. They have developed the total energy consumption models for both SISO and C-MIMO communication techniques with data aggregation and analysed the energy efficiency. Their simulation results show that the C-MIMO system outperforms the SISO system under some critical distance.

Another study in [49] shows that with proper timing and frequency synchronization between constituent nodes of the VAA, cooperative MIMO can realize the advantages of true MIMO techniques for WSNs. The performance of cooperative MIMO channels is almost equal to that of real MIMO channels but for a small SNR loss. Vertical-Bell Labs Layered Space-Time (VBLAST)-virtual MIMO is yet another classical CMIMO described in [50], which provides multiplexing gain by allowing a virtual antenna array to transmit N independent data streams. The core technique of this scheme is to point a data gathering node that can cope with more computational complexity than other normal nodes at the receiver.

Ali Dziri and Amira Ben Ammar in [51] proposed a novel energy efficient clustering and power management schemes for virtual MIMO operation in a multi-hops WSN. They have investigated a new joint residual energy and SNR thresholds based cooperative MIMO transmission. The proposed strategy is also based on the election of two cluster heads (CH) Master CH and Slave CH per cluster and the intermediate node relaying in an intra-cluster communication. These features led cooperative MIMO communication in both intra-cluster or inter-cluster transmissions. This protocol is dedicated to large scale WSNs. Simulation results in terms of network lifetime and average energy consumption have shown clearly that the proposed protocol outperforms the non-cooperative one.

In [52] Lamia Grira and Ridha Bouallegue investigated the energy efficiency of cooperative MISO (multi-input single-output) and MIMO in WSNs. They have evaluated the energy efficiency of cooperative MIMO system and compared it to a traditional SISO and a MISO schemes. Despite the extra energy consumption at emission and reception sides, cooperative MIMO proves its energy efficiency in wireless sensor networks, especially in large range distance. Hence depending on the distance, the appropriate $N_t - N_r$ subset of antennas can be selected. Simulation results proved that the cooperative MIMO approach seems better than the traditional SISO technique and Cooperative MISO but it causes a delay in transmission. It is also interesting to compare cooperative MIMO with cooperative relay techniques. They also compared this scheme according to different parameters like constellation size, pathloss component.

Various applications of C-MIMO in contemporary wireless networks are also studied to get the real life picture. In above discussion we have seen C-MIMO is vastly used in WSNs [43], [53]. Besides, it is also used in MANETs [54], WLANs [55], MIMO Cognitive Radio networks [56], cellular systems [28] for its better energy efficiency, link capacity, better delay performances and after all for better network performance.

2.4 Selective C-MIMO in WSN

A wireless sensor network typically consists of a large number of sensor nodes distributed over a certain region. If all the sensors in a terminal communicate with another group of sensors in WSN then it will highly increase interference among signals and eventually transmit power will rise. To avoid the random interference among different relay nodes, we may allocate all power to one/selected relays as proposed in [57] and [35], while all the other relays remain silent. It was shown in [57] that this selective relaying strategy is optimal in minimizing the outage probability for the DF space-time-encoded scheme under the total power constraint. In [35] selective approach is applied in industrial WSN and it shows better performance in network capacity.

In 2008 Md. Rakibul Islam and J. Kim proposed an energy efficient cooperative technique for the IEEE 1451 based wireless sensor networks [58]. Selected numbers of wireless transducer interface modules (WTIMs) are used to form a multiple input single output (MISO) structure wirelessly connected with a network capable application processor

(NCAP). Energy efficiency and delay of the proposed architecture are derived for different combination of cluster size and selected number of WTIMs. Optimized constellation parameters are used for evaluating derived parameters. The results show that the selected MISO structure outperforms the unselected MISO structure and it shows energy efficient performance than SISO structure after a certain distance.

At the same year these authors published another paper [53] regarding selective C-MIMO approach. According to [53] this selective C-MIMO is described briefly here. In their experimental analysis, sensors in transmitting side forward data bits to a DGN of receiving/relay side in a centralized wireless sensor network in Fig. 2.4(a).

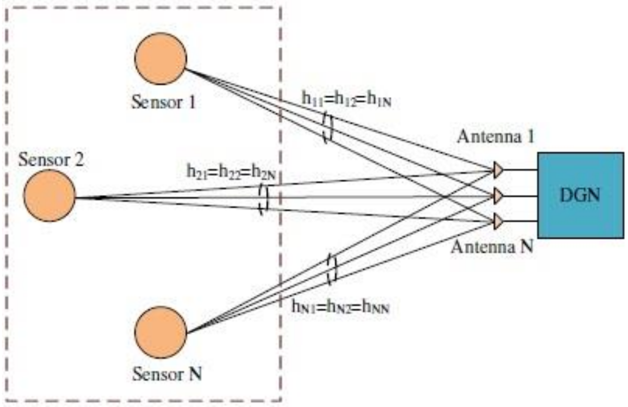


Fig. 2.4(a): System model of selective C-MIMO

For this system, among N_t number of transmitted antennas N_a number of sensors are active and the received discrete-time signal is attenuated by a channel matrix $\boldsymbol{H}$. This channel matrix $\boldsymbol{H}$ is explained before at the system model section as a zero-mean circulant symmetric complex Gaussian random variable with unit variance. The fading is assumed constant during the transmission of each frame. Channel condition is a critical issue in transmitting data to a distant receiver. To overcome this issue choosing among the inputs is a reliable technique. This is an idea of using selected number of transmitting antennas out of a number of available active antennas to transmit the data of all the other antennas. Their proposed selective approach is shown in Fig. 2.4(b). Antenna selection will be on the basis of channel condition. This selection procedure is used for the sensor cluster whose data are correlated.

In Fig. 2.4(b) we can see a DGN continuously sends signal bits to all the available sensors. After receiving the signal bits, these sensors estimate the channel and send the results to the cluster head. The cluster head then selects the sensors with better channel condition among the available sensors on the basis of channel estimation result. This estimation procedure goes on until the completion of the data transmission. After the sensors transmit their data to the cluster head, it aggregates the data [48] and sends all the data to the remaining active sensors within that cluster. It then sends a command signal to the selected sensors to start transmitting data.

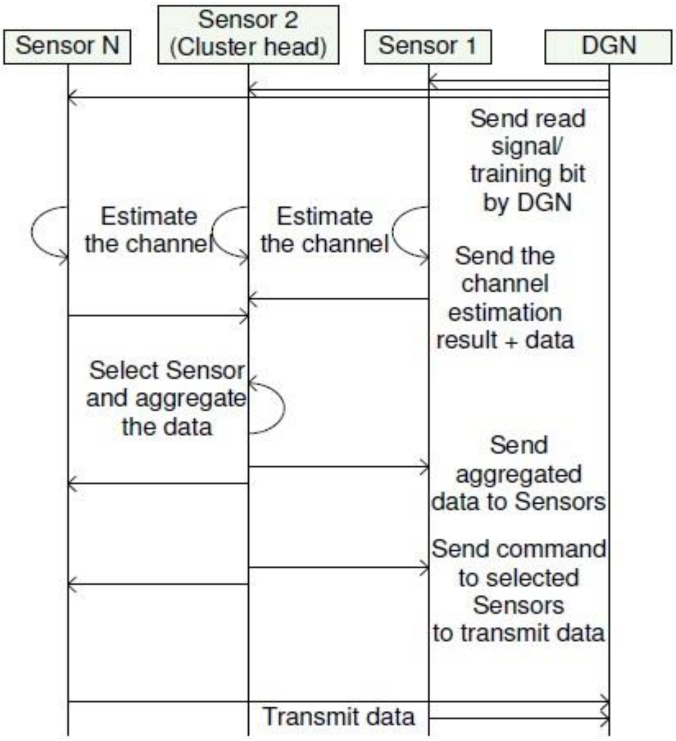


Fig. 2.4(b): Selective approach of Cooperative Communication.

As the DGN is not energy constrained, we excluded energy calculation at the DGN side. Their designed model is for two different cluster sizes and for correlated data type. They show that the selected cooperative MIMO structure outperforms the existing unselected C-MIMO as well as the SISO structure after some distance. The effect of constellation size on the total energy consumption is also investigated and it shows that cooperative technique remains energy efficient at a different distance for a different constellation size.

Applying error correcting codes in C-MIMO is another important topic for WSN. In [59] Md. Rakibul and Y.S. Han proposed a selective C-MIMO model considering Low Density Parity Check (LDPC) codes. It shows that the cooperative communication outperforms SISO transmission at the presence of error correction code. The energy efficiency remains almost unchanged in different encoding rates but it largely varies with the change in constellation size. BER analysis is also taken to show the similar error characteristics in the cooperative MIMO environment. Data with smaller encoding rate shows better BER results than larger encoding rate for a fixed SNR. Simulation is also performed in the situation of a fading environment. It is also found that cooperative communication is more energy efficient than SISO transmission in smaller targeted BER. Therefore it can be concluded that cooperative MIMO with LDPC can be a good choice for high reception quality signals.

2.5 MIMO with cooperative relay

Cooperative relay in MIMO ad hoc network is a completely new research topic. Shan et al. in [60] exploits the use of cooperative relay transmission (which is often used in a single antenna environment to improve reliability) in a MIMO-based ad hoc network to cope with harsh channel condition. They design both centralized and distributed scheduling algorithms to support adaptive use of cooperative relay transmission when the direct transmission cannot be successfully performed. The algorithm effectively exploits the cooperative multiplexing gain and cooperative diversity gain to achieve higher data rate and higher reliability under various channel conditions. Their scheduling scheme can efficiently invoke relay transmission without introducing significant signalling overhead as conventional relay schemes, and seamlessly integrate relay transmission with multiplexed MIMO transmission. They also propose a MAC protocol to implement the distributed algorithm. Their performance results show that the use of cooperative relay in a MIMO framework bring in a significant throughput improvement in all the scenarios studied, with the variation of node density, link failure ratio, packet arrival rate, and retransmission.

Chapter 3

Proposed Method

In this chapter, my proposed methodology is explained for total energy calculation of a C-MIMO model in WSN with cooperative relay placement. The overall idea of my proposed method for a C-MIMO model is depicted in Fig. 3.1. The proposed method uses the following steps: 1) Design a cooperative relay network, 2) Convert the model into C-MIMO, 3) Total energy consumption equation of C-MIMO with relay, 4) Expand the network into multi-hop scenario, and 5) Determine delay equation of the network.

