Power Optimisation and Relay Selection in Cooperative Wireless Communication Networks

Mohamad El Cheikh

A thesis submitted to the University of Hertfordshire in partial fulfilment of the requirements of the degree of Doctor of Philosophy

The programme of research was carried out in the Science and Technology Research Institute (STRI), University of Hertfordshire,

United Kingdom

August 2017

Dedication

Dedicated to the memory of my beloved mother

Abstract

Cooperative communications have emerged as a significant concept to improve reliability and throughput in wireless systems. In cooperative networks, the idea is to implement a scheme in wireless systems where the nodes can harmonize their resources thereby enhancing the network performance in different aspects such as latency, BER and throughput. As cooperation spans from the basic idea of transmit diversity achieved via MIMO techniques and the relay channel, it aims to reap somewhat multiple benefits of combating fading/burst errors, increasing throughput and reducing energy use. Another major benefit of cooperation in wireless networks is that since the concept only requires neighbouring nodes to act as virtual relay antennas, the concept evades the negative impacts of deployment costs of multiple physical antennas for network operators especially in areas where they are difficult to deploy. In cooperative communications energy efficiency and long network lifetimes are very important design issues, the focus in this work is on ad hoc and sensor network varieties where the nodes integrate sensing, processing and communication such that their cooperation capabilities are subject to power optimisation. As cooperation communications leads to trade-offs in Quality of Services and transmit power, the key design issue is power optimisation to dynamically combat channel fluctuations and achieve a net reduction of transmit power with the goal of saving battery life. Recent researches in cooperative communications focus on power optimisation achieved via power control at the PHY layer, and/or scheduling mechanism at the MAC layer. The approach for this work will be to review the power control strategy at the PHY layer, identify their associated trade-offs, and use this as a basis to propose a power control strategy that offers adaptability to channel conditions, the road to novelty in this work is a channel adaptable power control algorithm that jointly optimise power allocation, modulation strategy and relay selection.

Thus, a novel relay selection method is developed and implemented to improve the performance of cooperative wireless networks in terms of energy consumption. The relay selection method revolves on selection the node with minimum distance to the source and destination. The design is valid to any wireless network setting especially Ad-hoc and sensor networks where space limitations preclude the implementation of bigger capacity battery. The thesis first investigates the design of relay selection schemes in cooperative networks and the associated protocols. Besides, modulation strategy and error correction code impact on energy consumption are investigated and the optimal solution is proposed and jointly implemented with the relay selection method. The proposed algorithm is extended to cooperative networks in which multiple nodes participate in cooperation in fixed and variable rate system. Thus, multi relay selection algorithm is proposed to improve virtual MIMO performance in terms of energy consumption. Furthermore, motivated by the trend of cell size optimisation in wireless networks, the proposed relay selection method is extended to clustered wireless networks, and jointly implemented with virtual clustering technique.

The work will encompass three main stages: First, the cooperative system is designed and two major protocols Decode and Forward (DF) and amplify and forward (AF) are investigated. Second, the proposed algorithm is modelled and tested under different channel conditions with emphasis on its performance using different modulation strategies for different cooperative wireless networks. Finally, the performance of the proposed algorithm is illustrated and verified via computer simulations. Simulation results show that the distance based relay selection algorithm exhibits an improved performance in terms of energy consumption compared to the conventional cooperative schemes under different cooperative communication scenarios.

Acknowledgments

My sincere gratitude goes to my supervisor Professor Yichuang Sun for his guidance, advices and continuous motivation. I reached many academic milestones and developed a solid foundation for my future endeavours by dint of Professor Sun expertise and perceptiveness. With his effort this work is the first successful step toward the competition of my research work.

My words cannot express enough gratitude to my family for the affection and support they always offer to me. They have always stood by me and support me whenever I needed their affection means more than words can express and without them I wouldn’t reach this stage of my academic achievement.

I would like to thank Dr Fabien Delestre, and my colleagues for their assistance and support with some aspect of my work.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AF	Amplify and Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BR	Best Relay
CF	Compress and Forward
CH	Cluster Head
CSI	Channel State Information
CTS	Clear to Send
dBm	Decibel-milliwatts
DF	Decode and Forward
EF	Estimate and Forward
LAN	Local Area Network
LOS	Line of Sight
MAC	Medium Access Control
MFSK	Multiple Frequency Shift Keying
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output

mJ	Micro Joule
MQAM	M-ary Quadrature Amplitude Modulation
ms	Millisecond
OFDMA	Orthogonal Frequency Division Multiple Access
OR	Opportunistic Relaying
PHY	Physical Layer
PS	Partial Selection
QOS	Quality of Services
RTS	Ready to Send
SIMO	Single Input Multiple Output
SMS	Short Message Services
WSN	Wireless Sensor Networks

Declaration

Published Manuscripts

M. Cheikh *et al.*, "*Energy Efficient Relay Selection Method for Clustered Wireless Sensor Network.*" in 23th European Wireless Conference pp. 1-6,August 2017.

Fabien Delestre, Yichuang Sun, Gbenga Owojaiye and Mohamad El Cheikh " *STBC Based Pilot-Aided Channel Estimation Method for SFBC-OFDM Systems*." , The Post Graduate Network Symposium (PGNet 2014), PP.1-5,June 2014.

Foluwaso Tade, Goodwell Kapfunde, Yichuang Sun and Mohamad El Cheikh "*A Sphere Decoder for MIMO Detection using Improved Initial Sphere Radius*", The Post Graduate Network Symposium (PGNet 2014), PP.1-6 ,June 2014.

Manuscripts under Submission

M.Cheikh and Yichaung Sun "*An Energy Efficient Relay Selection Algorithm for Clustered Wireless Sensor Networks*", submitted to IEEE Transactions on Wireless Communications.

M.Cheikh and Yichaung Sun "*Energy Efficient Multinode Selection Algorithm for Virtual MIMO*", IEEE Transactions on Wireless Communications.

Chapter 1: Introduction

This chapter provides a brief introduction of the thesis. This includes the research motivation, research scope, problem formulation, the thesis contributions and the thesis structure.

1.1 The Evolution of Wireless Communications

Wireless networks have progressed over several generations, improving in terms of quality of services (QOS) through different aspects such as coverage area, mobility and data rate. The first generation of the wireless technologies were implemented in the 1980s, where analogue radio transmission was used to deliver basic voice services [1]. Following the first cellular system launched in the early 1979 by a Japanese company called Nippon Telephone and Telegraph [2]. However, the era of the cellular expanded into Europe few years later, with similar analogue systems such as Nomadic Mobile telephones and Total Access Communication Systems. Additionally, the Advanced Mobile Phone System was launched in the United State, offering higher data rate, handover and roaming services [3 4]. Subsequently, the second generation of mobile systems where announced around 1989, with digital capabilities introduced and enhancement in terms of the spectrum efficiency, short message services (SMS) and advanced roaming, followed by the third-generation networks providing new range of services such as video calls, and broadband wireless data with larger network capacity and improved spectral efficiency [5]. Consequently, the appearance of the fourth-generation network was triggered due to the dramatic increase in subscribers and user demand, offering higher speed data access, enhanced roaming services and broadband multimedia amongst other services, in addition of the aim to achieve IP architecture [6]. Although, the fourth generation haven't fully established yet, there are several developments in the direction of the fifth-generation wireless networks specifications in response of the enormous growth of wireless communication services [7]. However, the vision of wireless communication systems stirred from traditional cellular telephone systems toward a new class of smart electronics devices that can interact with each other in addition to providing connectivity between computers, mobile phones, monitoring systems and internet connectivity [8]. Thus, current wireless networks encompass wireless local area networks(LANs), wide-area wireless data systems, satellite systems, wireless sensor networks (WSN) and Ad-Hoc wireless networks with different coverage regions, performance requirements and different applications purpose [9]. Moreover, wireless systems allow distributed control systems with remote devices, sensors and actuators linked together via wireless channel offering new trend of wireless applications that include voice, internet access, web browsing, paging, short messaging, subscriber information services, file transfer, video teleconferencing, sensing, and distributed control [10]. However, different wireless applications have different performance requirements in terms of data rate, bit error rates (BER) and delay. Consequently, various requirements make it difficult to build one wireless standard that can satisfy all these requirements simultaneously. For example, voice systems demand low data rate (around 20 Kbps) and tolerate high probability of BER (around 10^{-3}), while data systems require minimum 1 Mbps data rate and BER around 10^{-8}. Thus, the hardware design of a wireless terminal, such as smart phone must operate in multiple modes to support different applications with different requirements, with high processing ability and very little power consumption [11]. Moreover, in wireless systems such as Ad-Hoc networks, nodes do not have regular access to charger, and the finite battery energy must be allocated efficiently across all layers which impact the wireless terminal design as different operation modes demand different signal processing techniques executed using different power levels [12].

1.2 Motivation

With the explosive growth of wireless devices technology, high data rate applications and the increase of mobiles subscribers' number in the last decades, there has been a dramatic increase in wireless data traffic [13]. Moreover, with applications such as mobile TV, video conference, multimedia streaming video sharing, online gaming and real-time services, wireless devices combine the capability of computer and the mobility of traditional cellular. Thus, to meet the user expectation additional infrastructures are required at extra cost of deployment and are considered as long-term evolution. Furthermore, with the prediction of higher growth in the future, alternative techniques have been the focus of work to efficiently use the wireless networks resources. In this regard, multiple input multiple output (MIMO), orthogonal frequency division multiple access (OFDMA) and cooperative communications have been well exploited in wireless networks and shown to be effective approaches to increase the network throughput and provide improved performance by the diversity achieved [14 15]. However, the deployment of MIMO is not always practical in wireless communications due to space limitations and the extra cost of deployment. The implementation of cooperative communication scheme, which spans from MIMO and relay channel concept, has shown as significant concept that improves the performance of wireless networks. The concept of cooperative communication has been paid increasing attention and widely studied to achieve high quality transmission by optimising the networks resources. Hence, several cooperation schemes, routing techniques and protocols have been proposed at the PHY and MAC layer showing potential advantages to meet the requirement of the future wireless communication systems [16 17 18]. In cooperative communication nodes coordinate, and cooperate reaping benefits achieved in MIMO by forming virtual relay antennas, or implementing single relay channel to forward a source signal message [19 20]. Cooperative communication schemes performance has been investigated in terms of outage probability, rate enhancement, channel capacity, power optimisation, coverage extension and others performance metrics [21].

1.3 Motivation

With different challenges in telecommunication sectors, it has been pointed that more than 2% of worldwide emission is caused by wireless communications, thus energy efficiency in telecommunication sector has attracted significant attention [22 23]. The urgent need of energy efficient communication was introduced into all wireless communication sectors, and research directions were shifted toward efficient energy communication strategies. Thus, different infrastructures, network architectures, new smart antennas, protocols, novel algorithms and new techniques were proposed in the literature. The proposed solutions lead to fundamental changes into the concept, structure of communication systems. Therefore, more attention was paid toward improving the current strategies implemented in wireless communication. Consequently, several energy efficient methods have been proposed such as Optimum resource allocation [24], energy efficient cooperation and virtual cell clustering [25]. One of the best solutions with high potential to reduce energy consumption is cooperative communication as the implementation of those schemes do not require additional infrastructure benefiting from the un-centralized architecture and the broadcast nature of wireless channel [26]. However, in wireless network mobile node operates on battery and do not have regular access to charger. The energy consumption is a vital functionality design issue especially for node equipped with finite battery capacity where the replacement is difficult or impossible such in sensor networks or Ad-Hoc networks [27]. Conversely, the benefit achieved via cooperation might come at the price of power as nodes scarify their own limited energy in cooperative mode [28]. Therefore, a trade-off between cooperation schemes and power consumption become the new design challenge in cooperative wireless networks especially with the unimpressive and slow advancement in battery technology compared with recent development in mobile technology. Hence, the question: does cooperative communication extend the battery life time of wireless mobile device?

Since wireless communication is achieved by the transmission of energy between two transceivers, the message should be received with sufficient power compared to the presence of noise, interference and other destructive components in the wireless channel to distinguish the original transmitted message (which is widely described as the signal to noise ratio (SNR). Therefore, the transmission range is the vital parameter that degrades the quality of the signal. The wireless system performance improvement when cooperative communication is implemented is mainly due dividing the transmission path into shorter links. Thus, the relay location is the major key design due to the impact on the total energy budget. This design issue is addressed by relay selection technique, whereby the node with the best link quality and minimize the total transmission distance is the optimal relay choice. Moreover, the cooperation strategy is another vital design consideration in those schemes. Thus, relay selection methods, channel condition, modulation strategy and power allocation technique are considered the fundamentals of an energy efficient cooperative communications.

1.4 Research Scope

The design of an energy efficient cooperative communication can be addressed by the necessity and benefits of cooperation, which raise the question of: when to cooperate, how to cooperate and with whom to cooperate?

First cooperation is employed when direct transmission suffers from bad link quality or transmission range limitation, then a source node might utilize a node(s) from an available set to forward the signal to the destination whereby the total transmission power budget is significantly reduced since the distances between transceivers are smaller compared to the direct transmission. Second, the cooperative node(s) selection is another consideration that covers the relay location, source-relay and relay-destination link conditions and resource allocation between involved node(s), considering the extra power consumption due to overhead signalling and additional circuit operations. Finally, to achieve better energy efficiency cooperation, modulation schemes and power allocation among participating nodes should be chosen carefully based on some system metrics.

The aim of this work is minimizing the total transmission energy cost. Hence, the proposed strategy encompasses two objectives: First, the relay selection technique jointly implemented with an adaptable power control to the system necessities. Second, the optimal cooperation strategy that encompasses the protocol and the modulation strategy.

The proposed method should be reliable, adaptive to channel condition and can be implemented in non-centralized fashion networks. In this regard, a literature review is given to understand the basic principles and implementation, advantages and drawbacks of cooperation schemes in wireless networks. This review covers the nature of wireless channel and the metrics to achieve better energy efficiency. Cooperative protocols are presented and analysed and computer simulations have been carried out to investigate the details and performance.

A relay selection method based on the optimal relay location subject to channel condition considering the circuit power consumption impact on energy consumption is proposed. Moreover, the transmission power is allocated subject to the transmission path distance and the channel condition. Furthermore, an adaptive modulation strategy is implemented, whereby the source and relay(s) switch between different modulation strategies subject to power constraint.

1.5 Thesis Contributions

The major contributions of this thesis are summarized as follows:

- An energy efficient distance based relay selection method is proposed for cooperative wireless networks, where simulation results show that the proposed method exhibits an improved energy saving compared to other relay selection methods. The performance is illustrated in terms of the energy cost per bit under bit error rate (BER) requirement for different channel models under different cooperative scenarios. A detailed explanation of the proposed method is provided in Chapter 3.
- The impact of the modulation strategy is investigated through numerical and analytical analysis and its shown that a reduction in total transmission energy cost can be achieved via the optimal constellation size selection. Numerical examples are given and significant energy saving is observed as the circuit energy consumption is minimized under different channel conditions.
- The error-correction code capability of reducing energy cost is investigated and the trade-off between transmission energy time and circuit operation time is inspected. Thus, through numerical results the correlation between transmission distance and energy consumption in coded system are illustrated.
- The energy consumption associated to the transmitting link and receiving link distances is investigated. Therefore, the transmit energy is allocated based on the path length and the channel condition. Simulation results illustrate the energy saving achieved at the source and the relay.
- An energy efficient distance based relay selection method is implemented in line with the optimal transmission strategy. This encompass, the link quality impact on energy cost evaluated through a predefined SNR threshold. Thus, relay(s) switch(s) between coded and uncoded system and implement the optimal modulation strategy.
- The proposed single relay selection method is extended to cooperative wireless networks where multiple relays forward the source signal. The approach is to integrate the concept

of single relay selection method and employ the selection metric in virtual MIMO systems where multiple relays participate in the transmission. Thus, the generalized distributed space-time coding (DSTBC)scheme is implemented jointly with the proposed energy efficient relay selection method. The proposed scheme achieves better performance in terms of energy consumption under BER requirement.

- Inspired by cell size optimization, the proposed relay selection algorithm is implemented in clustered wireless networks that require low latency. Multi-clustering technique is proposed to minimize the energy consumption under delay and BER constraints. In this regard, the modulation strategy and its impact on energy saving is investigated and MFSK and MQAM modulation strategy are considered.

1.6 Thesis Outline

The rest of the thesis is organized as follows:

In Chapter 2, an overview of cooperative communication concept, protocols and relay selections techniques is given. This includes the wireless channel characteristics and the wireless system parameters affecting the performance in terms of energy consumption. Moreover, the fundamental of energy efficiency in wireless communication is presented through analytical analyses.

In Chapter 3, the proposed energy efficient single relay selection method is given. For this purpose, the closed bit error rate (BER) expression form for coded and uncoded system in AWGN and Rayleigh fading channel is derived using MQAM modulation. Energy consumption closed form is derived, and the relay selection algorithm is presented. Performance of the proposed algorithm is compared with different techniques through results and simulations.

In Chapter 4, the concept of distributed Space-Time Block Code (DSTBC) in cooperative network where multiple relays participate in the transmission is presented. The energy efficiency relay selection algorithm is extended to wireless system where virtual MIMO is implemented. The energy consumption for different MIMO operation modes is derived and its show through simulation results the improvement in terms of energy saving of the proposed algorithm.

In Chapter 5, an energy efficient multi-clustering method jointly implemented with relay selection is proposed. For this purpose, a brief overview of clustering concept and techniques are given. Moreover, the energy consumption cost for MQAM modulation and MFSK modulation in AWGN are derived. The proposed algorithm outperforms traditional multi-hop transmission in terms of energy saving which is illustrated through simulation results.

Chapter 6 concludes this thesis where a summary of the thesis and the future research to be carried out are given.

Chapter 2: Concept of Cooperative Communication

In this chapter, an overview of cooperative wireless networks is given. It covers the wireless channel characteristics, cooperative communication concept and protocol of relay channel. Thus, the performance of AF and DF is investigated and illustrated through simulation results as the basis of the proposed algorithm. Moreover, the fundamental of energy consumption in cooperative communications is given.

2.1 Characteristics of Wireless Channel

In contrast to wired channel, the wireless channel is dynamic and unpredictable, which makes the analysis of a wireless communication system performance difficult. Thus, wireless channel characteristics ruled by the wireless channel atmosphere, is considered as the vital design key of any high performance wireless technology which is illustrated by the behaviour of the transmitted radio waves. In wireless medium, radio waves propagation is mainly affected by three different physical phenomena's: diffraction, scattering and reflection shown in Figure 2.1[29 30]. Diffraction occurs when the radio path between the transceivers is obstructed by sharp irregularities surfaces generating secondary waves of the original transmitted signal. In Scattering phenomena, the radio waves are deviated from the straight path by at least one small dimension obstacle compared to the wavelength. While in reflection phenomena, an object with very large dimensions compared to the wavelength deviate the radio waves. Thus, the propagation of a radio wave is an unpredictable process that is governed by different phenomena's and with variable intensity correlated with the environments and the times causing multiple copies arrival of the original signal at the receiver side.

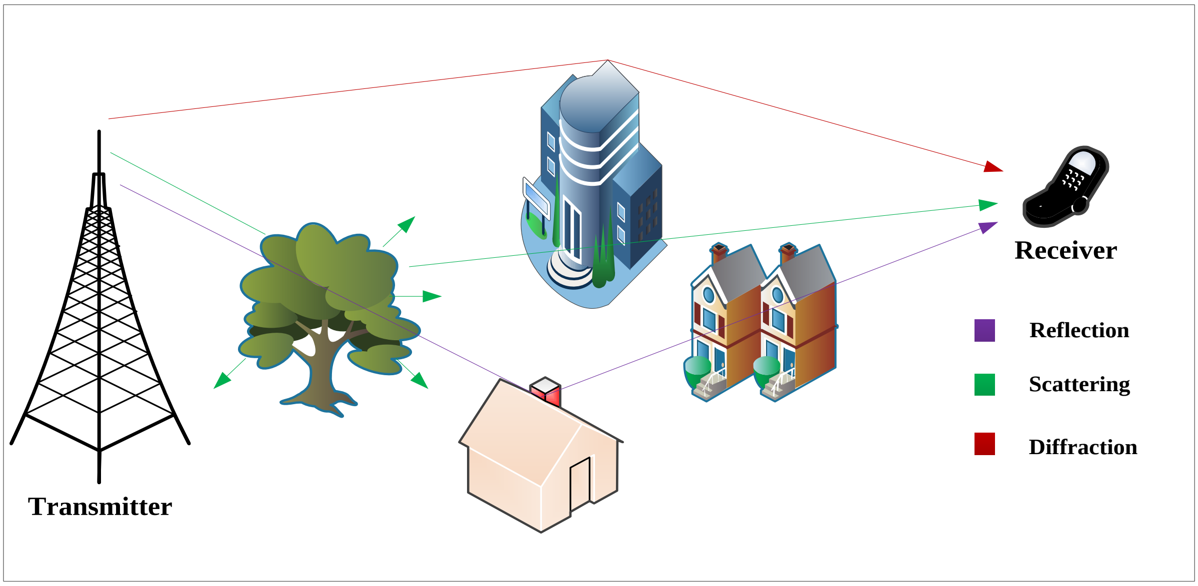


Figure 2.1: Multipath Fading Environment in Wireless Channel

Moreover, fading is another source of signal degradation in wireless channel causing a variation of the signal amplitude over time or/and frequency. Fading phenomena is characterized as a non-additive signal disturbance due to multipath propagation and is classified into two categories: large-scale fading and small-scale fading [31 32]. Large-scale is characterized by the average path loss due to the mobility of the wireless device over large distance and shadowing caused by large objects. On the other hand, small-scale fading refers to rapid variation of the signal strength due to the interference caused by multiple copies of the signal arriving from different paths over short mobile movement distances. In those phenomena's, different corrupted copies of the original transmitted signal message will arrive at the receiver at different time intervals leading to erroneous detection and recovery of the transmitted signal. Diversity techniques, such as spatial frequency and temporal frequency were employed in wireless systems to turn negative multipath effects into advantages [33 34 35]. Spatial diversity has been exploited by MIMO systems due to the simplicity of implementation and guaranteed diversity by the multipath experienced through different fading conditions.

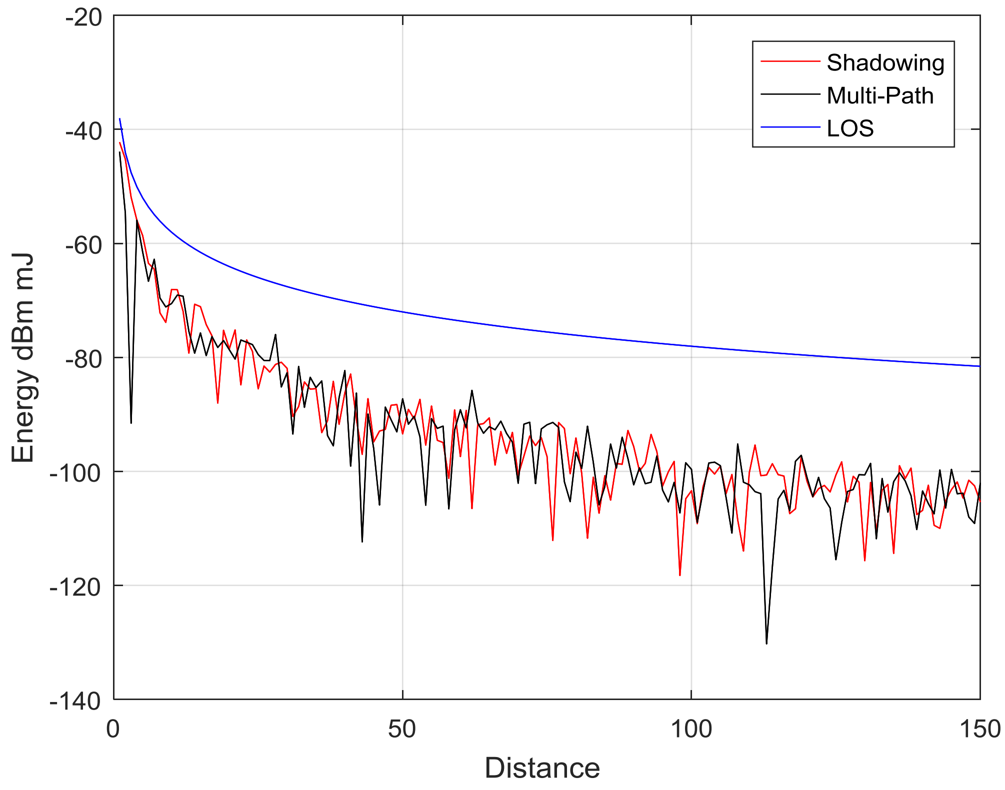


Figure 2.2: Signal Power Degradation in Wireless Channel vs Distance (Meters)

As shown in Figure 2.2, the signal power degrades monotonically with the transmission distance due to the random nature of fading eventually distorting the signal at the receiver side. Thus, the signal should be transmitted with sufficient power to guarantee a desired power level for correct decoding of the original message. In other words, the margin that guaranteed the received signal power above a given power threshold at the receiver side to achieve the required performance. Path loss is another vital factor that affect signal power strength, accounting all the gains and losses through the wireless channel between transceiver.

2.2 Cooperative Relay Network Concept

Inspired from the diversity achieved via MIMO techniques, cooperative communication concept was introduced into wireless network such as cellular and Ad-Hoc where the deployment of multiple antennas is difficult due to space limitation [36]. In cooperative communication, the transmitting node exploits the presence of available neighbourhood nodes capable of forwarding the signal towards the destination node. In these schemes, cooperative nodes might operate using different approaches, and single or multiple nodes participate and forward the source signal either by forming a virtual antenna array, or through single or multiple hops transmission. Cooperative communication schemes shown to be a significant concept that improve the performance of wireless systems in terms of outage probability, rate enhancement, channel capacity, power optimisation and coverage extension. Moreover, due to the dependence of the signal received power on the transmission distance even in straight line propagation without obstructions between transceivers, cooperative communication overcomes the transmission range limitation as the transmission path is divided into shorter paths. The concept of cooperative relay network introduced by Laneman et al and Sendonaris [37], based on the work of cover and El Gamal [38], has attracted considerable interest showing a high contribution in wireless system performance at low cost and complexity. The relay channel shown in Figure 2.3, is a topology used in wireless system where two nodes are interconnected by an intermediate node, the relay. The implementation of relay channel extends the coverage and combat the effect of shadowing through offering alternative paths with better link quality.

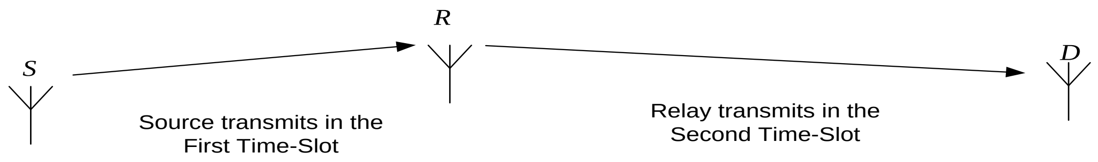


Figure 2.3: Relay Channel in Wireless network

The implementation of relay channel in cooperative communication, significantly differs from traditional fixed relaying concept as wireless terminals are expected to perform the task of cooperative agent in addition of transmitting their data as illustrated in Figure 2.4. Thus, the relay can be a transmitting source and/or a relay.

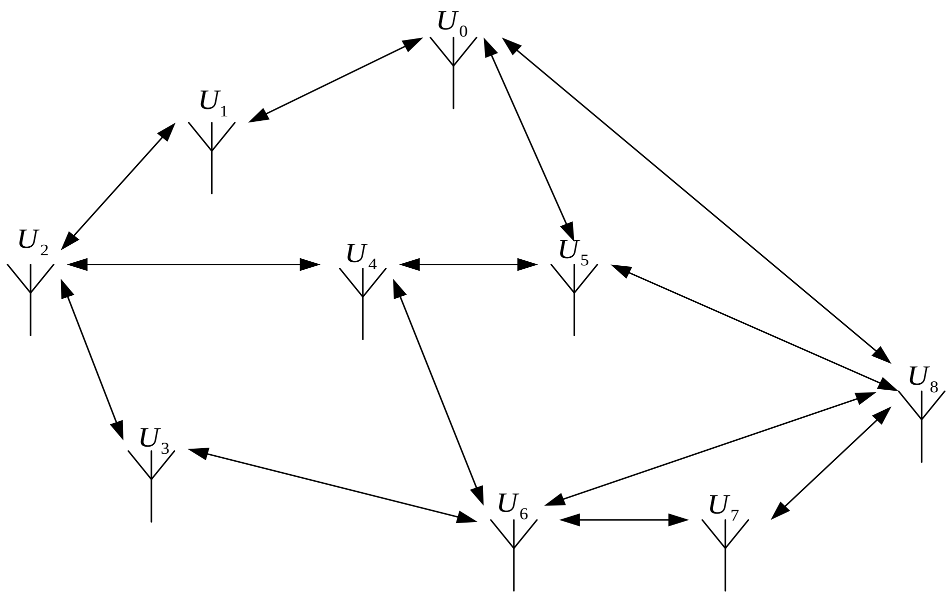


Figure 2.4: Cooperative Communications in Wireless Network

Figure 2.5 illustrate different relay channel implementation in cooperative network, where the source(s) forward(s) the signal through a vacant relay node(s) implementing different cooperation strategy. Moreover, the relay channel consists of two types: half-duplex and full-duplex. Half-duplex is the most popular scenario due to simplicity, where the relay can't transmit and receive at the same time. Full-duplex mode requires more synchronization, as the relay receives and transmits at the same time. An example of Half-duplex operation is illustrated in Figure 2.2, when R_2 forwards U_1 signal towards D,and can be expended to bidirectional transmission where two nodes communicate simultaneously utilizing the same relay such when U_1 and D use R_5 which improve the throughput Moreover, multi-hop transmission, Virtual MIMO transmission are employed in cooperative communication which are subject to system requirements. Multi-hop is an efficient technique to contend with shadowing and is mainly implemented in WSN.

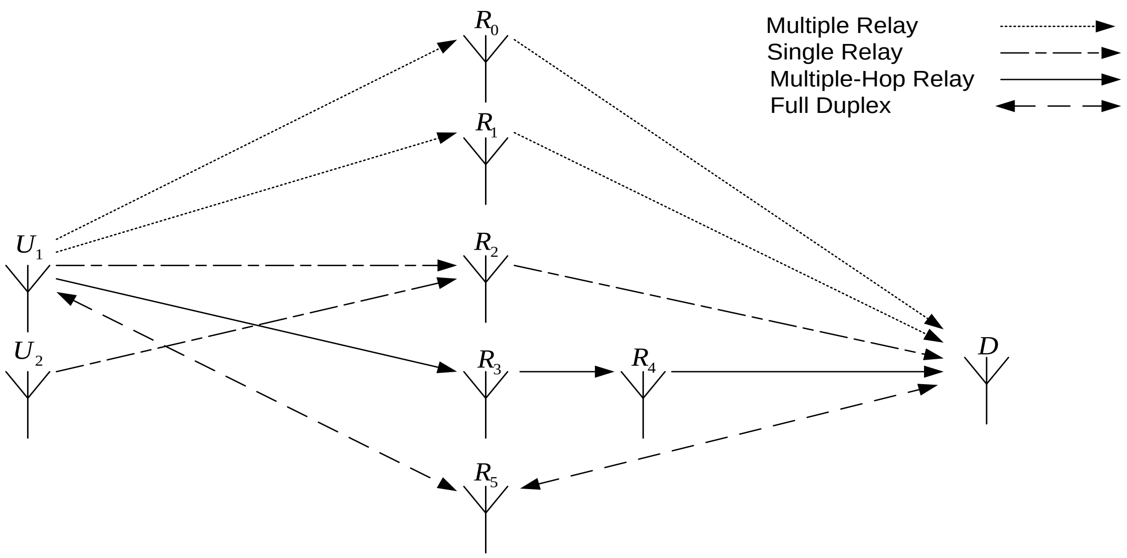


Figure 2.5: Relay Channel in Cooperative Wireless Network

An example of multi-hop transmission is given in Figure 2.5, where R_3 forwards U_1 signal to R_4 that forwards the signal to D. Virtual MIMO is used when the channel suffers from poor capacity, therefore the destination receives the source signal through multiple relay such as in the scenario where R_1 and R_2 forwards U_1 towards D. Furthermore, spectrum efficient is improved when the relay forwards multiple sources signal, which is implemented in clustered WSN. This scenario is illustrated when R_2 forwarding U_1 and U_2 signals after performing data aggregation. Cooperative communication schemes improve the wireless network performance in different aspects with an energy penalty observed in the synchronization and the additional circuit processing. The point to be made is that the performance improvement achieved via cooperation come at the cost of extra signalling, and an increase in circuit operations time. Thus, cooperative protocols should be carefully designed to enable users to forward other users signal in addition of transmitting their own data, with minimum complexity and latency. In addition of that, relays should operate with minimum power as they sacrifice their limited energy to enhance others terminal transmission. In summary, cooperative communication leads to interesting trade-offs in QOS and energy cost.

2.3 Protocols

In cooperative communication, relay channel is implemented using different protocols such as Estimate and forward (EF) and Compress and forward (CF), Decode and Forward (DF), and Amplify and Forward (AF) [39]. In EF relay retransmits the estimated signal without coding procedure, while in CF the relay transmits a sampled and compressed version of the received signal. However, the most popular protocols are DF and AF due to the simplicity of implementation [40]. In AF, the relay forwards an amplified version of the received source message without performing signal processing, while in DF protocol the relay transmits an encoded version of the source message. The major drawback of AF protocol is the amplified noise at the relay. Thus, in the case of weak source-relay channel, a high probability of an error propagation toward the destination due to false detection of the original signal message at the relay. To illustrate and compare AF and DF performance, the scenario given in Figure 2.3 used where the communication occurs over two-time slots. Its assumed that the relay is centred between the source and destination for a line of sight (LOS). The source broadcasts the message in the first-time slot and the relay forwards the received message in the second-time slot using either DF or AF. Its assumed that channels capture the multipath effect and remains coherent over the transmission time interval. h_{sr} , h_{rd} and h_{sd} present the source-relay channel, the relay-destination channel and the source-destination channel. P_r , P_b and N_0 represent the source transmission power, relay transmission power and the noise spectral density assuming a white Gaussian noise with variance and zero mean σ^2 . n_{rd} and n_{sr} are the noise captured by the relay-destination channel and source-relay channel respectively. Equal power allocation between the relay and the source and 4-QAM modulation are implemented. In the proposed scenario, the source transmits S_i and the received signal at the relay given by

$$S_r = h_{sr} S_i + n_{sr} \tag{2.1}$$

In AF protocol, the relay forwards an amplified version the signal, where the amplification factor β given in (2.2) [41]. While in DF protocol, the relay transmits an encoded version and the received signal at the destination for AF and DF are given in (2.3) and (2.4) respectively. The received SNR y at the destination used to evaluate the BER is calculated using equation (2.5) and represent the ratio of the signal transmit power to destructive factors in the wireless channel.

$$\beta = \sqrt{\frac{P_r}{(h_{sr}{}^2 P_s) + N_0}} \tag{2.2}$$

$$S_d = h_{rd} h_{sr} \beta S_i + n_{rd} \tag{2.3}$$

$$S_d = h_{rd} \tilde{S}_i + n_{rd} \tag{2.4}$$

$$\gamma = \frac{p_t \left|h_{ij}\right|_F^2}{p_n} G \tag{2.5}$$

P_t and P_n are the transmit signal power and noise power at the receiver side, and $\left|h_{ij}\right|_F^2$ is the Frobenius form of the channel matrix given in (2.6). G reflect the degradation of the signal transmit power with respect to the link budget given in (2.7)[42].

$$\left|H\right|_F^2 = \left|h_{sd}\right|_F^2 + \left|h_{rd}\right|_F^2 \tag{2.6}$$

$$G = -10\log\left(\frac{\lambda}{4\pi d_0}\right)^2 + 10\varepsilon\log\left(\frac{d}{d_0}\right) \tag{2.7}$$

λ , d_0 and ε are the wavelength, reference distance and the path loss exponent respectively. The SNR at the destination for DF and AF are given in (2.8) and (2.9) respectively [43].

$$\gamma_{DF} = \frac{p_r \left|h_{rd}\right|^2}{p_n} \tag{2.8}$$

$$\gamma_{AF} = \frac{\gamma_{sr}\gamma_{rd}}{1+\gamma_{sr}+\gamma_{rd}} \tag{2.9}$$

Its assumed that the source and the relay transmit power is set to 20dBm and the noise power is -174dBm/Hz. As in [44], the BER for M-QAM in Rayleigh fading channel is evaluated by

$$BER(\gamma) = 0.2\exp\left(-\frac{3}{2}\frac{\gamma}{2^b - 1}\right) \tag{2.10}$$

From Figure 2.6, it can be observed that DF and AF performance in terms of BER is undistinguishable at SNR below 12 dB, while DF outperforms AF at an SNR above 15 dB.

Moreover, 10−3 BER is achieved at approximately 20dB SNR for DF protocol, while 30 dB is the desired SNR threshold for AF protocol.