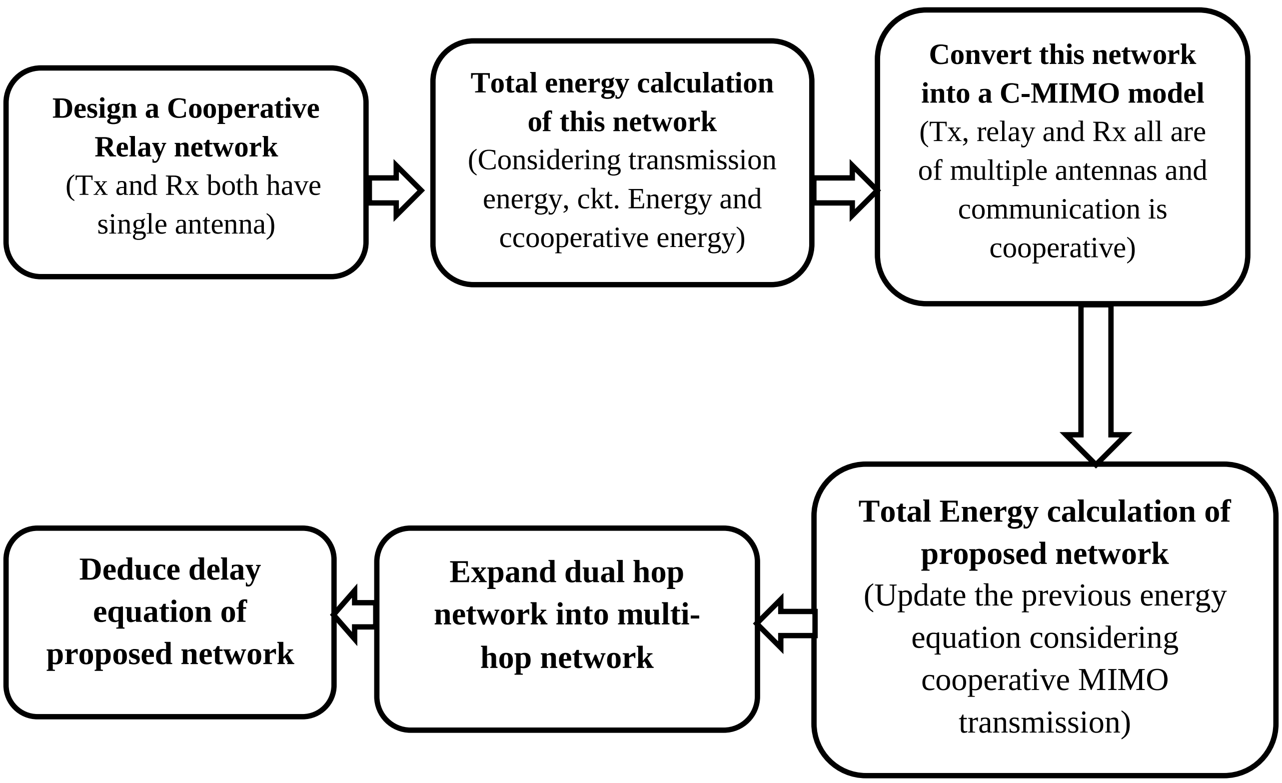


Fig. 3: Steps of the proposed method

3.1 System and Channel Models

At first a dual-hop cooperative relay network is considered in which a MIMO relay node is located anywhere on a line between source *S* and destination *D*, as shown in Fig. 3.1(a). The MIMO relay is occupied with *M* antennas. This model is then extended to the $(N + 1)$-hop network in which *N* cooperative relays ($R1, R2, \ldots, RN$) are located equidistantly on a line between *S* and *D*, as shown in Fig. 3.1(b). Each relay terminal is equipped with *M* antennas. Relay node amplifies the signal received from the preceding relay/source and then forwards it to the next relay/destination without performing any decoding.

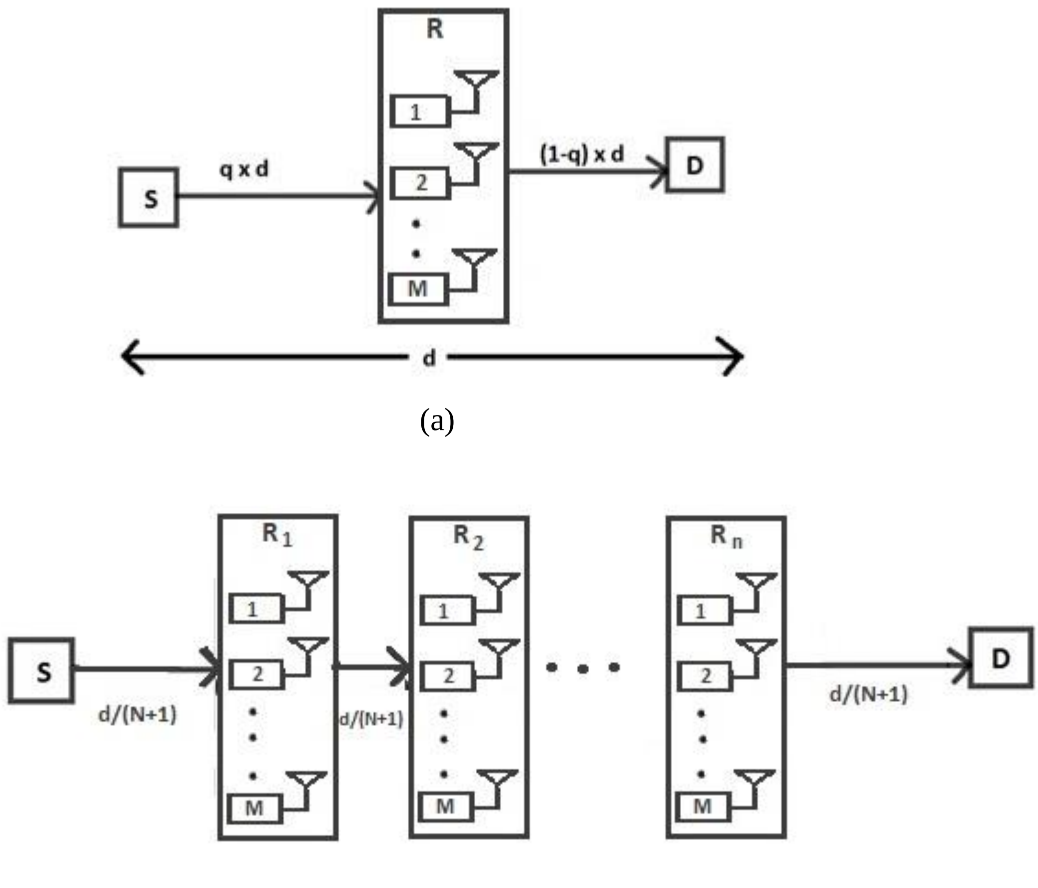


Fig. 3.1(a): Dual-hop relay network where *S* and *D* are separated by total distance *d*, and a single cooperative relay with M number of single antennas is located at distance $q \times d$ from *S* with $0 < q < 1$. (b): Multi-hop network in which *N* MIMO relays are placed equidistantly from each other; thus, each terminal has a separation of $d/(N + 1)$.

Additional assumptions of this primary system model are given as follows.

1) The idea of channel estimated antenna selection from [25] is considered here. According to [25] the use of selected number of sensors is more energy efficient than the use of all active sensors. We will select M_t number of antennas from relay cluster which will communicate wirelessly with destination.

2) The channel amplitudes of all the hops are mutually independent random variables and follow Rayleigh distribution. Furthermore, the fading channels are flat and remain almost constant over a symbol time. Thus, the average BER is a useful performance metric under these channel conditions.

3) The circuit power consumption is considered negligible when the terminals are inactive, i.e., when they are not transmitting nor receiving any data. This is a fair assumption if we have terminals that can efficiently be switched ON/OFF. For active time circuit power is considered and calculated using [7].

4) Cooperative diversity is available only in relay terminal; source delivers data to relay cluster, cluster sensors then process the data, amplify it and selected no. of M_t antennas delivers data to destination terminal; as shown in Fig. 1(a) and (b). Connectivity exists only between two neighbouring terminals. Power consumption for data processing due to local transmission, channel estimation and data aggregation in relay terminal is considered separately. This is also a reasonable assumption, particularly to keep the processing and control messaging to its minimum level for the calculation of total energy consumption. Note that this assumption has already been considered in many previous publications (e.g., [38-39]).

5) Instantaneous channel state information (CSI) is not available at the transmitting terminals, whereas perfect CSI is available at all the receiving terminals.

6) Interference is not considered because it is assumed that only one terminal transmits at any instant of time in its own allocated time slot as in [22] and [25].

7) It is well-known that the 4-QAM (or quadrature phase-shift-keying) scheme requires the same transmission energy as that of the BPSK for a given average BER. However, at the same time, the spectral efficiency of 4-QAM is twice when compared with that of the BPSK.

Hence, we consider b=2 in this paper, where b represents the bits per symbol. Since b can be easily mapped with the constellation size as $M = 2b$, the terms bits per symbol and constellation size are used interchangeably hereafter. Constellation size is chosen fixed for fixed transmission distance for both the local transmission and long haul transmission to make the energy consumption in line with the distance.

This scenario is then extended to a special C-MIMO model where source (S), relay (R) and destination terminals of above network transform into a network of sensor clusters. S, R and D each is occupied with data gathering node (DGN) and several sensors. Each sensor is occupied with single antenna. Sensors in one cluster transmit the data to the sensors in adjacent cluster and step by step the data reach the DGN. Connectivity between any two clusters is cooperative as shown in Fig 3.1(c). It shows the cluster to cluster communication of our proposed network.

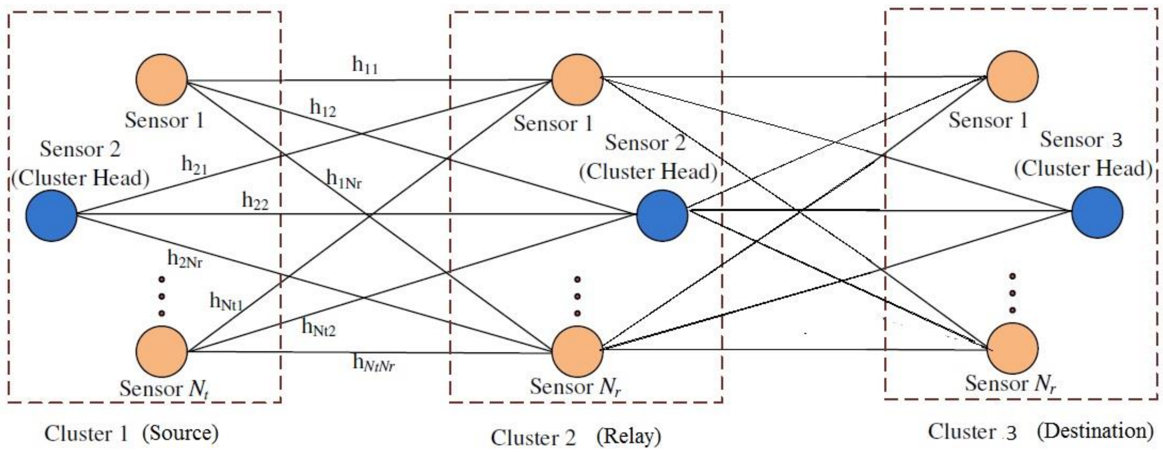
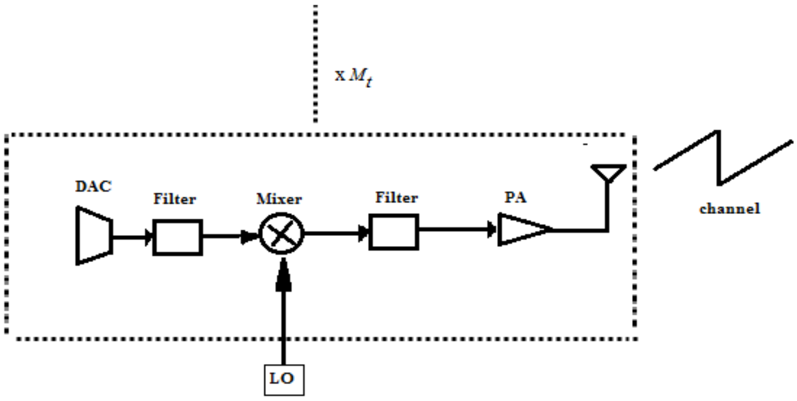


Fig 3.1(c): System model for cluster to cluster communication in wireless sensor network.