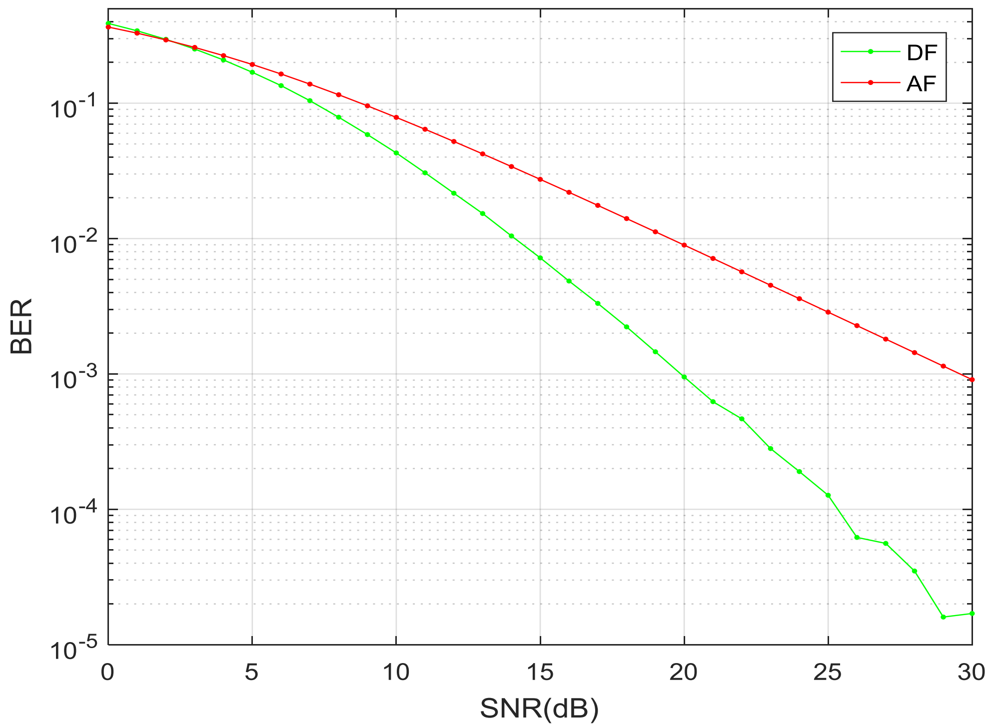


Figure 2.6: AF and DF BER performance vs SNR

From Figure 2.7 it can be clearly seen that DF outperforms AF in terms of the received SNR at the destination at different transmission distance which leads to better performance in terms of BER. Moreover, from Figure 2.8, DF outperforms AF in terms of the BER achieved at different transmission distance. In Summary, AF and DF performance depends on the link qualities. AF has the advantage of low complexity, while DF precluded the received noise at the relay. Moreover, relay implementation raises the task of selecting the best relay, thus relay selection schemes have been proposed for different performance requirement. To enhance the system performance, selective relaying, incremental relaying, adaptive relaying and selective DF protocols has been proposed in the literature.

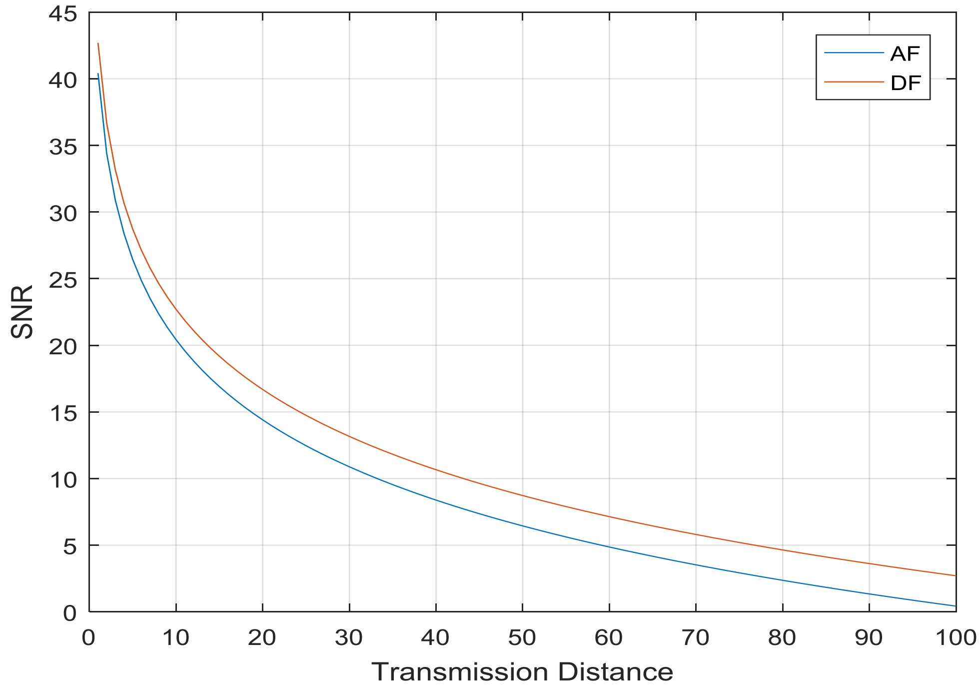


Figure 2.7: AF and DF SNR Degradation vs Distance (Meters)

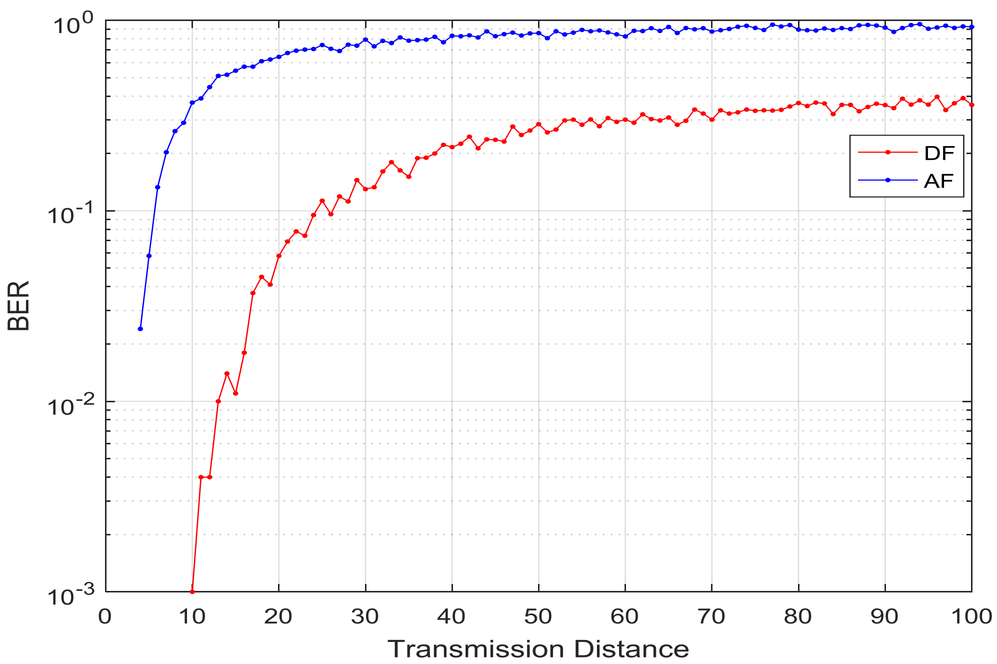


Figure 2.8: AF and DF BER performance vs Distance (Meters)

2.3.1 Relay Selection in Cooperative Communications

As relay channel implementation enhance the wireless system performance via the diversity of links that can provide a desired SNR at the receiver, relay selection has been investigated and different selection techniques have been proposed in the literature such as opportunistic relaying (OR), partial selection (PS) and best relaying (BR) [44 45]. Although relay selection schemes have and shown to be an effective approach to enhance wireless system performance, an energy penalty is observed due to additional nodes involvement in the transmission. Thus, from energy minimization perspective, different relay schemes were triggered and different selection methods were proposed [46 47 48 49]. Moreover, energy efficiency has been triggered by proposing routing and clustering techniques in WSN where node operate on battery without access to charger [50 51 52 53]. In summary, relay selection shown to be an effective technique to minimize power consumption if the network resources are optimised. Subsequently, the cooperation strategy should comprise all the parameters that affects the transmission energy cost. Thus, power allocation has been studied separately and jointly with relay selection under some performance requirements. The proposed power allocation strategy in [54] is based on achieving the target BER and SNR at the destination, where nodes having less noise and more capacity on their channel are allocated more power as they deliver signals more efficiently. In [55], the author proves that two-way relay transmission schemes (TWRT) are more energy efficient compared to direct transmission and one-way relaying. The optimal location of the relay in TWRT was investigated under total transmission rate jointly with power allocation [56] while in [57] the relay location was used to distribute power among nodes. In the same context, modulation strategy and coding are considered as energy is correlated to the bitrate [58]. Moreover, a feed back to switch between different transmissions modes was proposed in [59].

2.4 Power Consumption Fundamentals

From Figure 2.9, the power consumption in an RF transmitter consists of two components, the power amplifier P_{PA} and the circuit power P_c [60]. The first depend on link while the second is estimated based on the model used. Thus, the total transmission energy cost in a relay channel is given by

$$E = n\frac{(P_c + P_{PA})}{R_b} \tag{2.11}$$

where R_b and n are the system bit rate and the relay number respectively. These parameters are the vital design key of any energy efficient cooperative system. P_{PA} is minimized by targeting the link quality and transmission distance while R_b is addressed through modulation and coding. n is optimized by using the minimum number of relays for a target performance. In cooperative communications, the power problem can be formulated into two correlated sub problems: power saving and power control. The aim of power saving is to decrease power consumption by switching between different stats, and its addressed at the MAC layer where nodes are put into idle or sleep mode [63]. Power control is addressed at the PHY layer where nodes adjust the transmit power subject to a desired power level at the receiver. Furthermore, the number of relays, relay location, overheads and the protocol are critical key design to achieve an energy efficiency cooperative communication [61 62].

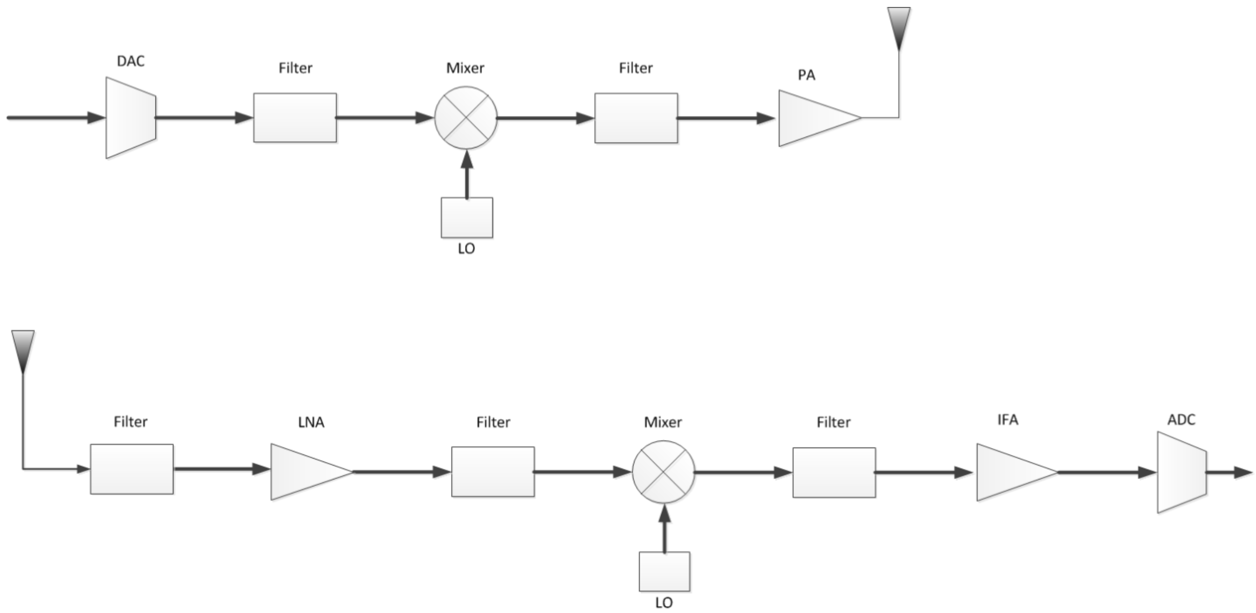


Figure 2.9: Transceiver block of RF chain

For a fixed rate system, the bit rate R_b is allied to the symbol rate R_s and the modulation strategy, thus the number of bit per symbol b is another optimisation parameter.

$$R_b = bR_s \tag{2.12}$$

To illustrate the relation between the transmission distance, modulation strategy and energy consumption for the scenario given in Figure 2.3 in DF cooperative mode, and we set a target BER of 10-3 at the destination, which require different SNR for different b. Using equation (2.10), and performing mathematical manipulation, the required SNR is given by

$$y = \frac{2}{3}(1-2^b)\ln(\frac{BER}{0.2}) \tag{2.13}$$

Using equation (2.8) in equation (2.12), the required power to achieve the required power level at the receiver for the target BER is given by

$$p_t = \frac{2}{3}(1-2^b)\ln(\frac{BER}{0.2})\frac{p_n|h_{rd}|^2}{G} \tag{2.14}$$

for fixed rate system, R_b equal the bandwidth B , $R_s = bR_b$, the energy per bit is given by

PhD Thesis by Mohamad El Cheikh,
School of Engineering and Technology, University of Hertfordshire, Hatfield, UK.

$$E_b = \frac{P_t}{R_b} \quad (2.15)$$

It can be clearly seen that energy consumption is correlated to b and the distance as for the same transmission distance, higher b elevate energy consumption per bit. Increasing the number of bit per symbol through modulation, decrease the transmission time and elevate the energy consumption. Thus, the modulation strategy is a vital key design to achieve an energy efficient cooperation. Moreover, the ratio of the received power to the transmitted power depends on the signal wavelength proportional to the carrier frequency. Thus, at high carrier frequency, the received signal power decrease faster. Figure 2.10 illustrates the relation between energy cost per bit, constellation size and transmission distance, where equation (2.14) is used to evaluate in the energy cost in an ideal scenario for a 10^{-3} target BER.

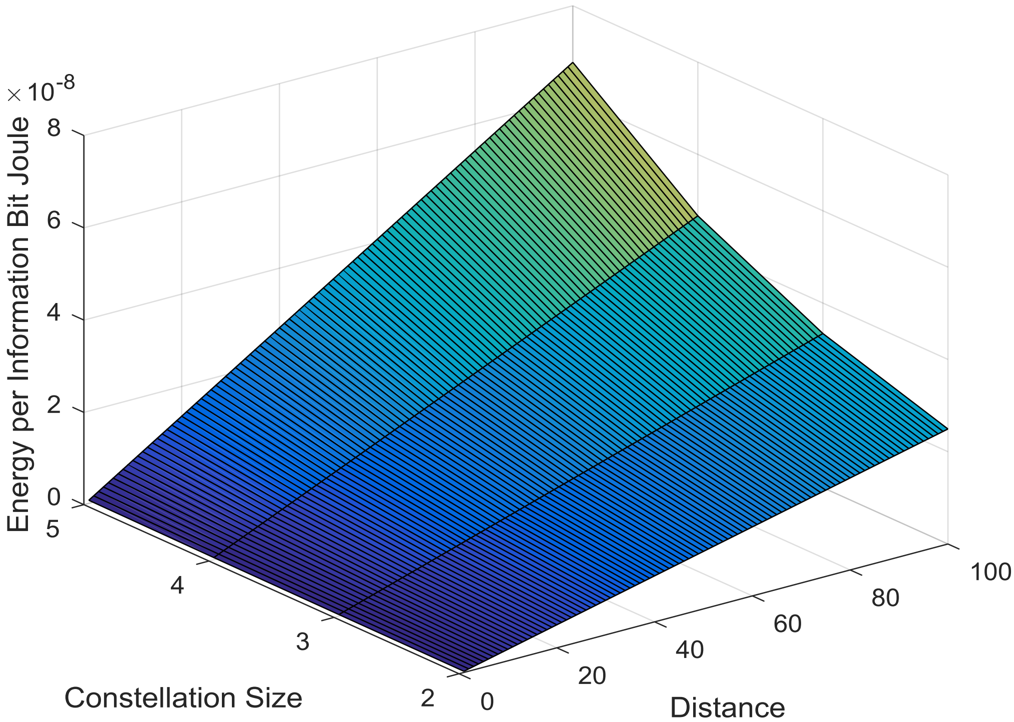


Figure 2.10: Energy Consumption vs Constellation Size vs Transmission Distance (Meters)

As most wireless systems are assigned a fixed frequency band, minimizing the total transmission power while maintaining a required power level at the receiver can be achieved by dividing the link into several shorter links. Thus, forwarding the signal through intermediate node decrease the transmit power for shorter distances between the transceivers, as its inversely proportional to the required power at the receiver. To investigate cooperative communication performance in terms of energy consumption, the model in Figure 2.4 is used, where the source communicates with the destination using direct transmission or through an intermediate relay implementing DF protocol. Equation (2.14) is used to calculate the energy consumption per bit for a target 10-3 BER. Figure 2.11 considers a comparison of direct transmission with DF by plotting the energy cost in dBm mJ against the transmission distance in meters for different constellation size. DF outperforms direct transmission in terms of energy consumption for the same constellation size and transmission distance. An interesting observation is that direct transmission using less number of bits then DF is more energy efficient. For example, direct transmission $(b=2)$ outperforms DF $(b=5)$ by 4dB. From an information theoretic perspective, higher modulations are less resilient to noise and needs higher signal to noise ratio to decrease the error probability. Therefore, requires higher signal power level at the receiver side to meet the SNR threshold for a target BER. Although, higher modulation minimises the circuit operation time, it decreases the transmit power. Therefore, to achieve an energy efficient communication, adaptive communication strategy is implemented subject to system performance requirements. Moreover, in short-range transmission where the circuit energy consumption is nonnegligible compared to the transmit energy, the total energy consumption is minimized by using the maximum system bandwidth through higher modulation. In this situation, the transmit energy consumption is less dominant in the total energy cost. This is because, the required transmit energy proportional to the distance between transceivers increase gradually following the link budget formula.

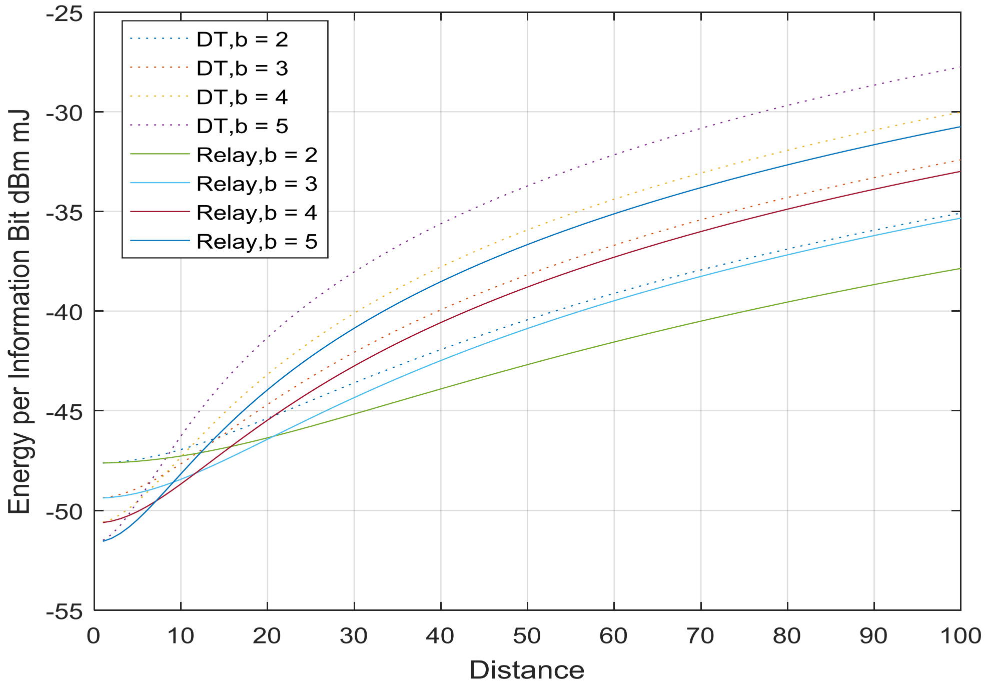


Figure 2.11: Energy Consumption of Relay Channel vs Direct Transmissionat Different Distance (Meters)

2.5 Summary

Energy efficiency became a standard design activity with huge potentials towards developing and improving current methods implemented in wireless systems without scarifying quality of service. However, cooperative communication schemes shown to be an effective low cost and low complexity solution where relay selection methods, power allocation, number of relays, adaptive modulation, clustering and cross layer design are the core of cooperation. Thus, those techniques are investigated from energy efficiency prospective in contrast to traditional research, where the aims are improving system performance in terms of throughput, channel capacity, latency etc. However, energy efficiency in cooperative networks is still an open issue but it has shown faster improvement compared to other solutions such as smart antennas, alternative infrastructure etc, seen as long terms evolution [64].