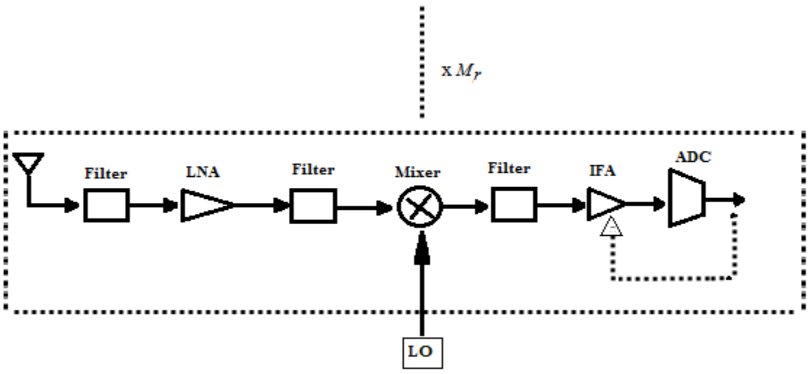
The system considers N_t number of sensors in the transmitting cluster, N_r number of sensors in the relay and receiving cluster and one antenna is placed at one sensor. Also, each element in the channel matrix $\boldsymbol{H}$ is assumed to be a zero-mean circularly symmetric complex Gaussian random variable with unit variance [14] and can be considered as follows.

$$H = \begin{pmatrix} h_{11} & h_{12} \cdots & h_{1N_r} \\ h_{21} & h_{22} \dots & h_{2N_r} \\ \vdots & \vdots & \vdots \\ h_{N_t1} & h_{N_t2} & h_{N_tN_r} \end{pmatrix}$$

The problem here is stated from the receiver point of view, so a network model is used to estimate the received energy. To calculate the total energy consumption, both the circuit and transmitter power are taken into count. The same transmitter and receiver blocks shown in [43] are used in this thesis. In [43] a general communication link connecting two wireless nodes is considered, which can be MIMO, multiple-input–single output (MISO), single-input–multiple-output (SIMO), or SISO. To analyse the total energy consumption, all signal processing blocks at the transmitter and the receiver are included in that model. However, in order to keep the model from being over-complicated, baseband signal processing blocks (e.g., source coding, pulse-shaping, and digital modulation) are intentionally omitted. We also assume that the system is coded. WSN is energy constraint in nature and the sensors work as intermediate devices when the data are transferred from a designated area to the data gathering node (DGN). Since decoding can be performed in the DGN, energy efficient decoding technique is not a concern for this paper. Encoding is one critical issue considered in the wireless sensor network. The resulting signal paths on the transmitter and relay/receiver sides are shown in Fig. 3.1 (d) & (e), where N_t and N_r are the numbers of transmitter and relay/receiver antennas, respectively, and we assume that the frequency synthesizer (LO) is shared among all the antenna paths. For the SISO case, we have $N_t = N_r = 1$.



d) Transmitter circuit block



e) Receiver circuit block

Fig 3.1(d): Transmitter Circuit block, (e): Receiver circuit block

Throughout the work, a system with narrowband, frequency-flat Rayleigh fading channels and perfectly synchronized transmission/reception between wireless sensor nodes is assumed. The fading is assumed constant during the transmission of each frame. In our model, a sensor with high residual energy is deployed as a cluster head and it remains the cluster head until the network dies. The cluster head broadcasts its status to the other sensors in the network. Each sensor node determines to which cluster it wants to belong by choosing the cluster head that requires the minimum communication energy. Once all the nodes are organized into clusters, each cluster head creates a schedule for the nodes in its cluster. This allows the radio components of each non-cluster-head node to be turned off at all times except during its transmit time, thus minimizing the energy dissipated in the individual sensors.

3.2 Cooperative MIMO in Cooperative Relay

Considering the above system and channel conditions, our own wireless sensor network is designed with cooperative MIMO in cooperative relay. Both cooperative relay and cooperative MIMO models are well-discussed and their behaviours are closely analysed in literature review section. We combine these two well-established techniques in our design to obtain a better energy efficient network. First we consider a dual hop network and then extend this to a multi-hop network.

3.2.1 Dual Hop Network

In the above section our cooperative relay network is constructed where source and destination each has single antenna. Now this dual hop relay network is transformed into a dual hop cooperative MIMO network. The MIMO relay in a MIMO network is incorporated. A specific cooperative MIMO scheme is used which will utilize channel selection method. The idea of channel selection is based on using selected number of transmitting antennas out of a number of available active antennas to transmit the data of all the other antennas. Antenna selection will be on the basis of channel condition. This selective approach [53] will make traditional C-MIMO more energy efficient. Our proposed dual hop network is described elaborately in below.

The system considers N_t number of transmitted antenna each placed at a sensor and N_r number of both relay antenna and received antenna placed at the network. For this system, N_a number of sensors being active, the received discrete-time signal is attenuated by a channel matrix H. We assume each element in H is a zero-mean circulant symmetric complex Gaussian random variable with unit variance. $h_{s,r}$ represents the source to relay channel matrix component and $h_{r,d}$ represents the relay to destination channel matrix component. Based on these components antenna selection or channel estimation occurs. Our proposed network model is shown in Fig. 3.2(a).

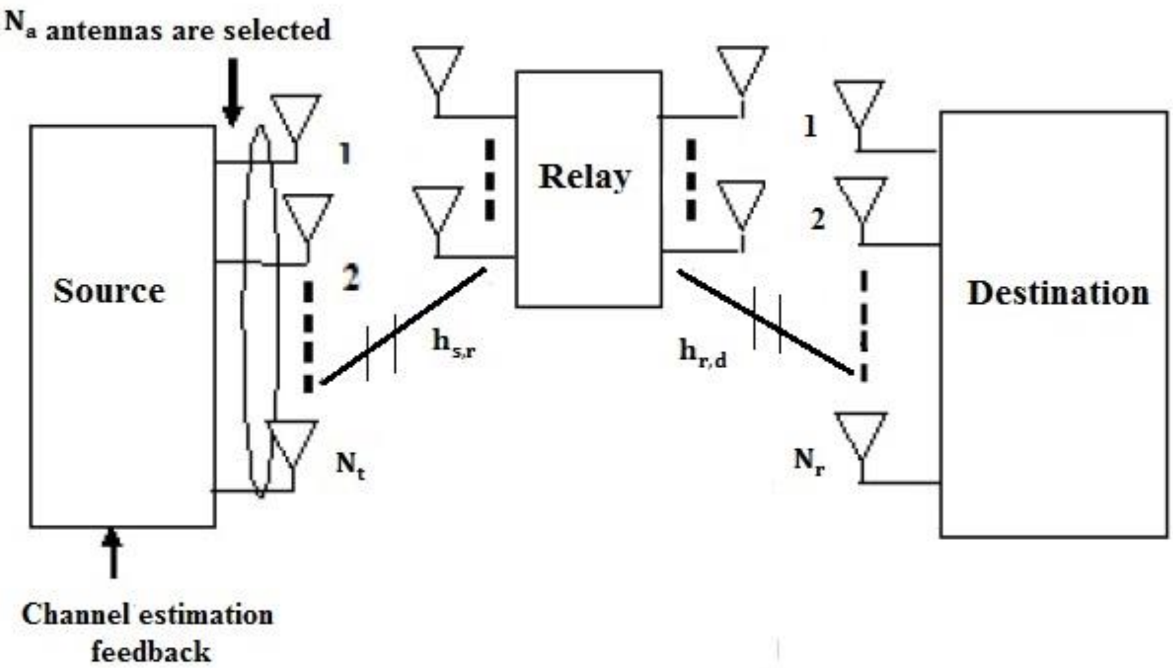


Fig. 3.2(a): Proposed dual hop network

In the above network, relay side DGN continuously sends training bits to all the available sensors in source terminal. After receiving the training bits, these sensors estimate the channel and send the results to the cluster head. The cluster head then selects the sensors with better channel condition among the available sensors on the basis of channel estimation result. This estimation procedure goes on until the completion of the source to relay data transmission. After the sensors transmit their data to the cluster head, it aggregates the data [48] and sends all the data to the remaining active sensors within that cluster. It then sends a command signal to the selected sensors to start transmitting data. As the DGN is not energy constrained, we excluded energy calculation at the DGN side.

After receiving data from selected antennas of source terminal, relay will amplify the data. We consider here only Amplify-and-Forward relay technique for its simplicity. Thus after amplification it will forward data to the receiver sensors through DGN. We will examine whether our proposed model show better performance in comparison with the existing models.

3.2.2 Multi-hop Network

We now expand our network to a multi-hop scenario. All the communication procedure is same as before except the hop numbers. We consider N=2 & 3 in our multi-hop network where N= Number of relay. Our extended network figure is shown in 3.2(b).

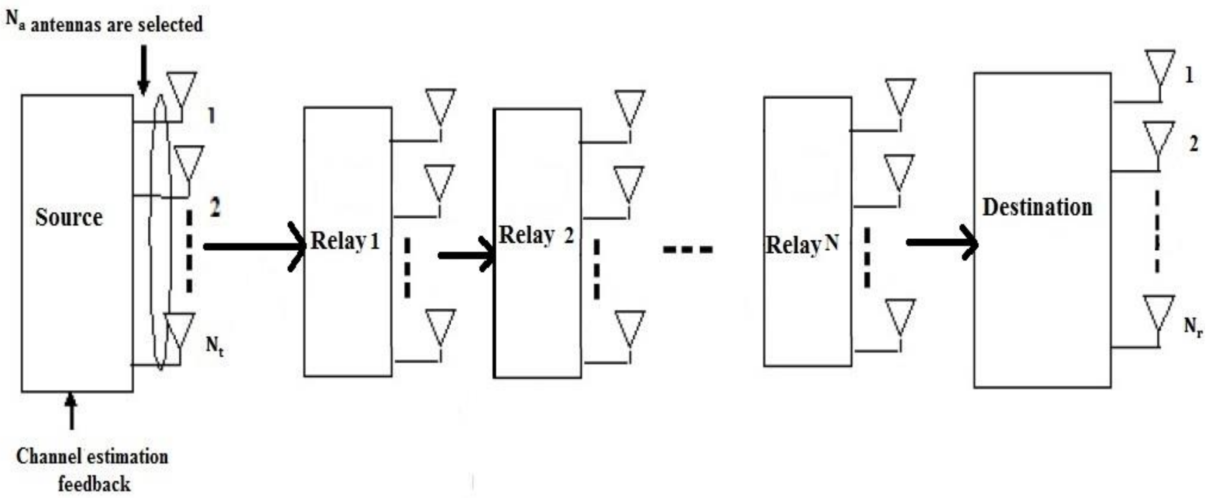


Fig. 3.2(b): Proposed multi-hop network

Above figure is for an ideal multi-hop scenario of our proposed method. Here, N numbers of relay terminals exist between source and destination. All the relays are AF relay. We will compare this multi-hop network's energy performance with the dual hop network and observe whether it's beneficial to use this structure in a sensor network environment.

3.3 Energy Calculation for Proposed Network

In the system model section, we've considered two network models; in the first model source and destination are of single antennas each, relay is of M antennas and relay type is cooperative. We will derive an equation of total transmission energy consumption for this model. In the second model we extend the first model by transforming single antenna based source and destination into multiple-input multiple-output (MIMO) type and place cooperative relay in between. We will derive a final equation of total energy consumption per bit which will consist of circuit energy, energy for cooperative communication and transmission energy.

The average BER P_b of square MQAM (with Gray coded signal constellation) over the Rayleigh fading channel is given as [46]

$$\overline{P_b} \approx c_1(b)E_\gamma[Q(c_2(b)\frac{\gamma}{b}) \quad (1)$$

where $c_1(b) \triangleq 4(1-2^{(-b/2)})/b$, and $c_2(b) \triangleq 3b/(2b-1)$. It is worth mentioning here that (1) is valid only for even values of b. Moreover, $\boldsymbol{E}\gamma[\cdot]$ denotes the expectation with respect to γ, and $Q(\cdot)$ is the Gaussian-Q function. Note that γ, denotes the end-to-end instantaneous SNR, and for the AF relay networks, it is given by [62] as

$$\gamma = \left[\prod_{i=1}^{N+1}\left(1+\frac{1}{\gamma_i}\right)-1\right]^{-1} \quad (2)$$

where $\gamma_i \triangleq {h_i}^2\ (P_i/(N_0B))$ is the instantaneous SNR of the i-th hop. Note that h_i is the channel amplitude following Rayleigh distribution. P_i is the transmission power of the i-th transmitting terminal, and N_0 is the power spectral density of the AWGN at the input of relays and the destination. Moreover, B denotes the channel bandwidth of each hop. The derivation of the exact closed-form expression of P_b from (1) is analytically intractable; however, its further approximation is possible from the results of [48] (overall, approximation is very accurate for asymptotic values of P_b or for high per-hop SNR values, as discussed in Section I; thus, we consider it as an equality hereafter) and is given as [61]

$$\overline{P_b} = \frac{c_1}{2c_2}\sum_{i=1}^{N+1}\frac{1}{\bar{\gamma}_i/b} \tag{3}$$

where $\bar{\gamma}_i \triangleq E({h_i}^2)$ $(P_i/(N_0B))$ is the average received SNR of i-th hop. Since $P_i/(N_0B)$= bE_i/N_0, we can write

$$\overline{P_b} = \frac{c_1}{2c_2}\sum_{i=1}^{N+1}\frac{1}{\bar{E}_i} \tag{4}$$

where $\bar{E}_i \triangleq E({h_i}^2)$ E_i/N_0. E_i is the transmission energy per bit of the i-th transmitting terminal. Note that, in (3), we have dropped the dependence of c_1 and c_2 on b for notational convenience. Now, $E({h_i}^2) \triangleq K{d_i}^{-a}$, where d_i is the length of the i-th hop, K is the path-loss coefficient [63], and a denotes the path-loss exponent (its typical values range from 2 to 4).

Now in our model we consider a specific MIMO case where relay antenna, $N_r = 4$ and selected antenna, $M_t = 3$. 2× 1 MISO Alamouti scheme is used for relay to destination path; here channel matrix, $= [h_1 \quad h_2]$. As shown in [14], the instantaneous received SNR is given by

$$\gamma_i = \frac{{\|H\|^2}_F}{M_t}\frac{\bar{E}_i}{N_0} \tag{5}$$

where the M_t in the denominator comes from the fact that the transmit power is equally split among transmitter M_t antennas. According to the Chernoff bound the average BER is given by [20] (in the high SNR regime)

$$\overline{P_b} \leq \left(\frac{\bar{E}_i}{M_t N_o}\right)^{-M_t} \tag{6}$$

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

$$\bar{E}_i \leq \frac{M_t N_0}{\overline{P_b}^{1/M_t}} \tag{7}$$

By approximating the bound as equality, we can calculate P_b, the average BER (which is actually an upper bound) for cooperative relay system according to (4), (9) and (10). Thus, we can obtain

$$\overline{P_b} = \frac{c_1}{2c_2} \sum_{i=1}^{N+1} \left(\frac{\bar{E}_i}{M_t N_0} \right)^{-M_t} \tag{8}$$

Proposition : Consider a dual-hop network as shown in Fig. 3.1(a), where q represents the location of the relay between the source and the destination. Let the transmit energy per bit of the network (for a given P_b and a fixed b) be $E_{tr} = E_1 + E_2$ with E_1 and E_2 being the transmit energy per bit of the source and the relay, respectively. Now, assume that both source and relay have statistical knowledge of their forward channels and that v is the energy allocation factor such that $E_1 = vE_{tr}$ and $E_2 = (1 - v)\, E_{tr}$ with $0 < v < 1$; then, the total transmit energy per bit with the optimal energy allocation is given as

$$E_{tr} = \frac{c_1 M_t N_0 d^a}{2c_2 \overline{P_b}^{1/M_t} K} \left[\left(q^{\frac{a}{2}} + (1-q)^{\frac{a}{2}} \right)^2 \right] \tag{9}$$

In the case of uniform energy allocation (i.e., substituting v = 1/2), E_t becomes

$$E_{tr} = \frac{c_1 M_t N_0 d^a}{c_2 \overline{P_b}^{1/M_t} K} \left[\left(q^a + (1-q)^a \right) \right] \tag{10}$$

It is worth mentioning here that if the relay is in the middle (i.e., q = 1/2), then the uniform energy allocation becomes the optimal allocation (i.e., $v = v* = 1/2$). In this case, both (9) and (10) are minimized and simplified to

$$E_{tr} = \frac{c_1 M_t N_0 d^a}{2^{a-1} c_2 K \overline{P_b}^{1/M_t}} \tag{11}$$

This E_{tr} is the total transmit energy per bit with optimal energy allocation. Now we will determine other energy consumptions to finally get the total energy consumption per bit.

The power consumption in the circuit block includes transmitter and receiver power consumption P_{ct} and P_{cr}, respectively. This power consumption is due to several power blocks such as P_{mix}, P_{syn}, P_{filt}, P_{filr}, P_{LNA}, P_{IFA}, P_{DAC}, and P_{ADC} which are the power consumption values of the mixer, the frequency synthesizer, the active filters at the transmitter and at the relay/receiver side, the low noise amplifier, the intermediate frequency amplifier, the D/A and A/D converter, respectively as shown in Fig, 3.1(d). The power consumption block for error correction is not considered as it is same for cooperative case and SISO case. The total power energy consumption per bit can be written as

$$P_c \approx M_t\left(P_{DAC} + P_{mix} + P_{filt}\right) + 2P_{syn} + M_r\left(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}\right) \quad (12)$$

To estimate the values of P_{IFA}, P_{DAC}, and P_{ADC} we use the model introduced in [40]. Thus, total energy consumption per bit (excluding energy for cooperative communication)of Fig. 3.1(a) model is

$$E_{tot} = E_{tr} + \frac{2P_c}{R_b} \quad (13)$$

Note that the factor "2" in (13) is due to the fact that both source and relay are involved in transmission in their respective time slots. Here R_b is the actual bit rate and can be replaced by $R_b^{eff} = \frac{F-pN_T}{F} R_b$when pN_T training symbols are inserted in each block to estimate the channel at the receiving cluster or DGN side. The block size is equal to F symbols and can be obtained by setting F = $\lfloor T_C R_S \rfloor$, where R_S is the symbol rate and T_C is the fading coherence time. The fading coherence time can be estimated from T_C = 3 4fmpπ where the maximum doppler shift f_m is given by $f_m = \frac{v}{\gamma}$ with v being the velocity and γ being the carrier wavelength [64]. The total energy consumption is estimated by multiplying E_{tot} by the number of bits *L* to be transmitted.

We now consider a linear multi-hop AF relay network, as shown in Fig. 3.1(b). This network is same as Fig. 3.1 (a) except there are *N* cooperative relays and *(N+1)* hops between source and destination. In this case, the transmission energy per bit (for given values of $\overline{P_b}$ and *b*) of (4) becomes

$$E_{tr(multihop)} = \frac{c_1 M_t N_0 d^a}{2c_2 K \overline{P_b}^{1/M_t} (N+1)^{a-2}} \quad (14)$$

If we add circuit power from (12) with above equation, we can get total energy consumption per bit of multi-hop network (excluding energy for cooperative communication) of Fig 3.1 (b) [29]

$$E_{tot(multihop)} = E_{tr(multihop)} + (N+1)\frac{P_c}{R_b} \quad (15)$$

Proof: The brief proof is as follows.

Let $\forall i$, $E_i = E/(N+1), d_i = d/(N+1)$. Then, substituting

$$\bar{E}_i = \bar{E} = K\left(\frac{d}{N+1}\right)^{-a}\left(\frac{E}{(N+1)N_0}\right) \quad (16)$$

in (8) and using the power model of [66], we get the result in (16). Using the results here, we are now able to quantify potential energy savings through relay networks in comparison with the direct transmission (single hop).