Chapter 3:Energy Efficient Relay Selection for Cooperative Wireless Networks

In this chapter, an energy efficient relay selection algorithm for cooperative wireless network is proposed. The energy cost per bit for coded and uncoded system in AWGN and Rayleigh fading channel is derived. The impact of coding gain and modulation strategy are investigated and the optimal solution is jointly implemented with the proposed distance based relay selection method. The proposed algorithm performance is compared to different relay selection techniques showing better performance in terms of energy consumption per bit.

3.1 Introduction

Relay selection methods have been implemented in cooperative communication networks to improve the wireless system performance in different criteria's, such as throughput, channel capacity, outage probability and coverage extension [65]. However, achieving high performance wireless system is correlated with the required power level at the receiving node and depends on the SNR at the receiver. For example, the capacity of relaying schemes in cooperative network depends on the received SNR using either DF or AF as seen in equation (3.1) [66]. Moreover, the relation between the achievable transmission rate under a transmit power $P_T = PG$ is evaluated in equation (3.2), where P and G are the received power and pass loss factor respectively [67].

$$\begin{aligned} C_{DF} &= \frac{1}{M}\log_2(1+\min\{\gamma_1,\gamma_2,....\gamma_M\}) \\ C_{AF} &= \frac{1}{M}\log(1+\gamma_{total}) \end{aligned} \tag{3.1}$$

$$R = W\log_2(1+\frac{P}{WN_0}) \tag{3.2}$$

Relay selection schemes were investigated from different performance perspectives under power constraint [68]. In [69], one-bit feedback to estimate the link SNR with a predefined threshold was proposed to select the relay under power constraint. Under outage probability constraint, the proposed relay selection method uses SNR threshold at the first hop, to achieve power saving through switching off relay with SNR below the threshold [70]. In [71], end to end SNR threshold was proposed to minimize network power consumption under throughput constraint. The method proposed in [72] addresses energy saving under data rate constraint. In this method, the energy level of candidate relays has been considered in the selection metric, to extend the whole network life time. In [73], power saving is triggered under time constraint. Moreover, energy efficient relay selection schemes were proposed for cooperative networks, using different selection metrics such as maximizing the SNR at the destination, choosing the hop with the best channel condition [74 75]. Furthermore, relay selection schemes and their impact in terms of the additional energy cost per transmission have been triggered from battery life perspective in [76 77]. Furthermore, relay selection based on the Channel State Information (CSI) is proposed in [78], while in [79], finite CSI is feedback to the transmit cluster to select a node with the best channel condition. Additionally, energy efficiency has been addressed by a minimum distance relay selection method in [80]. In addition to that, a relay selection method based on the relay location has been suggested to minimize Symbol Error Probability in [81]. Correspondingly, Energy efficiency was approached through power allocation in [82], where the authors propose minimizing the transmit power subject to mean square error target, while in [83] the authors allocate transmit power based on BER requirement. Comparatively, relay selection based on the optimal transmission distance, and the residual energy of the nodes has been proposed as a routing technique to extend the network lifetime in [84]. Maximizing the SNR is the core of the relay selection method in [85], by via virtual MIMO transmission between clusters. Furthermore, the relay location impacts on Energy efficiency has been investigated in [86], and single relay selection and multiple relay selection methods were proposed based on the relay distance to the source and destination. Likewise, the impact of the relay location on Energy efficiency has been studied in [87 88], from power minimization perspective by using fair power allocation among nodes. In Cooperative communication, the relay channel implementation mitigates the negative impact of path loss as the transmission topology is based on shorter links. The exploitation of multiple nodes in cooperative network is inevitable to provide higher reliability communication via the diversity of path available with different lengths and channel conditions, which improves the wireless system performance in terms of energy efficiency. Nevertheless, to achieve an energy efficient cooperative communication, relay selection should be jointly implemented with system optimization parameters to preserve high performance. Hence, the channel condition, modulation strategy, signalling overhead should be considered in the optimization policy. Benefiting from the broadcast nature of the wireless medium, we propose an energy efficient single relay selection algorithm, where the node with the minimum two path lengths forwards the source signal. The core of the proposed methods is minimizing the energy cost per bit, thus we address power saving by selecting the relay that offer a minimum total transmission path subject to system performance requirements. Furthermore, we investigate the modulation strategy impact on power consumption through numerical analysis and propose the optimal solution. In addition of that, we consider coded and uncoded system, and show their impact on energy consumption. Additionally, the channel gain is considered via the SNR threshold at the relay, whereby the successful relay mitigates the negative impact of the channel gain by adjusting the transmit power to meet the required SNR at the receiver side. Thus, different channels are considered for different transmission range. In comparison to [89], where the energy consumption per unit hop is minimized, we implement similar concept but the energy cost is calculated based on a target BER at the destination and the transmission range length. In contrast to [90], we select the relay under non-ideal scenario where the partial channel information is considered. As in [91], we benefit from the RTS/CTS signalling to select the best relay, but we allocate the power based on the transmission distance to minimize the total energy cost per bit. In contrast to [92], we investigate and choose the optimal modulation strategy before setting the SNR threshold. Relay selection has been intensively studied in the literature from energy efficiency prospective such as in [9394], or by using virtual MIMO as in [95 96 97]. To the best of our knowledge the relay location has not been proposed as selection metric with complete framework taking into consideration the modulation strategy and the channel gain impact on the total transmission energy cost.

The contributions of this chapter can be summarized as follows:

- In the literature, energy saving has been addressed at the relay or at the source, we consider minimizing the energy cost at the relay and at the source to minimize the total energy cost.
- All the signal processing blocks are considered to illustrate the trade-off between transmission energy cost and the circuit energy cost and the best modulation strategy is selected using numerical analysis. Thus, the relay and the source use the optimal modulation strategy.
- The effect of coding in terms of the transmission time expansion and its effect on energy consumption is considered. Hence, coded and uncoded MQAM and the energy consumption in correlation to the transmission distance are addressed. The relay and the source switch between coded MQAM and uncoded MQAM to minimize the energy cost.
- The channel gain impact on the total energy cost is studied, thereby allowing the relay and the source to adjusts the transmit power to restrain the harmful impact of the

channel gain. The source and relay estimate the channel gain from the packet exchange at the cooperation phase.

- A complete energy efficient relay selection algorithm implemented in line with the optimal communication strategy is proposed for AWGN and Rayleigh fading channel.
- Less complex adaptive solution to channel condition is proposed, as the selection is made at the relay in non-centralized manner without the need of additional signaling that escalate the energy cost.

The rest of the chapter is organized as follows: In Section 3.2, the system model and the proposed scenario are given. In Section 3.3, the signal behaviour in the wireless channel is analysed in terms of strength degradation over distance, and the impact of cooperation strategy on energy consumption are given. In Section 3.4, the energy cost affecting factors are elaborated, and the total transmission energy per bit are evaluated for AWGN channel and Rayleigh fading channel for coded MQAM and uncoded MQAM. In section 3.5 the proposed relay selection algorithm with link performance is given. In this regard, the impact of relay location, constellation size and coding gain are investigated through numerical example and the optimal solution is given is given. The performance of the proposed method is illustrated and compared to other methods through simulation using numerical values. In Section 3.6, the results are given in terms of the energy cost per bit, total energy cost per transmission to shows the improvement of the network performance in terms of energy saving. Finally, we conclude this chapter in Section 3.7.

3.2 System Model

We consider the network model shown in Figure 3.1, where two wireless nodes are connected through an intermediate node (the relay). In the proposed scenario, 100 wireless nodes are randomly deployed over $300m^2$ square network grid. Nodes operate in half-duplex mode and the reciprocal channel between nodes is similar in both directions. We assume nodes have all the network information, such as all the nodes coordinates on the network grid, and transmission time slot.

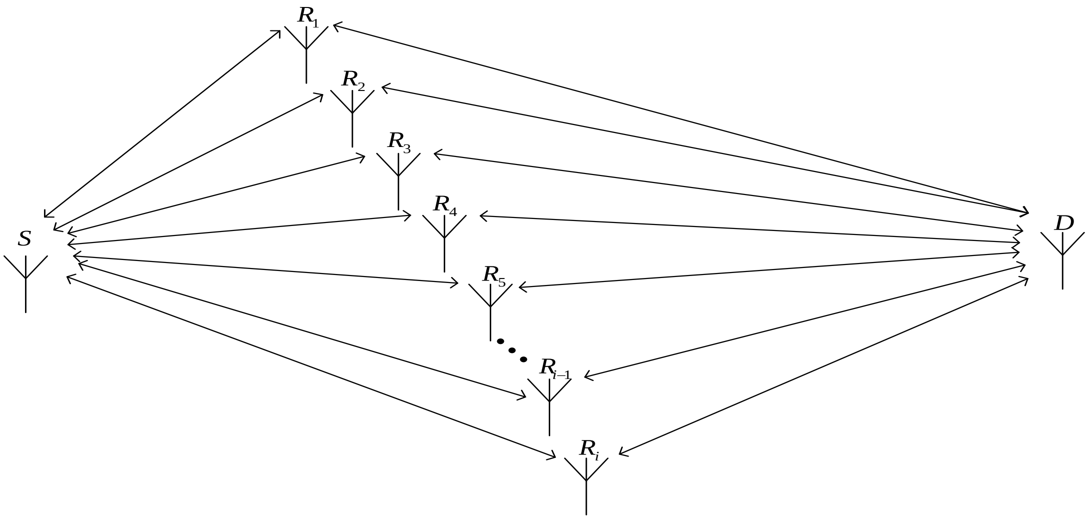


Figure 3.1: The Proposed Cooperative Network Scenario

We consider the cooperative scenario where the source (S), communicate with the destination (D) through the help of single relay (R). S transmits the message and the relay forward the signal using DF protocol, and the signal received at R and D are given by

$$S_R = h_{SR}\sqrt{E_{S_1}}S_1 + n_{SR}$$
$$S_D = h_{RD}\sqrt{E_{S_2}}S_2 + n_{RD}$$
(3.3)

Where h_{SR}, h_{RD} denotes the channel coefficients of $S-R$ and link respectively, with zero-mean and unit variance complex Gaussian random variable. n_{SR}, n_{RD} are the additive white Gaussian noise with average power spectral density N_0, with zero-mean and unit-variance. $\sqrt{E_{S_1}}$ and $\sqrt{E_{S2}}$ are the energy per symbol at S and $\boldsymbol{R}$.

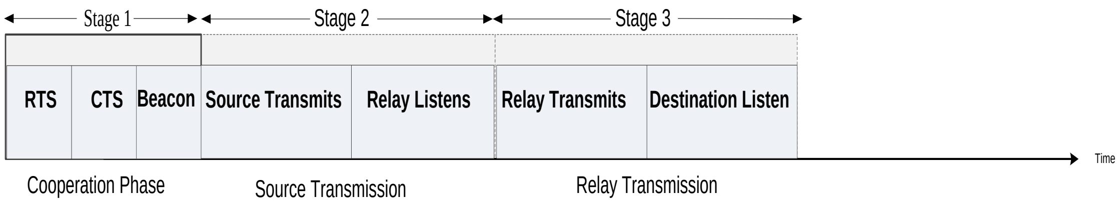


Figure 3.2: Cooperative Transmission Procedure

The communication implements time division multiple access (TDMA) shown in Figure 3.2 which comprises of three phases; cooperation phase, source transmission phase and relay transmission phase. In the cooperation phase, subsequent to RTS/CTS packets exchange between the source and the destination the relay selection take place. We implement selective DF whereby nodes that successfully decode RTS and CTS packets compete for the relay task subject to distance based threshold. The selected relay listens to the source transmission at Stage 1, and retransmits an encoded message at Stage 2. A complete synchronization between candidate relays is assumed, where the successful relay broadcast the Beacon message with sufficient power to reach all the candidate relays which omit any possibility of collision. Moreover, the source and destination exchange the RTS/CTS packets with sufficient power estimated based on the direct link path length. The proposed scenario is applicable for distributed wireless Ad-Hoc network and can be expended for any cooperative wireless system taking into consideration the systems provision such as the frequency operation bands, hardware architectures and performance requirement.

3.3 Transmission Distance Impact on Energy Cost

3.3.1 Signal Strength Degradation

For wireless system designs, a simple model that captures the essence of signal propagation without resorting the channel characteristics is the path loss model commonly used to illustrate the power degradation as a function of distance. The popular model to compute the ratio of the transmit to receive power is the Free-Space Path Loss given in equation (3.4), where the signal propagates along a straight line between transceiver without obstruction.

$$\frac{P_r}{P_t} = \left(\frac{G\lambda}{4\pi d}\right)^{\alpha} \tag{3.4}$$

However, the pass loss exponent changes subject to the propagation environment, antennas height and frequency, and tend to increase with the obstructions in the transmit path, which escalate the ratio of the received-to-transmit power. Figure 3.3 shows the ratio of the received-to-transmit power in dB against the distance in meters assuming unit power per meter, normalized antennas gain and path loss exponent α of 2 with no obstruction in the transmission path. It is obvious, that the path loss effects decrease by reducing between transceiver as the signal power degrades relatively to the signal wavelength λ and antennas gains G and it is inversely proportional to the square of the distance. Moreover, for different transceiver pair with same path distance, different path may have different path loss since the surrounding environments vary with the location of the receiver.

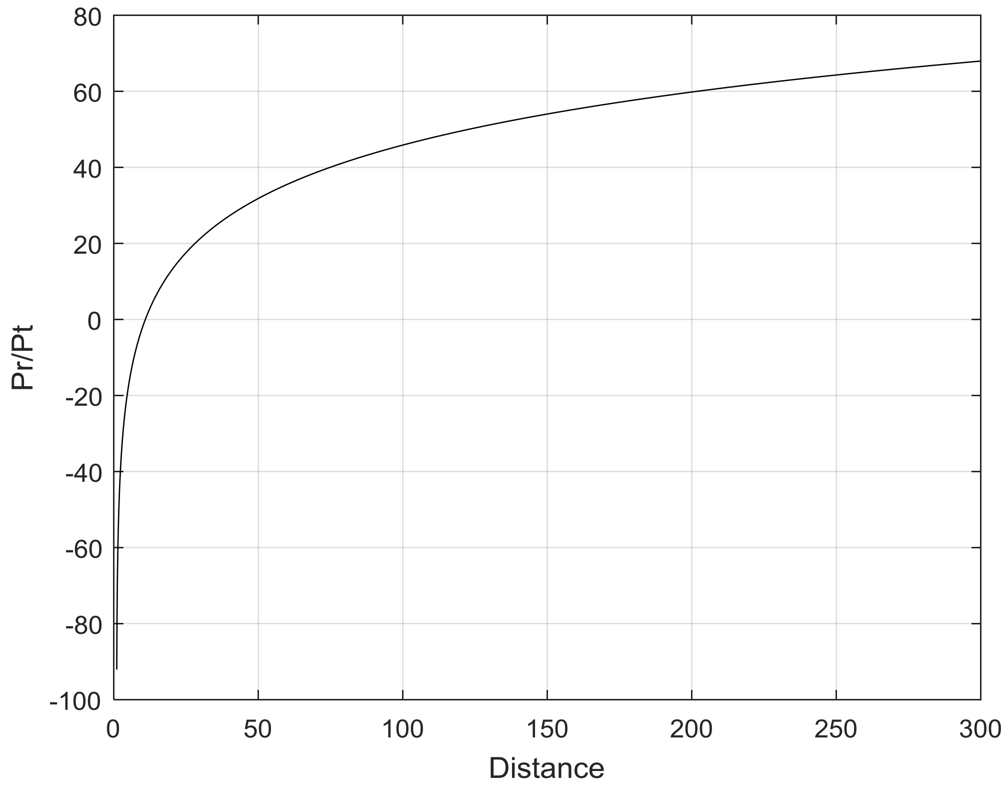


Figure 3.3: Free Space Path Loss Model Effect vs Distance (Meters)

Relay channel shown to be an effective approach to minimize the negative effects of the transmission path distance proportional to the path loss exponent as the link is divided into shorter links. However, in practical wireless system it is difficult to place the relay linearly in the centre between the transmitter and the receiver. Thus, the relay implementation can lead to an augmentation of the total transmission path as most of the placement of the relay is in triangular form, with non-equidistant distance to the transmitter and the receiver. Different relay placement scenarios can be examined such as the relay position close to the source or close to the destination, whereby one link length is minimized, but that might add an increase in the other link length. This scenario is observed in cooperative communication, where the closer relay to the source or the destination is utilized, which save energy consumption at the source or the relay without considering the overall transmission cost. Hence, the relay location is a vital design key to minimize the energy consumption which is investigated in Section

3.5.1and the relay selection policy based on the optimal location is given through the numerical analysis.

3.3.2 Cooperation Strategy

Forward error-correction codes shown to be efficient technique to reduce the required SNR desired for probability of BER, as it reduces the required received energy per bit at the receiver side [98]. However, this improvement in terms of energy saving is at the price of bandwidth expansion required to transmit the extra bits, in addition of the baseband energy consumption. As most practical wireless systems operate over fixed frequency band, the bandwidth expansion can be feasible in time domain only, which requires longer transmission time to transmit the information bits and error-correction bits [99]. Thus, additional circuit operation time is required leading to extra energy consumption that is linearly proportional to the transmission time. In coded systems, an energy saving can be observed as the coding gain decrease the required SNR at the receiver side [100]. Nerveless, it is shown that the benefit of coding varies with the transmission distance and the underlying modulation schemes. Hence a trade-off between energy consumption and additional transmission time required to commit the redundant bits should be considered [101 102]. Moreover, for certain transmission range, the circuit energy processing cost is dominant over the transmit energy. Thus, the overall energy consumption need to be considered to achieve the optimal transmission scheme, and the trade-off between the transmit energy and the escalation in transmission time for coded systems. Although, higher modulation decreases the amount of time spent on signal processing as the transmission time decrease, the transmission energy cost escalates significantly to meet the required desired power level at destination to send a given number of bits. Consequently, the constellation size is another optimization parameter and a trade-off between delay requirement and power constraint should be considered. Therefore, selecting the optimal modulation strategy minimize the transmission time which reduce the sum of transmission and circuit energy consumption.