Now we develop the mathematical model where we estimate total energy consumption for cooperative communication like Fig 3.1 (c). Cooperation can be occurred both on the transmitting side and the receiving/relaying side. Multiple nodes around the destination/relay node take part in communication such that cooperative reception is possible. Therefore, along with MISO, an equivalent SIMO or MIMO system can be constructed too. Similarly, local energy consumption is necessary due to the data aggregation among receiving nodes. The total delay requirement is accordingly altered. In order to compare the performance between the non-cooperative approach and the MIMO approach, some assumptions need to be made. We assume that there are N_t transmitting nodes and each has M_i bits to transmit, where *i=1,…,* N_t . For the non-cooperative approach, we assume that each transmitting node uses a different time slot to transmit the information to the remote node with uncoded MQAM. For the MIMO approach, the N_t nodes on the transmitting side will cooperate. Each node first broadcasts its information to all the other local nodes using different time slots. After each node receives all the information bits from other nodes, they encode the transmission sequence according to the Alamouti diversity codes [20]. Since each node has a preassigned index, they will transmit the sequence which the *i*-th antenna should transmit in an Alamouti MIMO system. On the receiving/relaying side, there are N_r nodes (including one destination node and $N_r - 1$ assisting nodes) joining the cooperative reception. The $N_r - 1$ assisting nodes first quantize each symbol they receive into n_r bits, and then transmit all the bits using uncoded MQAM to the destination node to do the joint detection.

Since the baseband processing is simple for Alamouti codes [20], we omit the baseband processing energy for simplicity. Therefore, the total energy consumption in each node only includes the transmission energy and the analog circuit energy consumption as we discussed in the previous section for MIMO systems. For local transmissions, we assume a *k*th-power path loss (loss $\propto (1/d^k)$) with additive white Gaussian noise (AWGN). For long-haul transmissions, we assume a Rayleigh-fading channel with square-law path loss. Within the local cluster (for both Tx side and Rx/relay side), if the maximum separation is d_m m, we assume each node will use a fixed constellation size according to all kind of distances. Since usually the long-haul distance between the remote node and the local cluster is much larger than d_m, we assume the long-haul transmission distance, denoted as *d*, is the same for each transmitting node. The total energy consumption in cooperative case is modelled as below

$$E_{CO} = \sum_{i=1}^{N_t-1} L_i E_i^t + E_{da} \sum_{i=1}^{N_t} L_i + E_{enc} \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i$$
$$+(N_t - 1)E_i^{t0} \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i$$
$$+E_M^l \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i$$
$$+ \frac{1}{b_{mimo}} \sum_{i=1}^{N_t} \sum_{i=1}^{N_r} \frac{L_i}{r} \gamma_i b_{lr} E_j^t \quad (17)$$

The energy cost per bit for local information flow on the Tx side, denoted as E_i^t , *i=1,...,* N_t, the energy cost per bit for local information flow on the Rx side, denoted as E_j^r, *j=1,..,*$N_r - 1$ can be calculated according to the result we obtained for SISO communication links in AWGN channels (see [46] and [47]). However, there is one thing we need to change for calculating E_i^t . Since there are always $N_t - 1$ receivers listening during the local transmission, the total circuit energy consumption on the receiver side should be the total energy consumption of $N_t - 1$ sets of receiver circuits. The energy cost per bit for the MIMO long-haul transmission, denoted as E_b^r , can be calculated according to the MIMO results discussed in the last section.

Thus in [58] E_i^t is the energy per bit needed to transmit the data from sensors to the cluster head. E_{da} is the energy dissipation per bit required in the cluster head for data aggregation. It depends on the algorithm complexity and can be expressed as

$$E_{da}(L) = \begin{cases} C_0 + C_1 \times L + C_2 \times L^2 & \text{for } O(n^2) \\ C_0 + C_1 \times L & \text{for } O(n) \end{cases}$$

(18)

where L is the number of transmission bits and C_0, C_1 and C_2 are coefficients depending on the software and CPU parameters. E_{enc} is the encoding energy per bit and is taken 1 μJ [65]. E_i^{t0} denotes the local transmission energy cost per bit for transferring the aggregated data to the remaining active sensors, γ is the percentage of remaining data after aggregation and it reflects the correlation between data amongst different sensors. *r* is the rate of LDPC encoding. Since the use of a rate *r = 1/2* makes the size of the data after encoding, 2 times the original data size, the $\frac{L_i}{r}$ term is used to represent the data size after encoding a message size of L_i with rate *r*. The same energy per bit E_i^{t0} is needed to transmit a command signal from the cluster head to the selected sensors. After receiving all the bits, the nodes encode the transmission sequence according to some diversity scheme, such as the STBC. E_M^l denotes the energy cost per bit for the long haul MIMO transmission which is derived in (11), i.e. $E_S^l = E_{tr}$. To find the number of symbols present in the received signal $\sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i$ is divided by the optimal bit size of the long haul transmission b_{mimo}. The number of symbols is then multiplied by the optimal bit size of the local transmission b_{lr} to find the total bit length. E_j^t is the energy per bit required to transmit the data from a sensor to the cluster head at the receiver side. N_r is the number of sensors at the receiving/relay cluster.

For the SISO approach, sensors transmit their data to the cluster head and as there is no burden for channel estimation, the cluster head will transmit all the aggregated data directly to the destination node without any cooperation. So the total energy consumption becomes

$$E_{SISO} = \sum_{i=1}^{N_t-1} L_i E_i^t + E_{da} \sum_{i=1}^{N_t} L_i + E_{enc} \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i + E_S^l \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i$$

(19)

where E_S^l denotes the SISO long haul transmission and can be calculated as a special case of MIMO transmission with N_t = 1 and N_r = 1, i.e. E_S^l is equal to E_{tr} of (11) where $M_t = 1$. In both SISO and C-MIMO case, fixed constellation size is used. Since the encoding energy using Richardson scheme is same for both C-MIMO and SISO approach, it is not considered in the equation for C-MIMO and SISO.

Considering selective C-MIMO as section 3.3, the total energy consumption for cooperative communication of (17) becomes

$$E_{SelectiveCO} = \sum_{i=1}^{N_a} \frac{L_i}{F} E_{ch} + L_{ch} \sum_{i=1}^{N_a-1} \frac{L_i}{F} E_i^t + \sum_{i=1}^{N_a-1} L_i E_i^t + E_{da} \sum_{i=1}^{N_a} L_i + E_{enc} \sum_{i=1}^{N_a} L_i \gamma_i + (N_a - 1) E_i^{t0} \sum_{i=1}^{N_a} L_i \gamma_i + L_c p_s \frac{L_i}{F} \sum_{i=1}^{x} E_i^{t0} \quad (20)$$

where E_{ch} is the channel estimation energy and is using 28 μJ/bit/signals in our simulation experiment [67]. Data size L_i is divided by the frame size F to find out the number of channel estimations required for the transmitted data size L_i as channel estimation is performed once in a frame duration. The second term is due to the transfer of channel estimation result to the cluster head. E_i^t is the energy per bit required to transmit from a sensor to the cluster head. L_{ch} is the number of bits needed to transfer the channel estimation result. The same energy per bit E_i^t is needed to transmit the data from sensors to the cluster head. E_{da} is the energy dissipation per bit required in the cluster head for data aggregation. It depends on the algorithm complexity. E_{da} is same as (18). L_c denotes the bit length of a command signal and $x = N_b - 1$ for the cluster head being a selected sensor and $x = N_b$ otherwise where N_b denotes number of selected sensors. p_s is the probability that a selected sensor will be changed in the next packet and is chosen 1/ N_a. After receiving all the bits, the selected nodes encode the transmission sequence according to some diversity scheme, such as the STBC. E_M^l denotes the energy cost per bit for the long-haul MIMO transmission. Here the circuit energy consumption at the DGN side is considered.

So, by adding (20) with (13) the total energy consumption equation of proposed dual hop network is found

$$\boldsymbol{E_t = E_{tot} + E_{SelectiveCO}} \quad (21)$$

And by adding (15) with (20) the total energy consumption equation of proposed multi-hop network is found

$$\boldsymbol{E_{t(multihop)} = E_{tot(multihop)} + N \times E_{SelectiveCO}} \qquad (22)$$

where N= No. of relay.

For the SISO approach in selective C-MIMO, there is no burden for channel estimation and the cluster head will transmit all the aggregated data directly to the destination node without any cooperation. So the total energy consumption of SISO in (19) becomes

$$E_{SISO} = \sum_{i=1}^{N_a-1} L_i E_i^t + E_{da} \sum_{i=1}^{N_a} L_i + E_{enc} \sum_{i=1}^{N_a} L_i \gamma_i + E_{tr} \qquad (23)$$

where E_S^l denotes the SISO long haul transmission and can be calculated as a special case of MIMO transmission where N_b= 1 and N_r= 1 with the predetermined constellation size for this particular case. In both SISO and MIMO, the constellation size is used as b = 3.

3.4 Delay Calculation for Proposed Method

Another tradeoff is the transmission delay since the MISO approach has different delay characteristics than non-cooperative approaches. In this section, we will compare the delay performance between the MISO strategy and the non-cooperative approach to show which one is more energy-efficient and causes less delay.

The total delay required is defined as the total transmission delay. For a fixed transmission bandwidth *B*, we assume the symbol period is approximately $T_s \approx (1/B)$. For the non-cooperative approach, according to [43] the total delay T_{tra} is given as

$$T_{tra} = \sum_{i=1}^{N_t} \frac{N_i}{b_i^0} T_s \qquad (24)$$

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

Accordingly T_{MIMO}, is given by [43]

$$T_{\text{MIMO}} = T_s \left(\sum_{i=1}^{N_t} \frac{N_i}{b_i^t} + \frac{\sum_{i=1}^{N_t} N_i}{b_m} + \sum_{i=1}^{N_r-1} \frac{n_r N_s}{b_j^r} \right) \quad (25)$$

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

Chapter 4

Experimental analysis

In this chapter, we evaluate the performance of the proposed methodology for C-MIMO with cooperative relay network. We will present our proposed model's performance by drawing the comparison with some other prominent and existing traditional models. Besides, in the latter part, we will also show the performance of our proposed method in case of changing other parameters with the increase of long-haul distance.

4.1 Energy Issue

Total energy consumption and energy efficiency are the key terms to evaluate the energy efficient performance. For simulation, it is considered that all the sensors in a cluster are transmitting the same data size of L_i= 10 kb. The simulation is performed based on the cluster size of N_t =N_r = 4 and antenna number for selective C-MIMO is, M_t =3. The overall parameters used in our simulation is listed in Table 4.1 where the power consumption values of various circuit blocks are quoted from [43].