3.4 Energy Consumption in Wireless Systems

3.4.1 Energy Cost Affecting Factors

According to [28], the total energy consumption in a typical RF transceiver given in (3.5), depends on the power amplifier P_{PA}, the circuit power P_C and is correlated to the circuit operation time T_{on} given in (3.6).

$$E = E_c + E_t = (P_c + P_{PA})T_{On} \tag{3.5}$$

$$T_{On} = \frac{LT_S}{b} \tag{3.6}$$

where $T_S \approx 1/B$ if a squared pulse is used, L ,b and B are the packet length, the number of bit per symbol and the system bandwidth respectively. The number of symbols required to send L as $L_S = L/b$. P_C is the sum of the DAC power P_{DAC}, ADC power P_{ADC}, mixer power P_{mix}, synthesizer power P_{syn} low noise amplifier power P_{LNA}, intermediate frequency amplifier P_{IFA} receiver filter power and transmitter filter P_{FILT} and P_{PA} is given by

$$P_{PA} = (1+\theta)P_{out} \tag{3.7}$$

where θ is the amplifier drain efficiency given in (3.9),and μ is the drain efficiency. ζ is the peak average ratio (PAR) given in (3.9) correlated to the constellation size $M = 2^b$.

$$\theta = (\frac{\zeta}{\mu}) - 1 \tag{3.8}$$

$$\xi = 3\frac{M - 2\sqrt{M} + 1}{M - 1} \tag{3.9}$$

Assuming free space propagation, the transmit power P_{OUT} to achieve a desired power level at the received for correct decoding is calculated according to the link budget and given by

$$P_{out} = \frac{(4\pi)^2 d^{\alpha} M_t N_f}{G_r G_t (\lambda)^2} \overline{E_b} R_b \tag{3.10}$$

where M_t, N_f, R_b, G_r, G_t, and λ are the link margin, receiver noise figure, bit rate, receiver antenna gain, transmitter antenna gain and wavelength respectively. α and $\overline{E_b}$ are the pass loss attenuation exponent and the required energy per bit at the receiver respectively. α is evaluated in (3.11) based on the distance d between transceivers and the threshold distance d_0 is given in (3.12).

$$\begin{aligned} \alpha &= 2 \;\; if \; d \leq d_0 \\ \alpha &= 3 \; if \;\; d_0 \geq d \end{aligned} \tag{3.11}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{3.12}$$

where ε_{fs} and ε_{mp} are the free space and multipath model transmit amplifier respectively.

3.4.2 Energy Cost of Uncoded MQAM System

For uncoded MQAM systems, the number of bit per symbol is given as $b = \log_2 M$, and to transmit L bits the number of MQAM symbols required is given as $L_s = L / b$. We denote the symbol duration as T_s and the number of bit per symbol is given by $b = {LT_s}/{T_{on}}$,where T_{on} is the time spent to communicates l bits. The average SNR $\bar{y}$ in uncoded MQAM is given by

$$\bar{y} = \frac{h_i P_r}{2B\sigma^2 N_f} \tag{3.13}$$

where P_r, h_i, N_f and $\sigma 2$ are the received power, channel gain, receiver noise figure and spectral noise power respectively.

3.4.3Energy Cost of Coded MQAM System

We consider a trellis-coded MQAM system, therefore, for the information bit block of size b consists of two groups of size b_1 and b_2. b_1 is encoded into b_k bits mapped to the constellation subset of 2^{b_k}. And b_2 are used to choose the constellation points 2^{b_2} within each subset. The constellation size is increased from 2^b to $2^{b_2+b_k}$, and the code rate defined as $R_c = b_1 / b_k$. A rate $R_c = b_1 / (b_1 + 1)$ code is usually used for subset selection. According to [103], $b_1 = 2$ is a good choice since it provides to achieve the major part of the coding gain. In the proposed model, a rate 2/3 code with 32 states is chosen and the coding gain $G_c = 3$ (4.7 dB). As a result, the final constellation size becomes 2^{b_c}, where $b_c = 1 + L / BT_{on}$ and the required SNR threshold to achieve a target BER is reduced by the coding gain [104].

3.4.4Energy Cost in Rayleigh Fading Channel

As in [102], the probability bound of BER for MQAM in Rayleigh fading channel is given by

$$P_e = \frac{4\left(\sqrt{M} - 1\right)}{\sqrt{M}\log_2 M} Q\left(\sqrt{\frac{3\bar{y}\log_2 M}{M-1}}\right) \tag{3.14}$$

where $M = 2^b$ is the constellation size and Q is the Marqum function given by

$$Q(x) = \int_x^{\infty} \sqrt{\frac{1}{2\pi}} e^{-\frac{u^2}{2}} du \le \frac{1}{2} e^{-\frac{u^2}{2}} \tag{3.15}$$

The average SNR $\bar{y}$ follow the Rayleigh distribution given by

$$\bar{y} = \int \frac{y}{\bar{y}} e^{-y/\bar{y}} \, dy$$

(3.16)

From (3.13) and the approximation given in [104]as $P_e <<< 1$,and using (3.13) the instantaneous SNR $\bar{y}$ for unity channel gain is given by

$$\bar{y} = \frac{3(M-1)(1-2P_e)^2}{2(1-(1-2P_e)^2)} \approx \frac{(M-1)}{6P_e} \tag{3.17}$$

where P_r , σ^2 and N_f are the signal received power, the noise power spectral density and receiver noise figure respectively. The required transmit power for the target BER at the receiver side is given by

$$P_r = \frac{2(M-1)2B\sigma^2 N_f}{3P_e} \tag{3.18}$$

using (3.10) in (3.17), the total energy cost per bit for uncoded MQAM is given by

$$E_b = ((1+\theta)N_f B\sigma^2 \frac{2^b - 1}{3P_e} G_d T_{on} + P_c T_{on}) / L \tag{3.19}$$

The total energy cost per bit for coded MQAM, reduced by the coding gain G_c and given by

$$E_b = ((1+\theta)N_f B\sigma^2 \frac{2^b - 1}{3G_c P_e} G_d T_{on} + P_c T_{on}) / L \tag{3.20}$$

3.4.5 Energy Cost in AWGN Channel

As in [102], the BER probability bound for uncoded MQAM in AWGN channel is given by

$$P_e \le 4(1-\sqrt{\frac{1}{2^b}})Q\left(\sqrt{\frac{3}{2^b-1}\bar{y}}\right) \le 4\left(1-\frac{1}{\sqrt{2^b}}\right)e^{-\frac{3}{2^b-1}\frac{\bar{y}}{2}}$$

(3.21)

Following the condition in [103] and setting equation (3.22) as equality, the BER probability bound is approximated as follow

$$P_e \approx 4(1-\frac{1}{2^b})e^{-\frac{y}{2}\frac{3}{2^b-1}}$$

(3.22)

using (3.18) in (3.19), the required received power for the target BER is given by

$$P_r = \frac{4}{3}N_f B\sigma^2(2^b-1)\ln\frac{4(1-{}^1\!/_{2^b})}{P_e}$$

(3.23)

The total energy cost per bit E_b for uncoded MQAM is given by

$$E_b = ((1+\theta)\frac{4}{3}N_f B\sigma^2(2^b-1)\ln(\frac{4(1-{}^1\!/_{\sqrt{2^b}})}{bP_e})G_d T_{on})/L + (P_c T_{on})/L \qquad (3.24)$$

and the total energy cost per bit E_b for coded MQAM is given by

$$E_b = ((1+\theta)\frac{4}{3G_c}N_f B\sigma^2(2^b-1)\ln(\frac{4(1-{}^1\!/_{\sqrt{2^b}})}{bP_e})G_d T_{on})/L + (P_c T_{on})/L \qquad (3.25)$$

3.4.6 Total Energy Cost

In the proposed scenario we omit the energy consumption for sleep power, the power consumed when nodes switch between different states as they are negligible compared to the circuit power and the total energy cost is given by

$$E_{Total} = \sum_{1}^{n} L(E_{Cr} + E_{Tx} + E_{Rx})_i + E_{RTS} + E_{CTS} + E_{Beacon} + E_{agg} \qquad (3.26)$$

where i is the node index, and n is the number of nodes involved in the transmission equal to two in the proposed scenario as single relay is employed. E_{Cr}, E_{Tx} and E_{Rx} are the circuit energy cost, transmission energy cost and the receive energy cost respectively. E_{RTS}, E_{CTS} and E_{Beacon} are the energy cost for the RTS packet transmission energy cost, CTS packet transmission energy cost, Beacon packet transmission energy cost respectively. E_{agg} the energy cost per bit to decode and encode the source signal at the relay. RTS and CTS packet length is 80bitsas in [104], and the Beacon message length is set to 80 bits.

3.5 TheProposed Relay Selection Algorithm

3.5.1 The Impact of Relay Location

In typical wireless network, the relay location is not linearly placed between S and D, which leads to an increase in the total transmission distance compared to ideal scenario where the relay is centred between $S$and D within a line of sight and the difference is given by

$$\begin{aligned} d_i &= d_l = d_1 + d_2 \\ d_i^2 &= d_1^2 + d_2^2 \\ d_n &\neq d_l \\ d_l &= d_3 + d_4 \\ d_n^2 &= d_1^2 + d_2^2 \end{aligned} \tag{3.27}$$

where d_1, d_2 and d_l are the $S-R, R-D$ and $S-D$ path length. And d_t is sum of $S-R$, $R-D$ path length. This escalation in total transmission distance for different relay position is illustrated in Figure 3.4, where the sum of squared $S-R$ path length and squared $R-D$ path length is plotted against squared≤≥ path length in meters for different scenarios assuming a unit energy per meter. IS and NIS refer to ideal scenario and non-ideal scenario respectively. In IS, the relay is linearly placed for different position between S and D, while in NIS we use random relay location positioning following triangular arrangement. We investigate two cases, the first when the relay is closer to the source and the second when the relay is closer to the destination. The results verify the hypotheses of transmitting via a relay minimize the squared transmission distance, except in the case where the path length or path length is slightly comparable with $S-D$ path length. This can be observed in the case of non-ideal scenario for a relay placement near to the destination. Conversely, in the non-ideal scenario when the $S-R$ path length and $R-D$ path length is slightly comparable to half of $S-D$ path length, relay implementation outperforms direct transmission in terms of overall distance per meters.

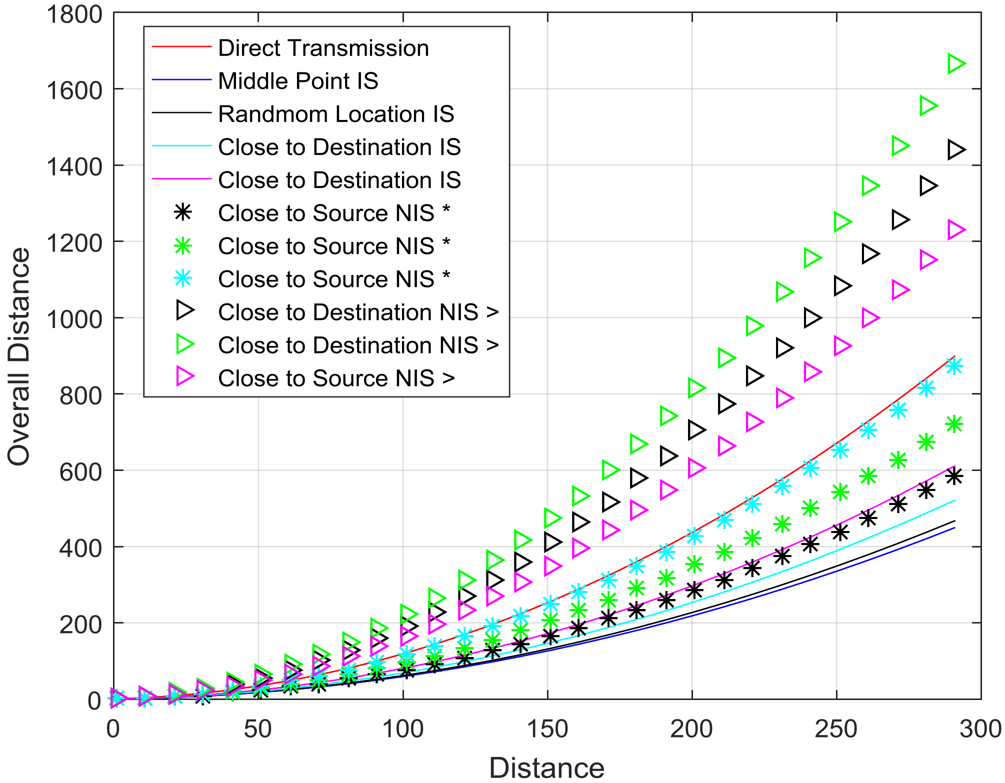


Figure 3.4: The Impact of Relay on the Total Transmission Distance (Meters)

The relay location is a key factor to suppress the additional energy cost that might elevate due to the escalation in the distance. To examine that, we plot the transmit energy cost per bit using equation (3.24) and the parameters given in Table 3.2 for different relay location with respect to total path distance in an ideal scenario for different constellation size $M = 2^b$ [103]. From the results, it can be clearly observed for different constellation size the total transmission energy cost is minimized for an equidistant relay distance to the source and to the destination such as a ratio of 0.4 and 0.6. From Figure 3.5, it can be clearly observed that the energy cost decreases monotonically with the relay moving toward the midpoint and the energy cost at a distance ratio of 0.4 and 0.6 is the identical. Thus, from this observation, a node is considered as a potential relay candidate, if the following condition is satisfied.

$$\frac{d_1}{d} > 0.4 \;\; and \;\; \frac{d_1}{d} < 0.6 \qquad (3.28)$$
$$d_t^2 = d_1^2 + d_2^2 \le d_l^2$$

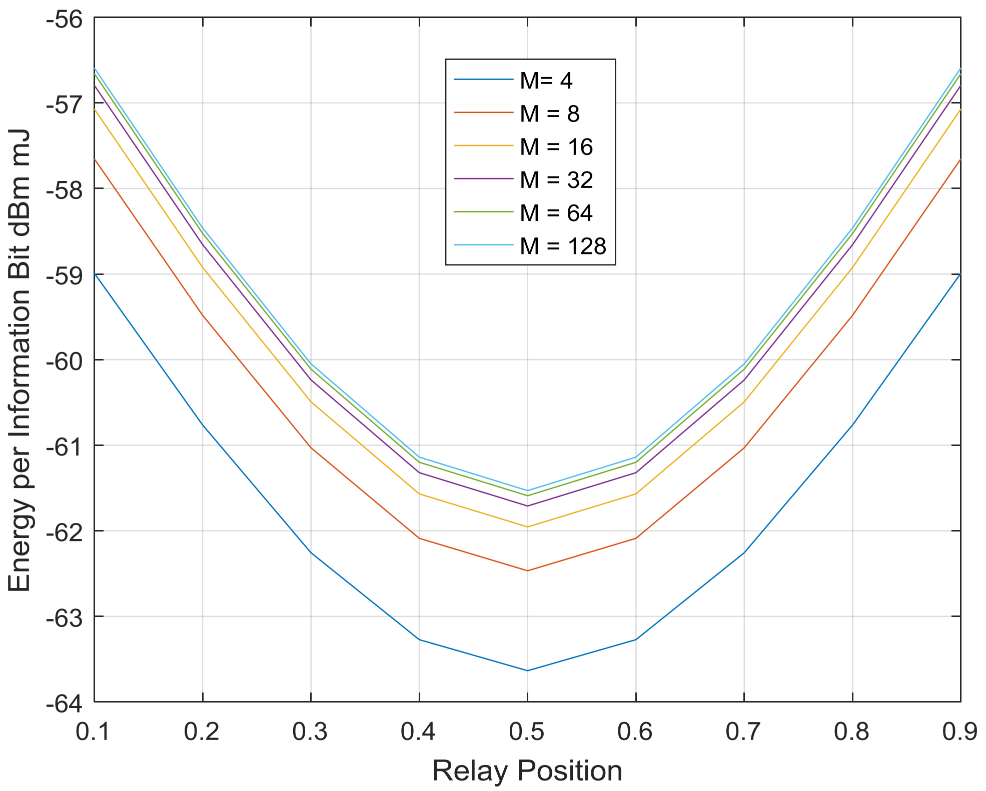


Figure 3.5: Impact of the Relay Location vs Constellation Size (Linear Placement)

The same experiment is repeated for triangular nodes placement, and we plot the transmission energy per bit for different constellation size against the ratio of the overall path length to the direct transmission path in Figure 3.6. Similar to the ideal scenario, with an equidistant relay position to the source and the destination less energy is consumed using different constellation size.

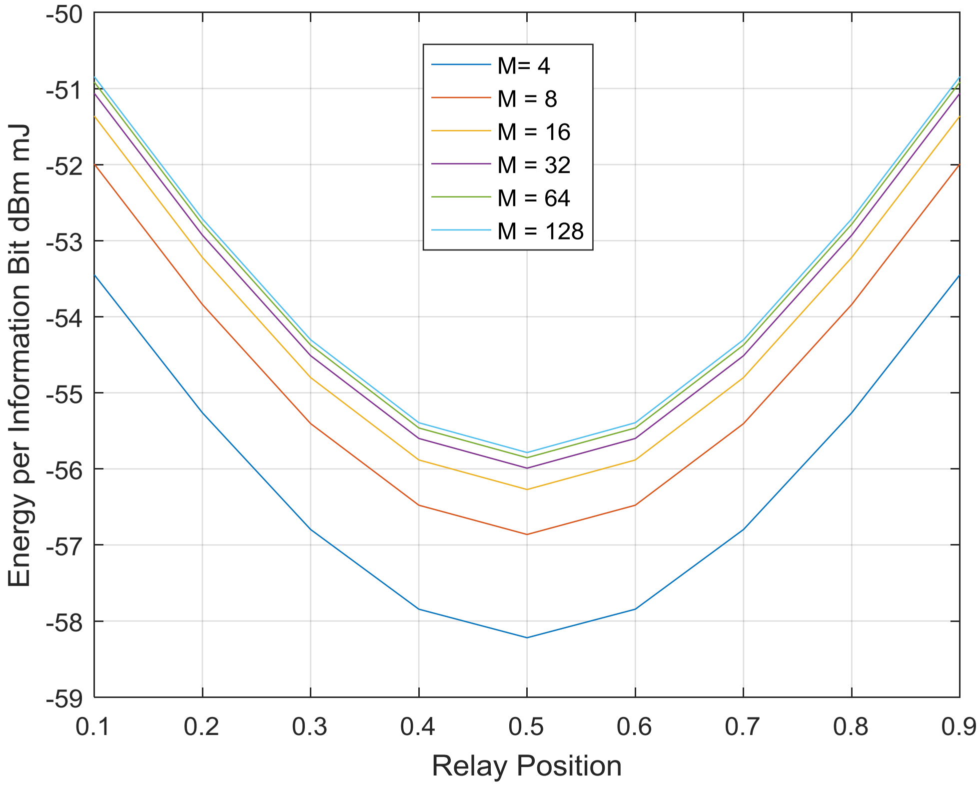


Figure 3.6: Impact of the Relay Location vs Constellation Size (Triangular Placement).

From the above observations, the relay selection policy is based on satisfying the condition in equation (3.29) and correct decoding for the RTS/CTS messages and its given by

$$\begin{aligned} & E_{\mathrm{Re}} \leq E_{Dt} \\ & d_1 \geq 0.4 d_t \quad \& \, d_2 \leq 0.6 d_t \\ & d_t^2 = d_1^2 + d_2^2 \leq d_l^2 \\ & \gamma_1 \geq Th_1 \quad \& \quad \gamma_2 \geq Th_2 \end{aligned} \tag{3.29}$$

where $E_{\mathrm{Re}}, E_{DT}, d_1, d_2, \gamma_1, Th_1, \gamma_2$ and Th_2 are the total energy for relay transmission, total energy for direct transmission, $S-R$ path length, $R-D$ path length, $S-D$ path length, instantaneous SNR of $S-R$ link, instantaneous SNR of $R-D$ link, SNR threshold for $S-R$ link and SNR threshold for $R-D$ link respectively. However, the results in Figure 3.5 and Figure 3.6 show higher energy consumption for higher constellation size. In section 3.5.2 we investigate the modulation strategy impact on energy consumption.

3.5.2 Optimal Modulation Strategy

Although higher modulation decreases the amount of time spent on signal processing, as T_{On} decrease, the transmission energy cost escalates significantly to meet the required desired power at destination. Thus, the constellation size is another optimization factor to achieve an energy efficient communication. To examine the impact of the modulation strategy on energy consumption, we use a specific numerical example with total transmission distance of 5 meters and plot the energy cost in dBm mJ for different value of M for coded and uncoded system in AWGN channel and Rayleigh fading channel.

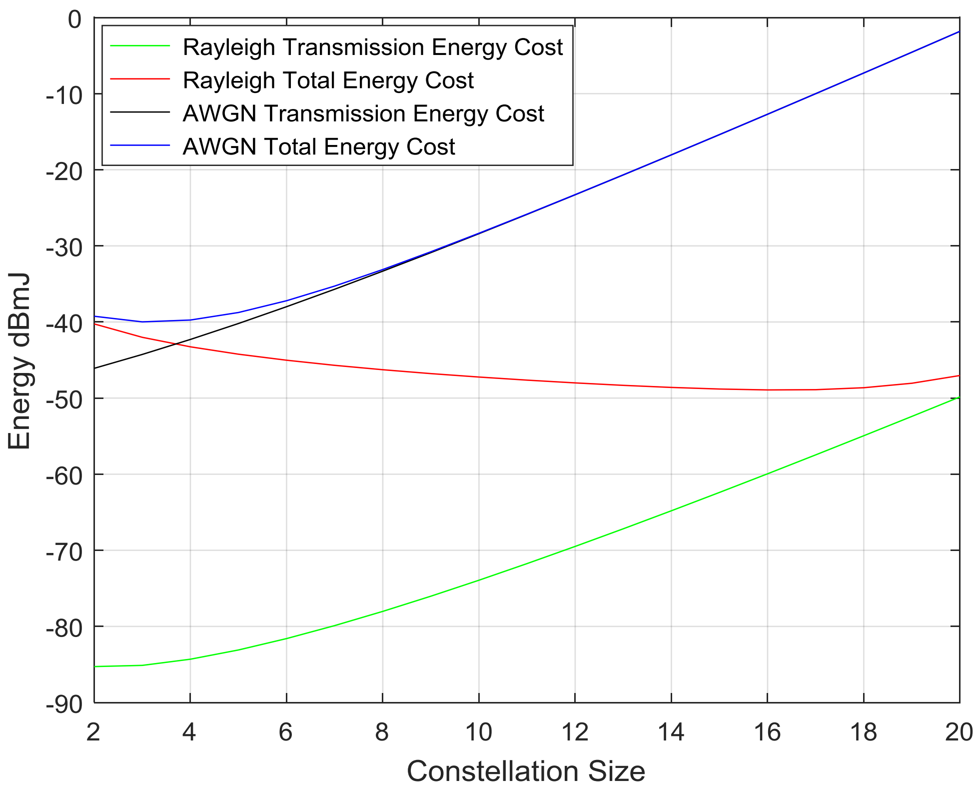


Figure 3.7: Total Energy Consumption vs Constellation Size (Uncoded MQAM, AWGN)

Figure 3.7 illustrates the transmit energy consumption and circuit energy consumption against the constellation size in AWGN and Raleigh fading channel for uncoded MQAM. In AWGN channel, the transmission energy cost increases linearly with respect to M , while the total energy cost start increasing for M greater then 4, with minimum energy consumption at 4. From this observation 4 is the optimal value. For Rayleigh fading channel, the transmission energy cost increase linearly with M while total energy cost has a minimum value - 48 dBm mJ for M around 8. Thus, the optimal constellation size is 8.

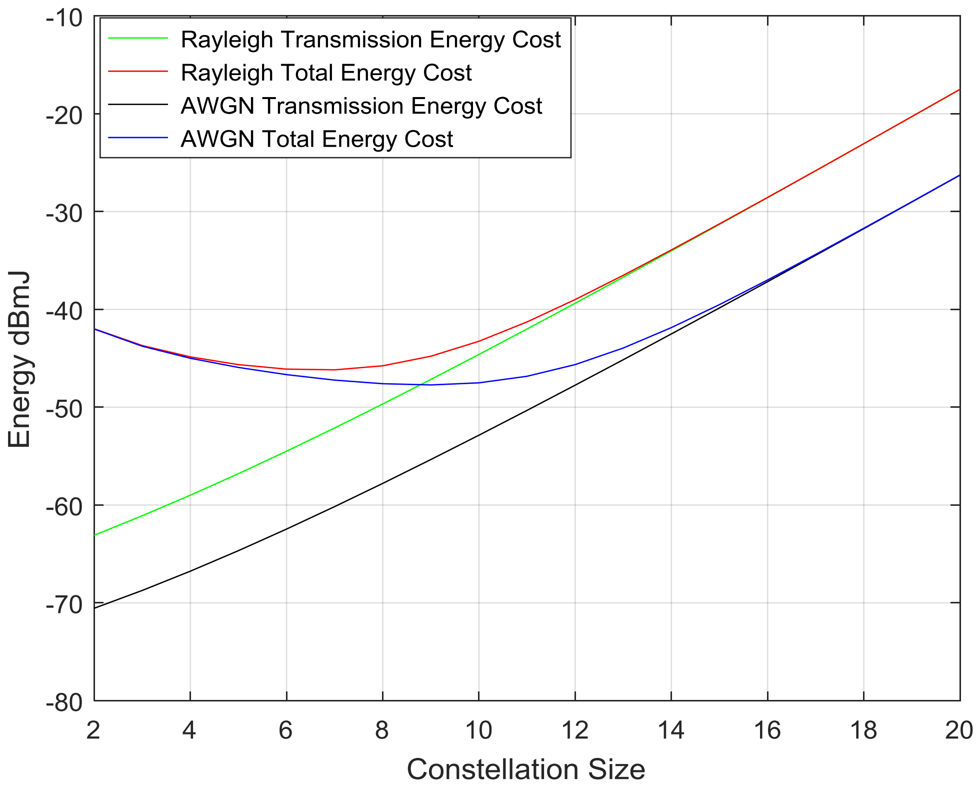


Figure 3.8: Total Energy Consumption vs Constellation Size (coded MQAM,AWGN)

We repeat the same experiment for coded MQAM and the results are plot in Figure 3.8. For AWGN channel, the total energy cost increases slowly for M greater than 12 while a linear increase in the transmission energy cost is observed. Thus, the optimal value of M is 8 as a total energy of around -45 dBm mJ is consumed. For Rayleigh fading channel, the transmission energy cost linearly increases with M, while the minimum total energy consumption is achieved for M around 8, while a linear increase is observed above this value. The observations in Figure 3.7 and Figure 3.8, confirm the necessity of a trade-off between higher modulation and energy cost.

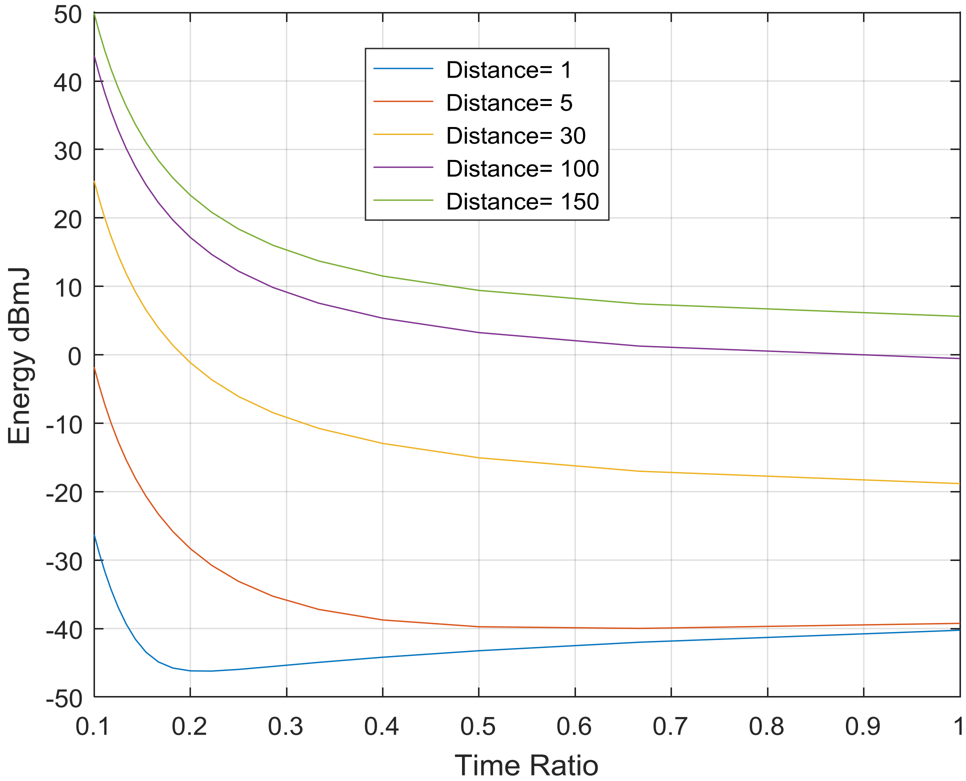


Figure 3.9: Delay vs Energy Consumption at Different Distance(Meters), (AWGN, uncoded MQAM)

Based on the results in Figure 3.7 and Figure 3.8, the constellation size is another factor that increases energy consumption, mainly the transmission energy cost. Although higher constellation size decreases the transmission time which improve the system performance in terms of latency, a trade-off between energy cost and constellation size is a must for an energy efficient communication. However, as wireless terminals operate under some delay deadline to communicate given number of bit, optimizing the constellation size subject to energy constraint should consider the transmission range impact as transmission energy cost escalate relatively to the distance between transceivers. Therefore, we plot the transmission energy cost at different transmission range for different constellation size against the T_{on}/T where the transmission deadline T and T_{on} are calculated using equation (3.6). Figure 3.9 shows the transmission energy cost in AWGN, and for low delay requirement and longer path distance such as 150 meters, a transmission energy cost of 50 dBm mJ is required for 0.1 representing the ratio of b over b_d (calculated based on the transmission deadline).We repeat the same experiment in Rayleigh fading channel and the results are plot in Figure 3.10 for different transmission distance. Similar observation to the results in AWGN, where longer transmission range requires higher transmit energy to minimize the delay with slightly better performance in terms of energy.

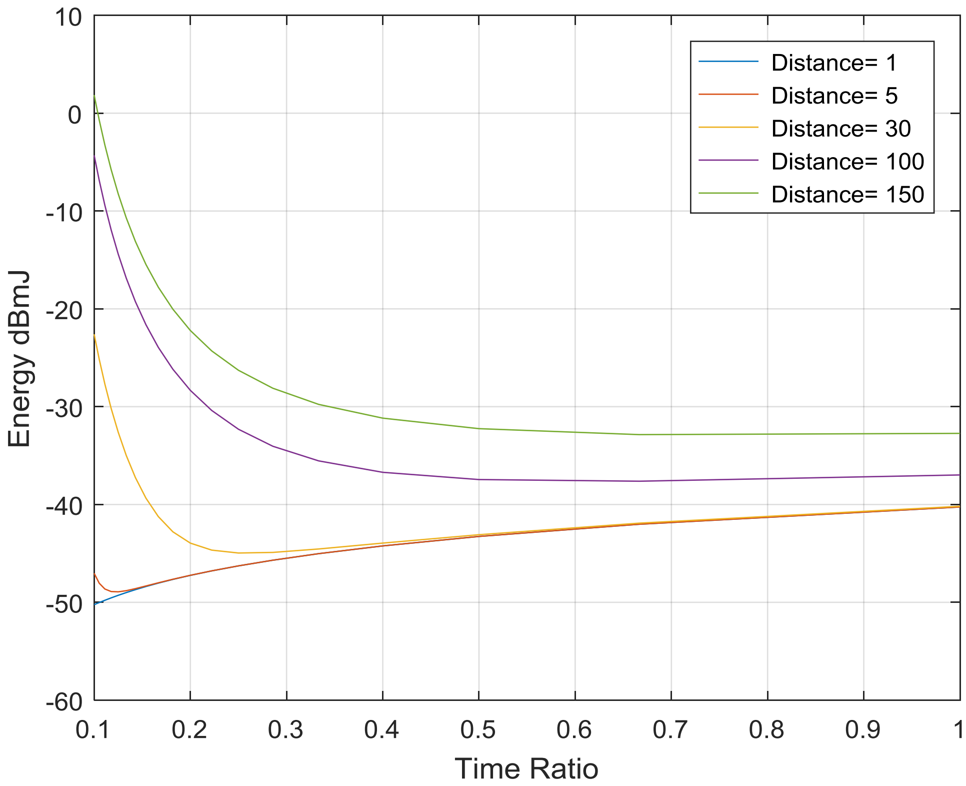


Figure 3.10: Delay vs Energy Consumption at Different Distance (Meters),(AWGN, coded MQAM)

To examine the effect of the coding gain, we repeat the same experiments for coded MQAM, using different transmission range in AWGN and Rayleigh fading channel and the results are given in Figure 3.11 and Figure 3.12 respectively. For AWGN channel, an improvement of 3dB is observed for a transmission range of 150 meters and ratio of 0.2 compared to uncoded MQAM. Likewise, same outcome can be observed for coded MQAM in Rayleigh fading channel as illustrated in Figure 3.12. In summary, minimizing the energy by optimizing the constellation size is subject to system requirements.

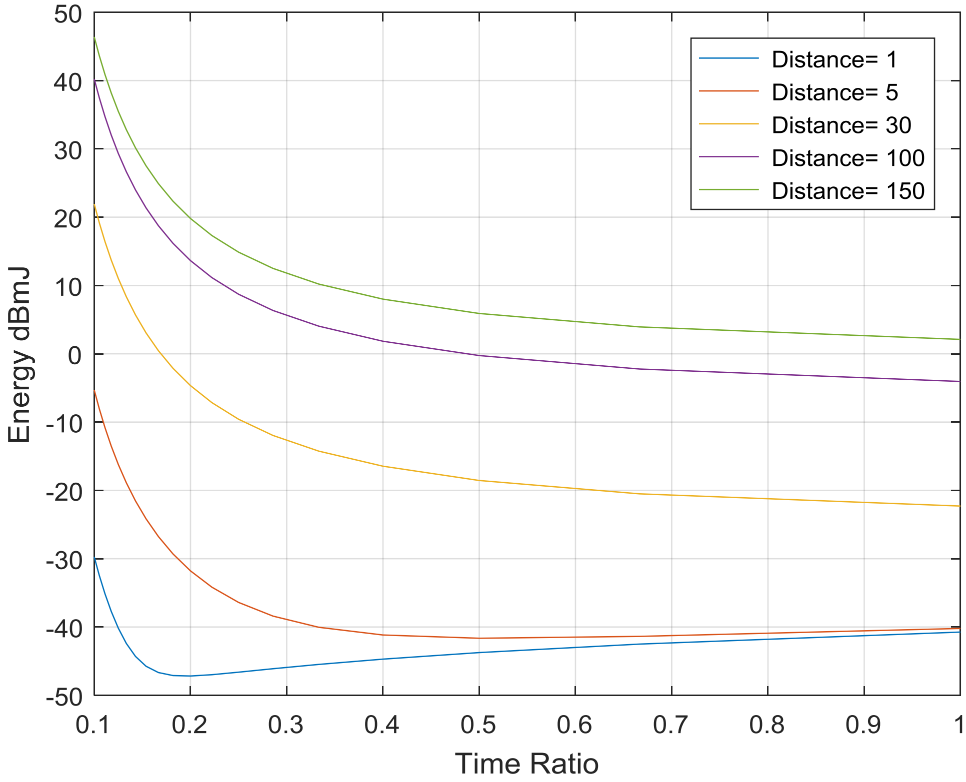


Figure 3.11: Delay vs Energy Consumption at Different Distance(Meters), (Rayleigh, uncoded MQAM)

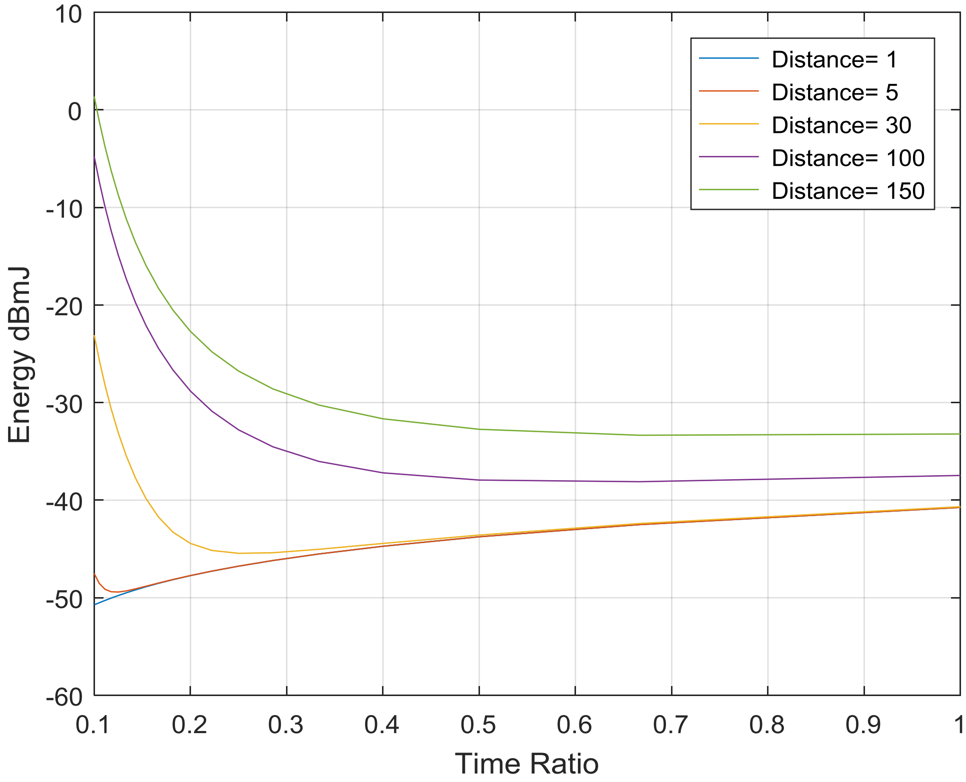


Figure 3.12: Transmission Deadline vs Energy Consumption at Different Distance (Meters), (Rayleigh, coded MQAM)

3.5.3 Impact of Coding on Energy Consumption

In the previous section, we investigate and compare the performance of different communication strategies in AWGN and Rayleigh fading channel, where we consider the impact of the relay location and the constellation size on the performance in terms of energy consumption. In this regard, uncoded MQAM and coded MQAM systems are considered which shown different performance in terms of energy consumption. However, the error correction coded decrease the required SNR threshold for a target BER, consequently the required power level at the receiver side is reduced. Nerveless, this might add an energy penalty due to the message length extension since extra bits are added. Moreover, extra energy consumption as the coded and complementary transmission time that impact the total energy cost and might comprise delay. Whether coded systems reduce energy cost per bit is not clear, as it is correlated to other parameters in the energy cost equation.