Table 4.1: System parameters

$f_c = 3.5$ GHz	a = 3.5
$G_tG_r = 5$dBi	b = 2
$B = 10$ MHz	$\eta = 0.35$
K= 10^{-3}	$N_0 = -174$ dBm/Hz
$N_f = 10$ dB	k = 2 for local comm.
$E_{da} = 5$ nJ/bit/signals	k = 3 for long haul comm.
$P_b = 10^{-4}$	$P_{mix} = 30.3$ mW
$M_l = 40$ dB	$P_{LNA} = 20$ mW
$P_{syn} = 50$ mW	$P_{filr} = 3.5$ mW
$P_{filt} = 3.5$ mW	

In Fig. 4.1(a) total energy consumption per bit is shown for a cooperative relay network's data transmission which has been explained at section 3.1. From Fig. 4.1(a) it is clear that the cooperative relay model is more energy efficient than traditional dual-hop and multi-hop relay network where Tx, relay and Rx all are consisted of single antenna nodes.

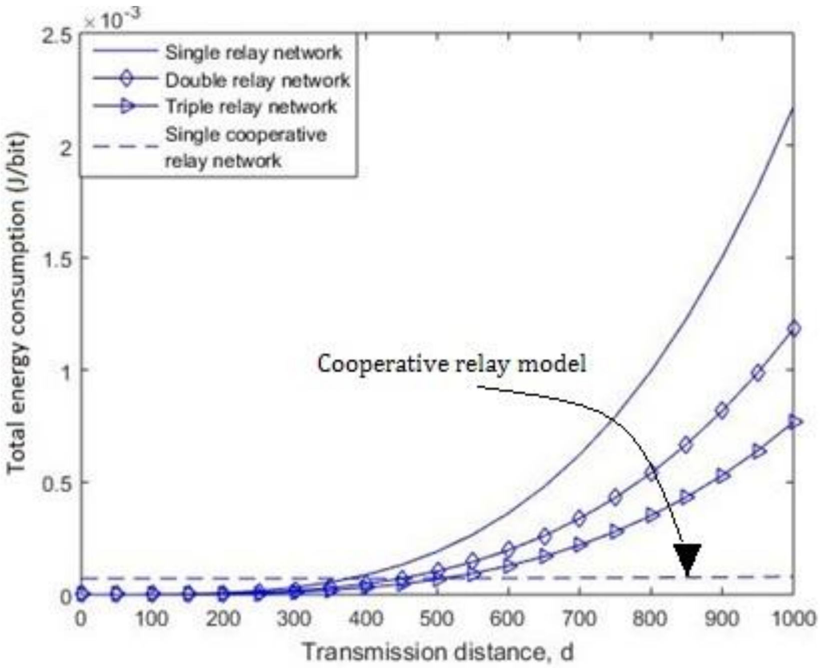


Fig. 4.1 (a): Comparison of total energy consumption among simple relay and cooperative relay networks over distance

Here we consider equispaced dual-hop and multi-hop relay networks. For cooperative relay network, we consider relay consists of $N_r = 4$ sensor antennas and relay location is in the middle. It is clear in above Fig. that there exists a *crossover* distance above which the cooperative relay network is more energy efficient than the traditional multi-hop systems. This is because for short distances circuit energy is more dominant than transmission energy. Since circuit energy of cooperative relay network is higher than traditional relay networks, for shorter distances simple relay networks is more energy efficient. As soon as long-haul distance increases transmission energy of traditional relay networks also increases, but transmission energy of cooperative relay network decreases. We find the crossover distance for dual hop network is ~ 350 m , for hop=3 this distance becomes ~ 450 m and for hop=4 becomes ~ 500 m . We also understand the fact that using *N* number of single relays between Tx and Rx side consumes more energy than a single cooperative relay cluster with N relay antennas. This proves the importance of cooperative communication in wireless sensor network.

Now we will show numerical result of our proposed model's energy consumption and make necessary decisions based on the findings. We first compare between existing C-MIMO with selective C-MIMO network. Selective cooperative MIMO is based on channel estimation [25]. In Fig. 4.1(b) we see that selective C-MIMO shows better performance than traditional C-MIMO [7] as well as traditional SISO. In the traditional C-MIMO we use N_t $=N_r$ = 4 and in selective C-MIMO we use selected antennas, M_t =3. Also we consider SISO as a special kind of C-MIMO where N_t $=N_r$ = 1.

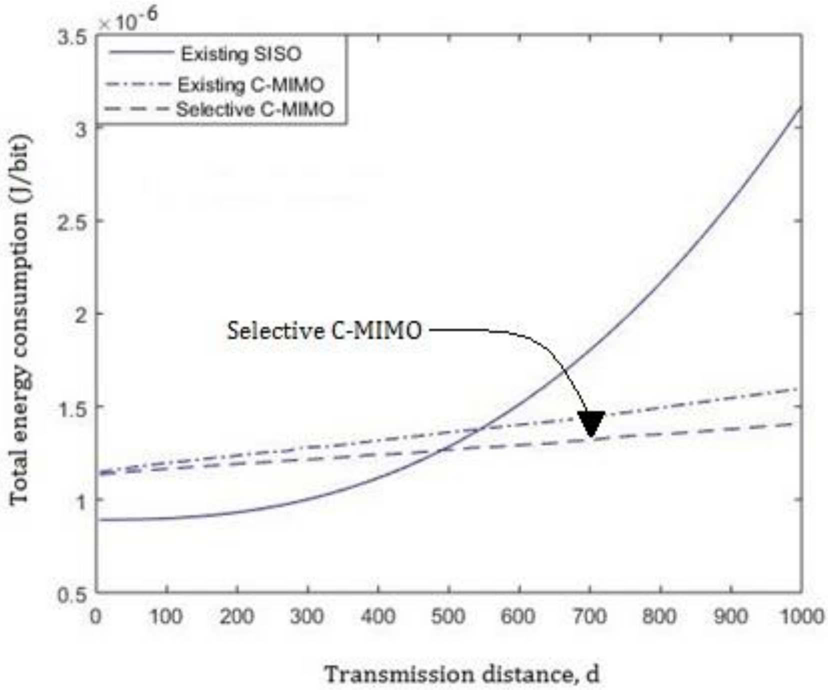


Fig. 4.1 (b): Comparison of total energy consumption among SISO, C-MIMO and selective C-MIMO over distance

Here three network models are shown and their energy consumptions over transmission distance are drawn. We consider transmission distances from 0 to 1000 m. It is clear from the figure that for shorter distances (<500 m) SISO model work very efficiently consuming least energy consumption. Logic behind this is low transmission power consumption for SISO as sensors transmit their data to the cluster head and there is no burden for channel estimation, the cluster head will transmit all the aggregated data directly to the destination node without any cooperation. But if we increase transmission distance over a specific crossover distance, we observe an increase in transmission power for SISO which results increase in total energy consumption per bit highly. On the other hand, in traditional C-MIMO model transmission energy decreases with the increase of distance. After crossing that crossover distance C-MIMO shows excellent performance in reducing total energy than SISO. A comparatively new approach 'Selective C-MIMO' is again applied to the existing C-MIMO approach. From figure it is evident that selective C-MIMO performs even better than traditional C-MIMO. There is also a crossover distance (~ 480 m) from where SISO performance stars to degrade than this technique. Surprisingly selective C-MIMO method consumes less overall energy than traditional C-MIMO for all distances, short to long. So, we will use selective approach in our proposed C-MIMO model.

In above findings we get two models- C-MIMO and cooperative relay, which are more energy efficient than the traditional WSN models. Our goal is to find a more energy efficient network model that shows better results than the existing ones. We have already proposed that model in system model section. Our proposed model is the combination of the selective C-MIMO and cooperative relay. All the terminals- source, relay and destination have multiple sensor antennas. We assume sensor numbers are same for all, i.e. N_t $=N_{relay=}$ N_r = 4. Selected number of antennas by channel estimation is also same, $M_t = 3$.

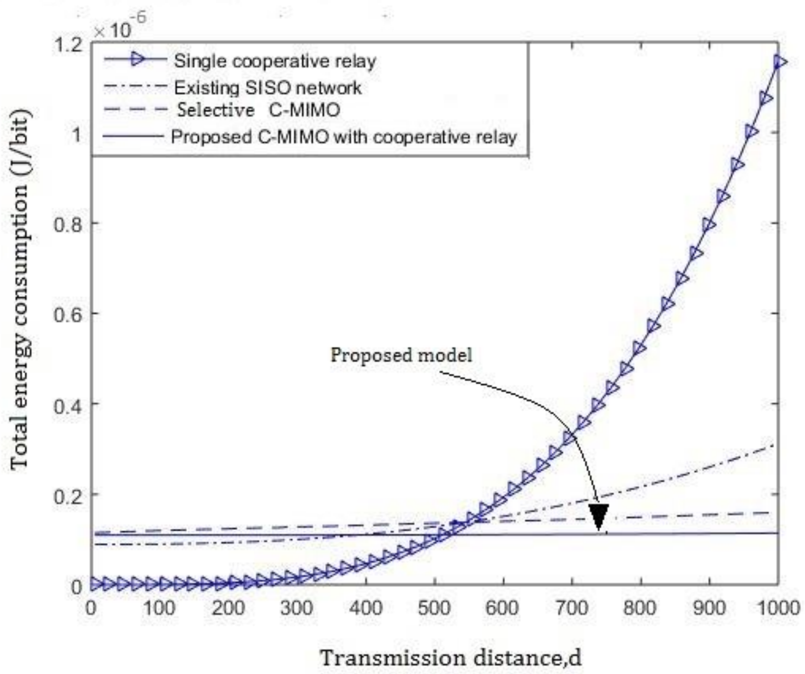


Fig. 4.1 (c): Comparison of total energy consumption among existing methods and proposed method over distance

In fig. 4.1(c) the comparison among proposed method and existing methods are shown. We observe our proposed method shows expected performance in energy consumption. From above figure we can see our proposed method shows better performance than SISO, C-MIMO and cooperative relay networks. Combination of cooperative relay and C-MIMO bring the benefits from both and make the model more efficient. Here a crossover distance is present as well. For distances <500m single cooperative relay works best due to its low transmission energy and low circuit complexity. Above 500m distance this model becomes heavy in energy consumption because of its high transmission power. After this distance SISO and selective MIMO perform better than cooperative relay model. Because the energy needed to transfer data is much less due to cooperative communication. In fig. 4.1(c) it is clear that the model we propose consumes least total energy per bit than all other existing models after some crossover distance. For cooperative relay model in C-MIMO this crossover distance is ~ 500 m. In longer transmission distances cooperative relay and C-MIMO both models improve network performance by reduction in transmitting energy and cooperation in intra and inter cluster antennas. Thus our proposed network model performs great at long transmission distances and from simulation results the distance is above 500m.

In our proposed scheme we have used a cooperative relay in C-MIMO model where relay is in the middle. There must be an optimum relay location for which the cooperative relay network performs the best. We try to find that optimum location using our simulation technique. In fig. 4.1(d) we determine total energy per bit for three different *q* values, where q represents the relay location between source and destination as shown in Fig. 3.1(a).