The performance of coded system in AWGN and Rayleigh fading channel are considered for different transmission range and different constellation size. For AWGN and Rayleigh fading channel, the total energy cost per bit for different constellation size against the transmission distance for coded and uncoded MQAM is used to illustrate the performance and results are given in Figure 3.13. For high constellation size, coded system outperforms uncoded system over certain transmission range. For M =16, coded system consumes less energy for a 10 meters transmission distance. For a 32-constellation size, the total energy consumption for 40 meters transmission range is around -8 dBm mJ, while coded system consumes -18dBm mJ. However, 4 constellation size uncoded MQAM outperforms 64 coded MQAM by 10 dB at transmission distance of 42 meters. Hence, it's essential to address the energy consumption problem addressing the necessity of coding modulation transmission in line with optimizing the constellation size.

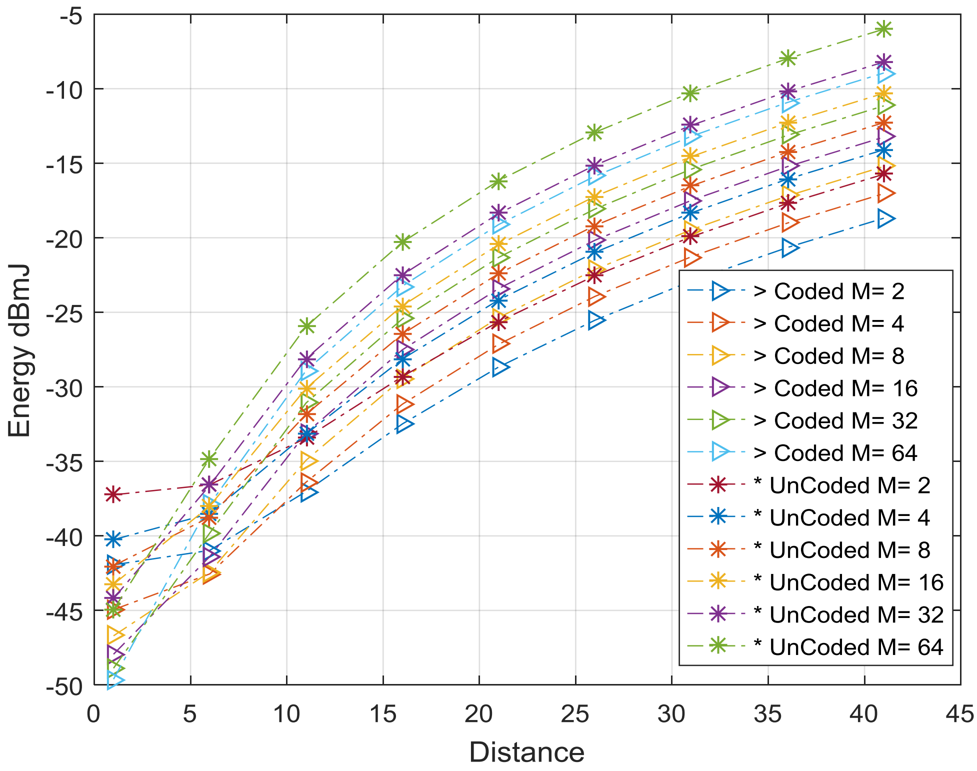


Figure3.13: coded MQAM vs uncoded MQAM at Different Distance (Meters), (AWGN)

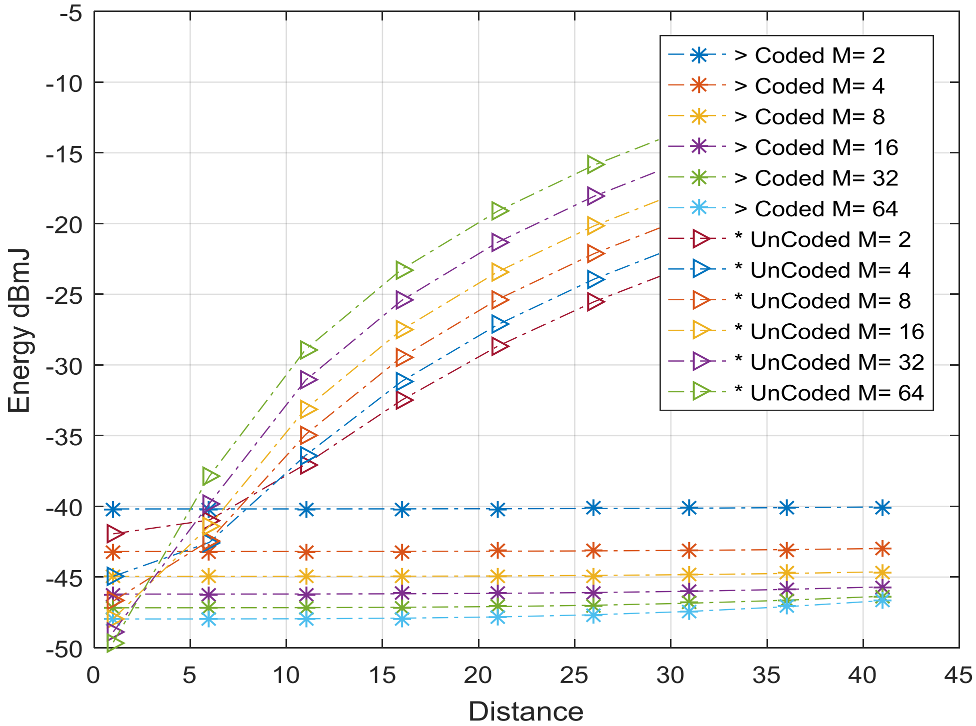


Figure 3.14: coded MQAM vs uncoded MQAM at Different Distance (Meters), (Rayleigh)

Figure 3.14 illustrate the performance of coded MQAM and uncoded MQAM in Rayleigh fading channel. For uncoded system, the energy consumption increases monotonically in line with the transmission range and the increase in the constellation size, while coded system shows slow increase in respect to the distance for different constellation size. Moreover, for a transmission range greater than 7 meters, coded system outperforms uncoded system. For example, assume a node transmits 2Kb packet within 100 ms deadline with 10 KHz bandwidth system over 50 meters, the minimum constellation size for coded system calculated using equation (3.6) is 2 with100ms transmission time. For a constellation size of 8 the transmission time is around 66 ms. Using the same constellation size in coded system, the transmission time is around 100ms following the ratio given in (3.30). However, to communicate the same packet within 66ms, the coded system must use a 32 constellations size Coded system consume around -7dBm mJ in AWGN, while uncoded system consumes around -13 dBm mJ over 50 meters transmission range.

$$T_c = \frac{T_{on}}{G_c} \tag{3.30}$$

Thus, the efficiency energy transmission strategy is using coded MQAM, with a transmission time of 100ms and energy cost around -13dBmmJ per bit, as uncoded MQAM consumes -5 dBm mJ per bit. For Rayleigh fading channel, the optimal solution is communicating the packet using coded MQAM with a constellation size of 3, with -44 dBm mJ total energy consumption per bit and transmission time of 100ms. Based on these observations, with different performance requirement, it's more energy efficient to switch between coded MQAM and uncoded MQAM in line with the optimal modulation strategy. Although error code correction minimizes the SNR threshold through the coding gain, this come at the price of transmitting additional redundant bits. Thus, for better BER, higher code gain is required which add additional energy cost and decrease in the overall system rate. The optimal modulation strategy is given by

$$\begin{aligned} &\min imize \quad E_t^i\left(b^j\right) \\ &subject\ \ to\ \ b-b_{\min}>0 \\ &\qquad\qquad\quad b_{\max}-b>0 \end{aligned} \tag{3.31}$$

where i is the node index and j coding scheme index. Node computes the energy budget for all different b for coded and uncoded modulation subject to transmission deadline. Using a convex optimization, the optimization problem is solved by the interior point method in the format given in (3.32) [105].

$$\begin{aligned} &\min imize \quad E(b) \\ &subject\,to \quad E^i(b^j)>0 \end{aligned} \tag{3.32}$$

where i and j represents different energy cost for different b. The node start with minimum b, calculates the energy cost, and update b in case the cost is minimized. Minimum and maximum value of b is evaluated based on the transmission deadline requirements.

3.5.4 Relay Selection Algorithm

In the proposed method, all the nodes within the source transmission range are considered as potential relay candidate subject to satisfying the following condition

$$\begin{aligned} \gamma_1 > T_1 \\ \gamma_2 > T_2 \end{aligned} \tag{3.33}$$

where γ_1 and γ_2 are the instantaneous SNR of the source-relay link and relay-destination link, and T_1 and T_2 are the SNR threshold for source-relay link and relay-destination link. From the RTS/CTS exchange messages of the MAC protocol in [106], potential relays estimate the SNR of both links and compete to win the relay role if the condition in (3.31) is satisfied. Moreover, candidate relays estimate the channel gain from the received signal SNR as they have the source and destination coordinates on the network gird, and the transmit power used at this stage. The relay selection is completed in un-centralized manner, and the cooperation procedure is given in Figure 3.7 and the proposed algorithm pseudo-code is given in Table 1, and the optimization policy is given by

$$\begin{aligned} &Minimize \quad E_1 \,\&\, E_2 \\ &subject\ to\ d_1 \geq d_{Min} \,\&\, d_2 \leq d_{Max} \\ &\qquad\qquad P_e \leq P_{req} \\ &\qquad\qquad d_1^2 + d_2^2 \leq d^{\alpha} \\ &\qquad\qquad P_t \leq P_{Max} \\ &\qquad\qquad T_{on} \leq T_d \end{aligned} \tag{3.34}$$

Candidate relay set their timer Δ_i using equation (3.33), and it's clear that the node with minimum sum distance of both links has the smaller timer value and has the priority to send the flag to win the relay role.

$$\Delta_i = \frac{d_l^2}{d_{SR}^1 + d_{RD}^2}\phi \tag{3.35}$$

where d_{SR}^1, d_{RD}^2 and d_l are the candidate source-relay path length, relay-source path length and source-destination path length respectively. T is the transmission deadline time, and ϕ represent the cooperation time given by

$$\phi = \frac{T_d}{L} n \tag{3.36}$$

where n represents the number of nodes within the source and destination transmission range, and T_d the transmission deadline. n is evaluated using the Bernoulli distribution given in (3.35) that compute the probability of finding n out of k node within a circle with the radius equal the source transmission range.

$$P(n|k) = \binom{n}{k} P^k (1-P)^{n-k} \tag{3.37}$$

and P is given by

$$P = \left(\frac{r_0}{R_0} \right) \tag{3.38}$$

where r_0 and R_0 are the desired source transmission range and the source-destination path length. In Table 3.1, n, k, s and R represent the number of nodes in the network, number of nodes within the source and destination transmission range and the successful relay respectively. While D_{Min}, D_{Max} and P_{Max} are the $S-R$ minimum link distance threshold, $S-R$ maximum link distance threshold, and the maximum transmit power calculated based on $S-D$ path length. As nodes have network information, they estimate D_{Min} and D_{Max} in both direction and if the node satisfies the condition in (3.28), it compute condition (3.31) from the RTS/CTS messages exchange calculate the transmission energy cost using (3.19, 3.20, 3.24, 3.25) subject to system requirement. Using equation (3.26), subject to satisfying the policy in equation (3.32), the node set the timer based on equation (3.33). The node with minimum sum of link length has the minimum time and the priority to send the Beacon message and win the relay role. S use equation (3.19, 3.20, 3.24, 3.25) to calculate the required energy and adjust the transmit power. Based on the transmission time deadline, the successful relay jointly estimates the optimal constellation size, and the preference modulation strategy. The transmission strategy information is feedback to the source and the destination in the Beacon message.

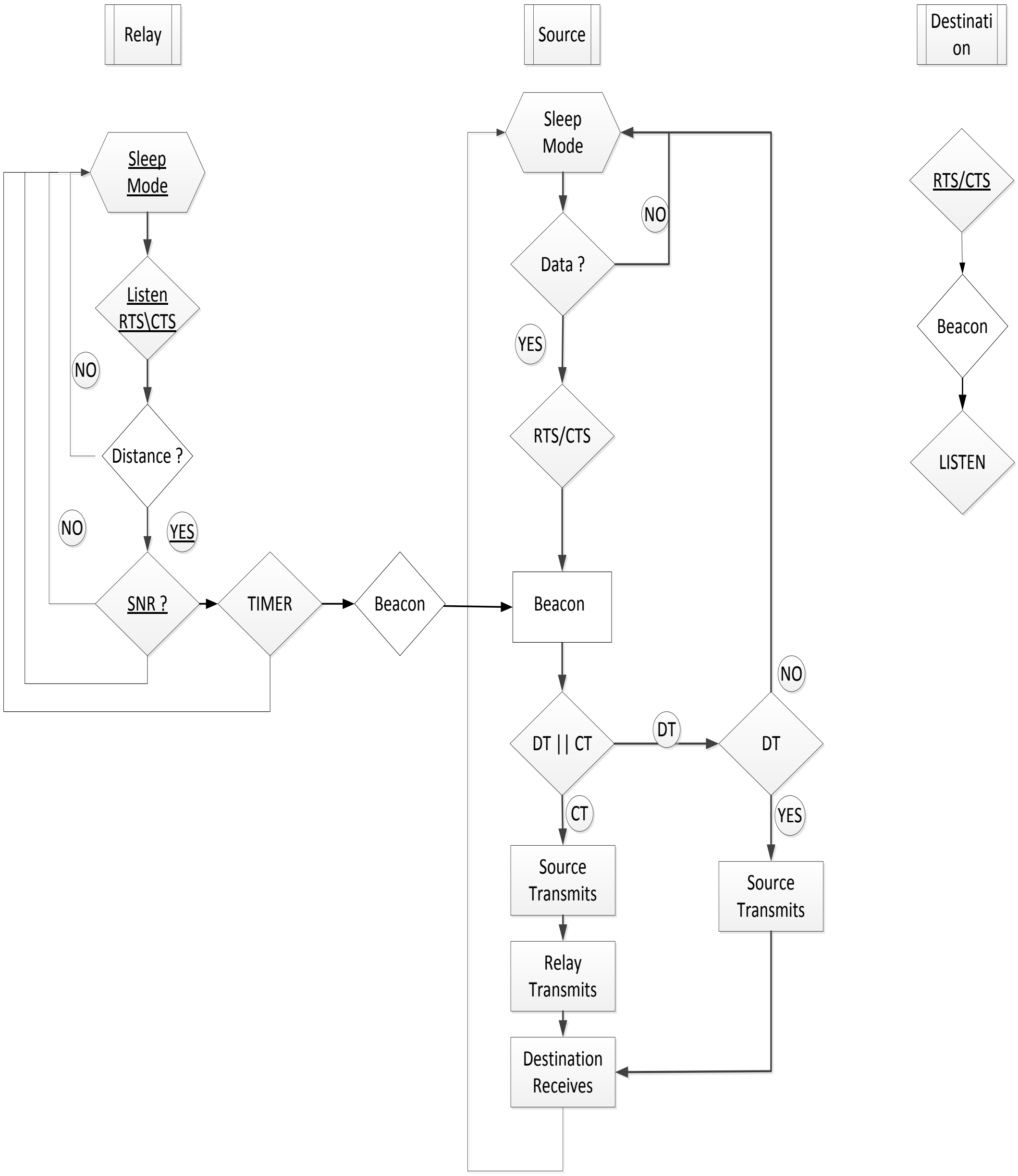


Figure 3.15: Cooperative Transmission Procedure

Table 3.1: Relay Selection Algorithm Pseudo Code

```
1.  S: Transmit node
2.  Relays: Relay candidates
3.  D: Receiving node
4.  R: Selected relay
5.  for each S-R
6.  S: Set D_Max && D_Min
7.  Relays: if Equation (3.28) is not satisfied, Sleep Mode;
8.  S: transmits RTS;
9.  D: transmits CTS;
10. Relays: if Equation (3.31) is not satisfied, Sleep Mode;
11. Relays: Execute Equation(3.33);
12. S: for Equations(3.33),
                    DELAY();
                    if(Beacon)
                          R:excute Equation (3.32);
                          Break;
                    endif;
                    end for;
13. S: if (!Beacon):
                          Direct Transmission
          end if;
14. S:do Equations (3.19, 3.20, 3.24, 3.25);
15. R:do Equations(3.19, 3.20, 3.24, 3.25);
16. S: Transmits;
17. R:Transmits;
18. D: Receives;
19. endfor;
```

3.5.5 Performance Evaluation

The probability of n out of m nodes $\Pr(n/m)$ satisfying the condition in (3.31) is correlated with the desired SNR and the received SNR at the node given by

$$\Pr(n/m) = \frac{m!}{n!(m-n)!} e^{m\beta} (1-e^{\beta})^{m-n} \tag{3.39}$$

where $\beta = P_{re} P_r^{-1}$, and P_{re} is the required power at the receiver and received power at the receiver respectively evaluated in (3.23) and (3.28) for AWGN and Rayleigh fading channel. The received P_r is evaluated using (3.24) given by

$$P_r = P_t \left(\frac{G\lambda}{4\pi d} \right)^{\alpha} \tag{3.40}$$

The probability of successful transmission is given by

$$P(S) = P(\gamma_1 > T_1)P(\gamma_2 > T_2) \tag{3.41}$$

where T_1 and T_2 are evaluated for AWGN and Rayleigh fading channel are given in (3.40) and (3.41) respectively. Where G_c is the coding equal to one in case of uncoded MQAM.

$$T_1 = T_2 = \frac{2(M-1)}{3G_c} \ln \left(\frac{1 - \frac{1}{\sqrt{M}}}{P_e} \right) \tag{3.42}$$

$$T_1 = T_2 = \frac{M-1}{6P_e G_c}$$

(3.43)

and the required power P_{Tr} at the relay for AWGN and Rayleigh fading channel is given by

$$P_{Tr} = \frac{(1-2P_e)^2 2B\sigma^2 N_f}{x(1-(1-2P_e)^2)} \tag{3.44}$$

To examine the effect of the relay location with respect to the total path length of 150 meters, the transmit power to is set to $P_{max}/2$ at the relay and the source for different constellations size. Moreover, an ideal channel is assumed and the destination drop the received packet if the BER fall below 10^{-3}.