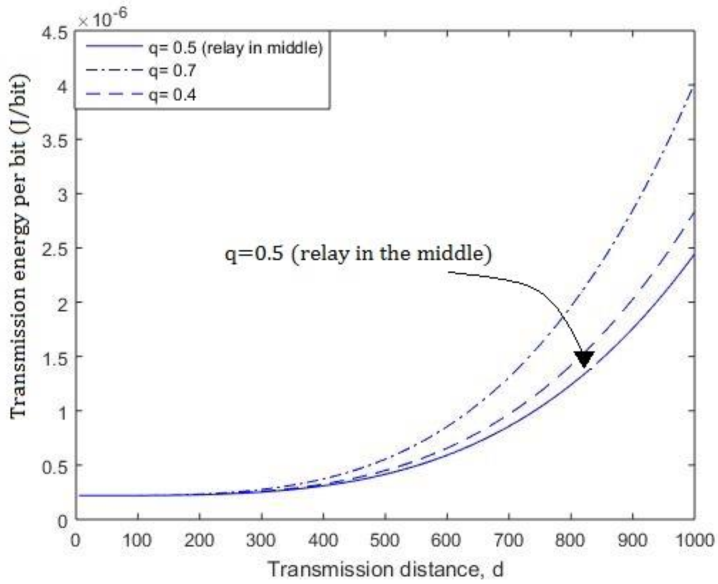


Fig. 4.1 (d): Total energy consumption over distance varying relay position

Now we extend our model to multi-hop setting. But at first we will analyse other multi-hop networks to understand the existing outcomes. In fig. 4.1(e) we draw energy curves for simple relay network and cooperative relay network. Both are drawn for N=1,2 & 3. Here N denotes the number of relay terminals.

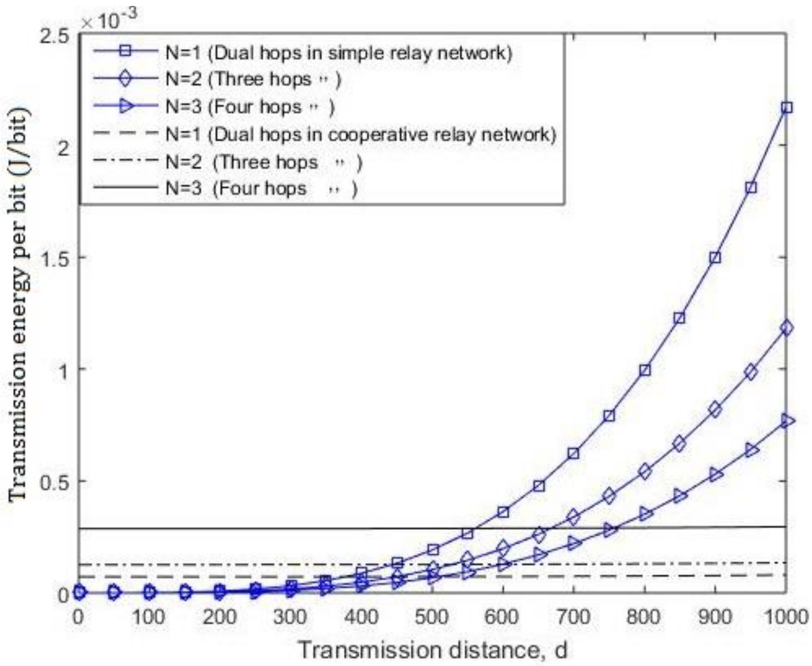


Fig. 4.1 (e): Total energy consumption over distance varying hop counts in simple relay and cooperative relay network

Traditional relay network is defined as a network of source, relay and destination where all are consisted of single antenna devices. If we increase relay numbers in such a network, it will improve energy efficiency. Because the more the relays, the lesser the transmission energy. Thus we find among dual, three and four hops networks four hops network gives better energy saving. If we apply this multi-hop technique into traditional cooperative relay where source and destination are of single antenna devices and relay is of cooperative MIMO type, we find opposite results. From above picture we observe the total energy consumption of cooperative relay network increases as we increase the hop number. The reason behind this is the increase of circuit complexity with hop number. For N=1, circuit is least complex, circuit power is P_c from (12) and we get the least energy consumption. For N = 2 &3 circuit power is multiplied by 3 & 4 respectively according to (15) and for this reason circuit energy consumption increases with hops. Though multi-hops reduce transmit energy in cooperative relay network, it cannot overcome the high circuit power consumption and hence, the overall energy elevates. So multi-hops in simple cooperative relay is not feasible in terms of energy efficiency. We should find another technique which will reduce energy of multi-hop cooperative relay network.

In our proposed model we try to set up a multi-hop scenario and analyse the results in Fig 4.1(f). Here we consider N=1,2 & 3 as before where N=number of hops. We find in our simulation that multi-hop network increase energy efficiency for C-MIMO with cooperative relay.

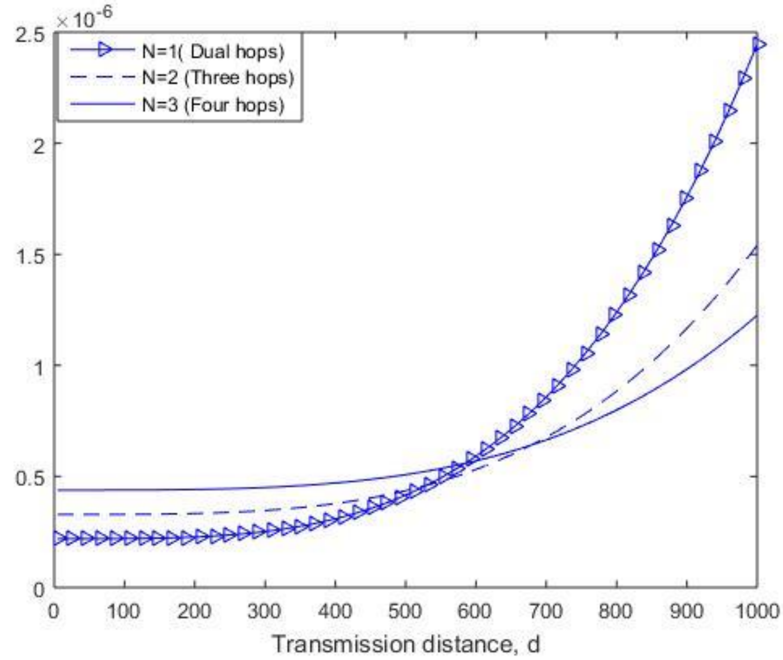


Fig. 4.1 (f): Total energy consumption over distance of proposed network varying hop counts

From above figure we observe that for <600m distances multi-hop C-MIMO model with cooperative relay is not good enough to use in WSN. As prior knowledge of Cooperative relay we can say that this behaviour is expected. Because total circuit power plays dominant role in total energy consumption in short to medium distances. Thus we get the best performance for N=1 in cooperative relay based C-MIMO network and for N=3 energy performance degrades same as before. But the exception occurs if we consider long distance above 600 m. Despite having high circuit power, we observe least energy consumption in the three hops network after the crossover distance. Because for N>1 total transmit energy of the network starts to reduce and it also reduces the effect of circuit power in total energy calculation. Thus we conclude from fig. 4.1(f) that our proposed C-MIMO model with multi-hop cooperative relay can be more energy efficient when used for long transmission distances.

Finally we will determine energy efficiency of our proposed model and compare it with traditional C-MIMO and selective C-MIMO. Energy efficiency is calculated using below equation

$$EE_1 = (E_{proposed\ CMIMO} - E_{SISO}) \,/\, E_{SISO}$$

$$EE_2 = (E_{selective\ CMIMO} - E_{SISO}) \,/\, E_{SISO}$$

$$EE_3 = (E_{CMIMO} - E_{SISO}) \,/\, E_{SISO} \qquad (26)$$

The total energy that we have calculated from energy simulation results are being divided by E_{SISO}, total energy consumption of SISO network. From energy consumption curves we've already achieved the least energy consumption for our model network. Comparison curves from simulation are given in Fig. 4.1(g).

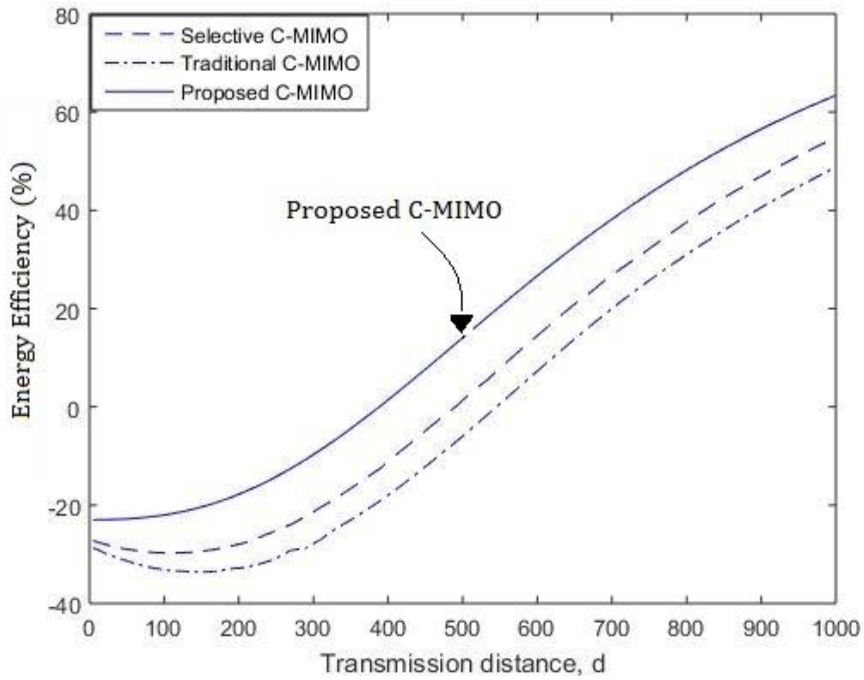


Fig. 4.1 (g): Comparison of energy efficiency among SISO, C-MIMO and proposed network over transmission distance

In Fig. 4.1(g) the same parameters are again compared over three network models. From above it is clear that selective C-MIMO is more energy efficient than traditional C-MIMO. We select 2 sensors among 4 in the selective approach. This approach uses channel estimation to find better channels according to channel gain. This channel selection procedure selects less sensor antennas from the sensor cluster. It is clear that less energy is needed to transmit any data with selected antennas than to transmit the same data with all antennas in a terminal. Thus selective approach is better than traditional C-MIMO in terms of energy efficiency. We use this selective C-MIMO for our proposed model and place cooperative relay in the middle. Thus our model uses advantages from both cooperative relaying and selective approach in C-MIMO. From the simulation result above, we find that our proposed model is even more energy efficient than selective C-MIMO and efficiency gets better with the increase of transmission distances. From the simulation result above, we find that our proposed model is even more energy efficient than selective C-MIMO and efficiency gets better with the increase of transmission distances. We have simulated for the distance upto 1000 meters. We could have got higher efficiency if we would have simulated for longer distances. From the result we can see that the efficiency is around 65% for our proposed model where M_t = 2 , 56 % for selective C-MIMO and 50% for traditional C-MIMO.

4.2 Delay Issue

The total delay required is defined as the total transmission delay. For a fixed transmission bandwidth B, we assume that the symbol period is approximately $T_s \approx 1/B$. The total delays in the case of SISO communication is defined as

$$T_{SISO} = T_s \left(\sum_{i=1}^{N_t} \frac{L_i}{b_{l_t}} + \frac{1}{b_{SISO}} \sum_{i=1}^{N_t} \frac{L_i}{r} \gamma_i \right) + t_{da} \quad (27)$$

where N_t is the number of sensors at the transmitting cluster. L_i is the transmit data size, b_{l_t} is the transmission bit size at the transmitter side local communication and b_{SISO} is the transmission bit size for long haul SISO transmission. r is the rate of LDPC encoding. We use r=3/4. Since the use of a rate r = 3/4 makes the size of the data after encoding, 4/3 times the original data size, the $\frac{L_i}{r}$ term is used to represent the data size after encoding a message size of L_i with rate r. is divided by the optimal bit size of the long haul transmission bmimo to find the number of symbols present in the received signal. t_{da} is the time taken for data aggregation.

The total delays in the case of cooperative MIMO communication is defined as

$$T_{CO} = T_s\left(\sum_{i=1}^{N_t}\frac{L_i}{b_{l_t}} + \sum_{i=1}^{N_t}\frac{\frac{L_i}{r}\gamma_i}{b_{l_t}} + \frac{1}{b_{MIMO}}\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i\right)$$
$$+T_s\frac{1}{b_{l_r}}\left(\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i\right) + t_{da} + t_{ch} \quad (28)$$

where t_{ch} and t_{da} are the channel estimation and data aggregation delays respectively. The term $T_s\sum_{i=1}^{N_t}\frac{L_i}{b_{l_t}}$ is for the delay due to the local transmission from sensors to the cluster head. The $T_s\sum_{i=1}^{N_t}\frac{\frac{L_i}{r}\gamma_i}{b_{l_t}}$ term is due to the local transmission from cluster head to the sensors. The $T_s\frac{1}{b_{MIMO}}\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i$ term is caused by the long haul MIMO transmission. The $T_s\frac{1}{b_{l_r}}\left(\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i\right)$term is due to the local transmission at the receiver side. The assisting nodes first quantize each symbol they receive into nr bits, then transform all the bits into symbols using $b_{l_r}$and transmit to the cluster head to do the joint detection.

The delay difference is calculated using the following equation. We assume the value of $t_{ch} \approx 0$.

$$DD = T_{MIMO} - T_{SISO}$$
$$= T_s\left(\frac{1}{b_{SISO}}\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i - \sum_{i=1}^{N_t}\frac{\frac{L_i}{r}\gamma_i}{b_{l_t}}\right)$$
$$-T_s\frac{1}{b_{MIMO}}\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i - T_s\frac{1}{b_{l_r}}\left(\sum_{i=1}^{N_t}\frac{L_i}{r}\gamma_i\right) \quad (29)$$

The value of n_r is chosen at the receiver based on the optimized transmitted constellation size. From above equation it is evident that the delay difference will determine whether our proposed model is delay efficient or not. If delay difference is positive then it will prove that proposed C-MIMO scheme has smaller delay in comparison with the SISO network. As we already know that this SISO network is a special type of C-MIMO model where Tx and Rx both have multiple sensors but only cluster heads will communicate with each other, i.e. $N_t = N_r = 1$. The figure below will compare between selective cooperative MIMO and SISO approach. Selective C-MIMO with M_t = 2 and r = ¾.

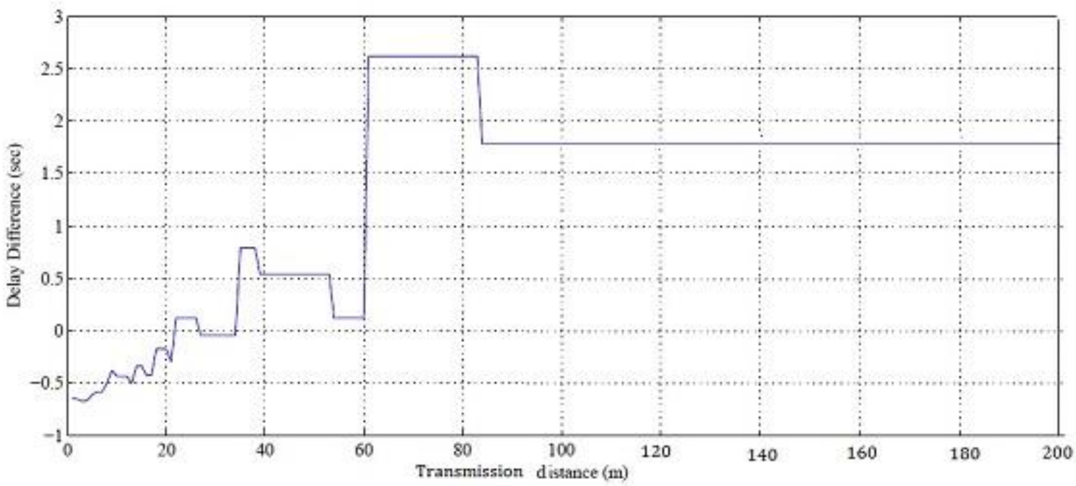


Fig. 4.2 (a): Delay difference between SISO and traditional C-MIMO over distance

From figure above we see a delay efficiency curve which is fully positive from 35 m and takes a big positive impulse in 60 m. Positive delay difference means SISO has larger delay than selective C-MIMO. Here selective C-MIMO outperforms SISO after 60 m and continues afterwards.

Using equation (26) we again compare our proposed C-MIMO model with the selective C-MIMO based on their delay performances. Both of models use M_t = 2 and r = ¾. The difference is - our model network uses cooperative relay in a C-MIMO environment where the selective approach is a single hop C-MIMO network with no relay functioning. Comparison shows our designed model's better efficiency in delay performance.

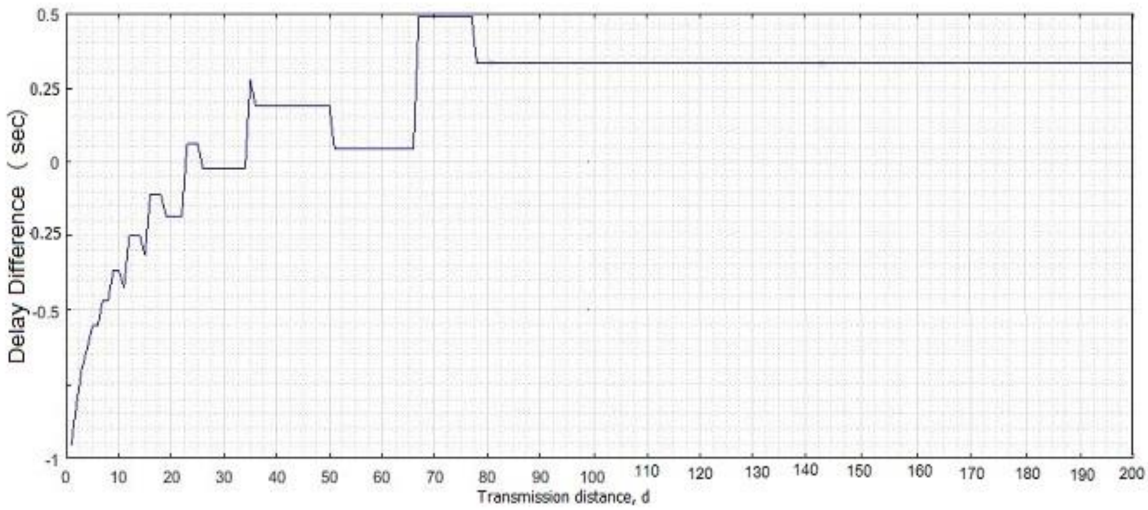


Fig. 4.2 (b): Delay difference between SISO and proposed network over distance

From above figure we realize that the delay difference curve is fully positive from 40 m and takes a big impulse at 68 m. It is clear that our proposed C-MIMO technique will outperform SISO in delay performance after 68 m. And after 68 m transmission distance, difference remains positive afterwards. Thus we can conclude that after a short range of distance our model network can be used efficiently with smaller delay.

Chapter 5

Conclusion

5.1 Summary of the contributions

Cooperative MIMO and cooperative relay have become two key technologies for achieving green communication in wireless sensor networks. When WSN is in a harsh environment or transmission distance is very long, using only C-MIMO or only cooperative relay can be tedious or sometimes not efficient enough. Depending on the network coverage and link capacity optimal hop count also varies a lot. For this reason, we try to combine these two approaches to get a picture of the overall improvement in energy efficiency and delay performance than their conventional transmissions. We first show the energy comparisons among traditional relay schemes and cooperative relay scheme. Cooperative relay saves a good amount of energy than the conventional relay systems after crossing certain distance. We also compare the total energy consumptions of SISO, traditional C-MIMO and selective C-MIMO approaches. Simulation results show that selective C-MIMO is the best performed approach among the three latter approaches. There is a crossover distance as well after which C-MIMO performs better than SISO. Then we design our network model with these two best performed approaches putting up together and apply LDPC code into it. Amplify-and forward cooperative relay is considered in our model. We run simulations on this model to find total energy consumption per bit and measure the differences with other conventional methods. We observe from the energy curves that after around 500 meters transmission distance, our proposed C-MIMO model becomes energy efficient than traditional C-MIMO and SISO models. For our proposed dual hop network, more energy efficiency is achieved when relay is in the middle. We then extend our model to multi-hop scenario. It is observed from simulation that crossover distance is higher with the increase of hops and if transmission distance is >700 m four hops network becomes more energy efficient than three hops and two hops networks. We also determine our proposed model's delay performance and compare it with SISO and C-MIMO models. Simulation results show that our proposed C-MIMO outperforms SISO model after 68m.

5.2 Future works

Although our proposed method shows better result it is possible to enhance its performance by introducing some more features in it. In our model we have considered multiple sensor antennas in source and relay side. In our future work we want to analyse cluster to cluster communication where the receiver will also perform a cooperative reception. Being inspired by the outcome of this research, we want to develop a multi-hop C-MIMO model with N numbers of AF relay. We also want to develop the model with decode-and-forward (DF) cooperative relay. Later on, analysis and comparison between DF and AF relay could be the advanced focus of the future study.

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