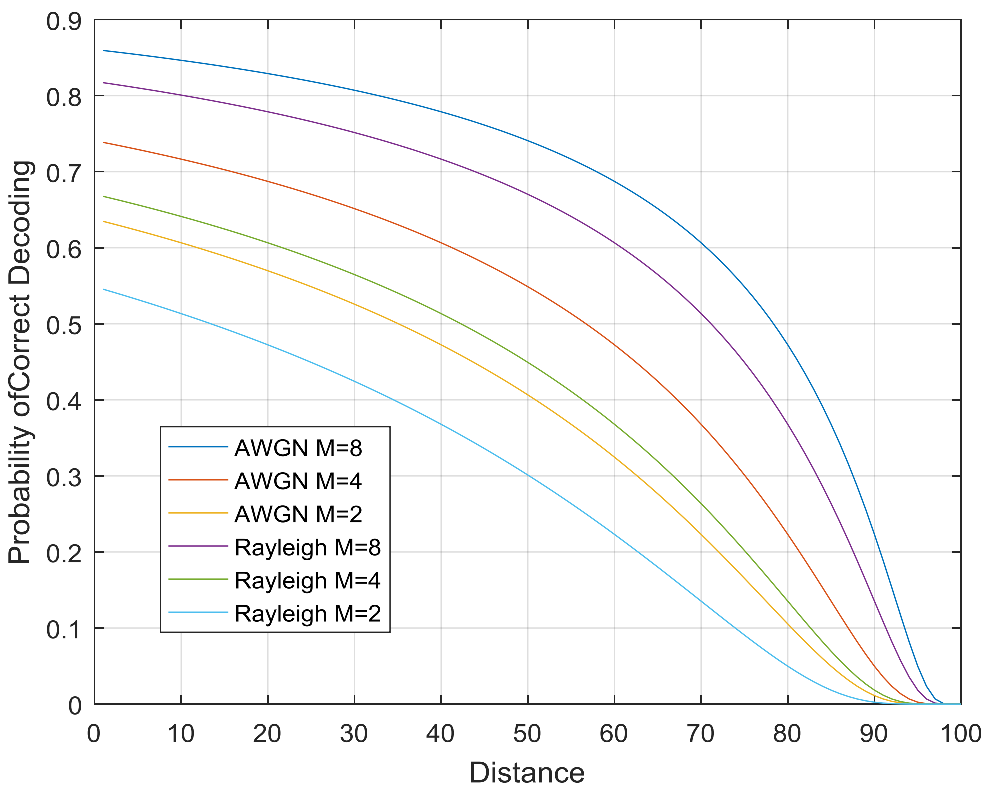


Figure 3.16: Probability of Successful Transmission at Different Distance (Meters), (AWGN, uncoded MQAM)

Figure 3.16 shows the probability of correct decoding in AWGN and Rayleigh fading channel against the transmission distance. For different transmission strategy in both channels, the probability of error increase with the transmission distance, and in correlation to constellation size. the same experiment is repeated for coded MQAM, and the results are given in Figure 3.17. Similar to uncoded MQAM, probability of correct decoding in coded MQAM system decrease with transmission distance although better performance observed due to the coding gain. For example, the probability of correct decoding at 60 meters transmission range is 0.6 for a constellation size of 6 in Rayleigh channel in uncoded MQAM, while the probability of correct decoding for coded MQAM is 0.8 at the same condition as observed Figure 3.16.

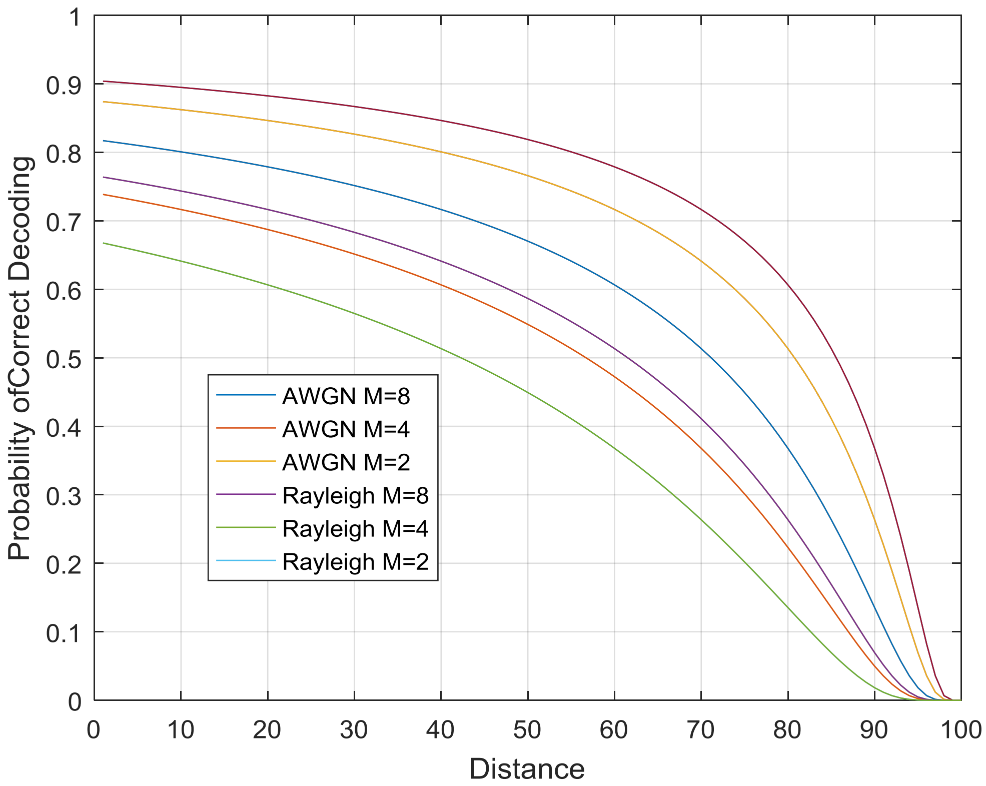


Figure 3.17: Probability of Successful Transmission at Different Distance (Meters), (Rayleigh, coded MQAM)

the number of available candidate relay is examined based on a probabilistic approach for coded and uncoded MQAM in AWGN and Rayleigh fading channel. The Probability that a node is a successful relay is evaluated in equation (3.37) where m is evaluated using (3.39) and the maximum source transmission range set to 150 meters while the overall transmission distance between the source and the destination is assumed 250 meters. Thus, candidate relays should have $S-R$ length lower than the source maximum transmission range which determines the number of available candidate nodes m. Consequently, the node with instantaneous SNR above the required threshold is considered as potential relay. For each transmission range the source compute the state of the node and if the condition in (3.43) is satisfied, the counter is increased by one.

$$P(n=1)=\Pr(n/m)P(\gamma_1 > T_1)P(\gamma_2 > T_2) \tag{3.45}$$

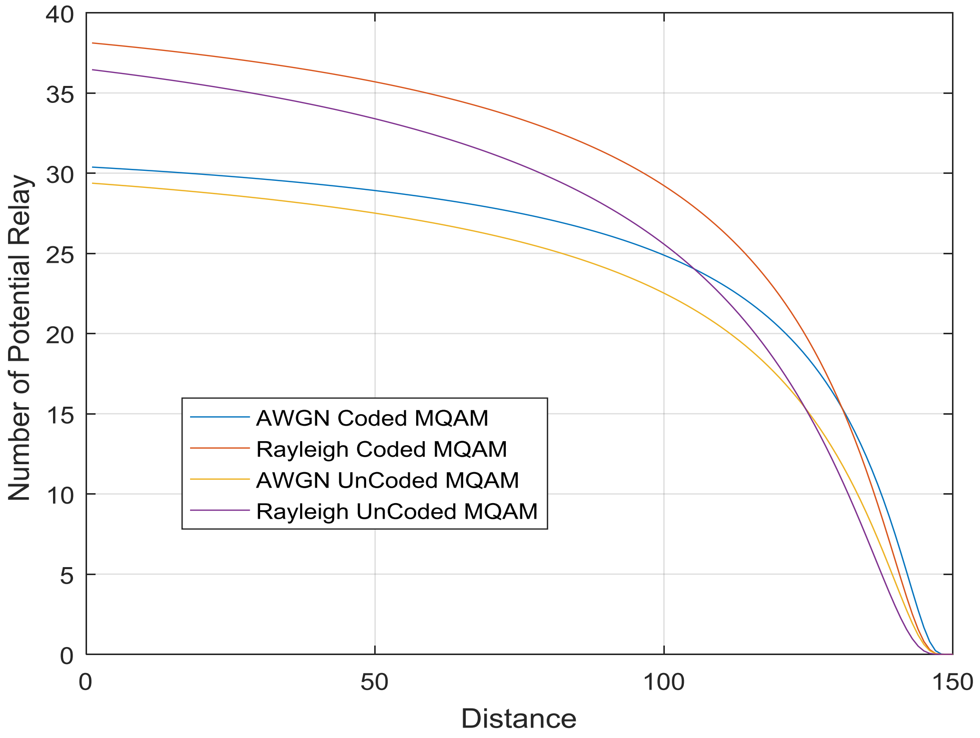


Figure 3.18: Number of Potential Relays vs Distance (Meters)

Figure 3.18 shows the number of potential relays against distance in meters. In AWGN scenario, coded and uncoded MQAM have the same performance and it can be clearly seen that a drastic decrease in the number of candidate relay arises at distance above 100 meters. Furthermore, in Rayleigh fading channel we examine the same result with a slightly poorer performance compared to AWGN channel for coded MQAM and uncoded MQAM. For all the examined scenarios, the probability of the high number of candidate relay is at a transmission distance below 50 meters. This observation is used to set the timer in equation (3.34). In other word, for a desired transmission distance of 100 meters, the source use for uncoded MQAM in Rayleigh fading channel, while equal 30 is used for coded MQAM in Rayleigh channel. This approach minimises the time spent at idle state for the source and candidate relays, as the source should receive the Beacon message within 1ms after the RTS/CTS exchange, in case of 20 successful relays and 100ms transmission deadline.

3.6 Simualtion Results

The performance of the proposed algorithm is evaluated using the parameters given in Table 2. the performance of the proposed algorithm is illustrated in terms of energy cost per bit at the source, energy cost per bit at the relay and the total energy cost. The performance of the proposed algorithm is compared with three different techniques named as: relay selection at the source, relay selection at the destination and Threshold based relay selection. For the three methods the selection is done based on equation (3.39). For the source relay selection method, the node with minimum path length to the source is the successful relay, while in relay selection at the destination the node with minimum distance to the destination is the successful relay. In both methods, relay compete using equation (3.33) with a significant modification. d_{RD} is set to zero in destination relay selection while d_{SR} is set to zero in source relay selection method. In Threshold based relay selection method, the node that satisfy the condition in (3.39) and has the minimum desired SNR of both link is the successful relay, and candidate relay compete using equation (3.44), following the same procedure in equation (3.39), where the relay with minimum SNR has the priority to send the beacon message and win the relay role.

$$\Delta_i = \frac{y_{SR} + y_{RD}}{y_{SD}} \phi \qquad (3.46)$$

the source, destination and the relay transmits RTS, CTS and Beacon using equation,(3.19) or (3.20) or (3.24) or (3.25) based on the channel model used and the modulation strategy, and the transmit power is set to $P_{\max}$ calculated based on direct transmission path length. Moreover, full synchronization between nodes is assumed and the probability of collusion is omitted. Through the simulation, the proposed algorithm is referred as the optimal location. A 100 ms transmission deadline is assumed and the proposed method switch between coded and uncoded MQAM to satisfy the system performance requirement explained in section 3.5.3. Results are illustrated for coded MQAM or uncoded MQAM separately as other relay selection methods communicate using coded MQAM or uncoded MQAM. Moreover, the proposed algorithm selects the optimal constellation size and switch between coded MQAM and uncoded MQAM in contrast to others selection methods where the constellation size follows the observation in section 3.5.2.

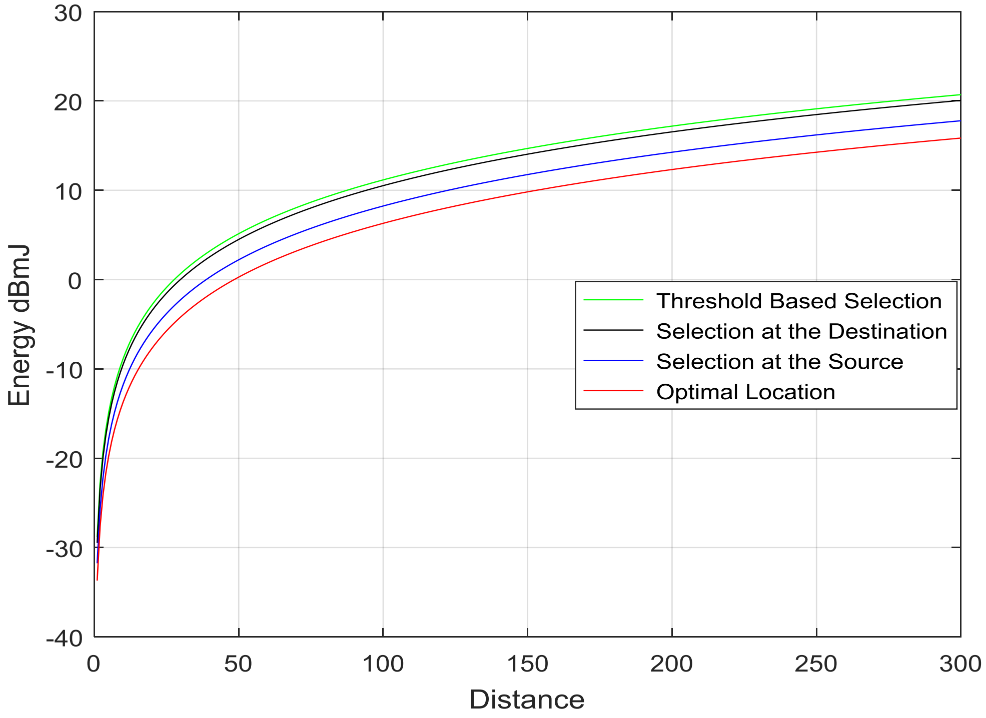
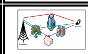


Figure3.19: Source Energy Cost per Bit at Different Distance (Meters), (Rayleigh, uncoded MQAM)

Figure 3.19 considers the energy cost per bit at the source and relay respectively in Rayleigh fading channel for uncoded MQAM. The proposed algorithm outperforms the three methods in terms of energy consumption per bit showing an improvement around 3dB at different transmission distance.

Table 3.2: Simulation Parameters

Parameters	Annotation	VALUE
Drain Efficiency	η	0.35
Thermal Noise PSD	N_0	-171dBm / Hz
Target Bit Error Rate	P_e	10^{-3}
Carrier Frequency	f_c	2.5GHz
Bandwidth	B	$1MHz$
Packet Length	L	$200Kb$
Link Margin	M_l	$40dB$
Transmission Deadline	T	$100ms$
Mixer Power	P_{MIX}	
ADC & DAC Power	P_{DAC}, P_{ADC}	$15.4mW$
LNA Power	P_{LNA}	$20mW$
Active Filter Power	P_{FILR}, P_{FILT}	$2.5mW$
Frequency Synthesizer Power	P_{SYN}	$50mW$
Receiver Noise Figure	N_f	$10dB$
Intermediate Frequency Amplifier Power	P_{IFA}	$3mW$

.

Figure 3.20 illustrate the energy consumption at the relay for different transmission range, and the proposed algorithm outperforms other methods at different transmission distance. From Figure 3.19 and Figure 3.20, the proposed algorithm shows better performance by around 4dB compared to the destination relay selection method as in the constellation size is considered in the optimization metric. Moreover, compared to the threshold based selection the optimal location shows 3 dB improvement as the bit energy cost is calculated based the path length and using the optimal modulation strategy, while in threshold based relay selection, the source and relay transmit power subject to achieve SNR level at the receiver.

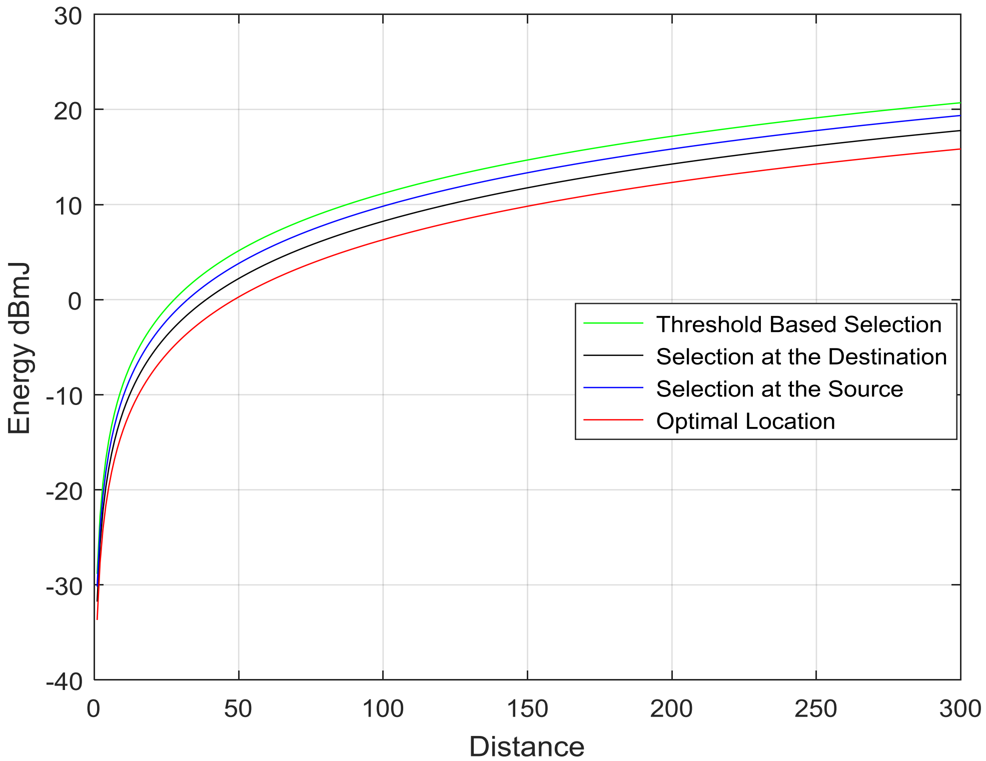


Figure 3.20: Relay Energy Cost per Bit vs Distance (Meters) (Rayleigh, uncoded MQAM)

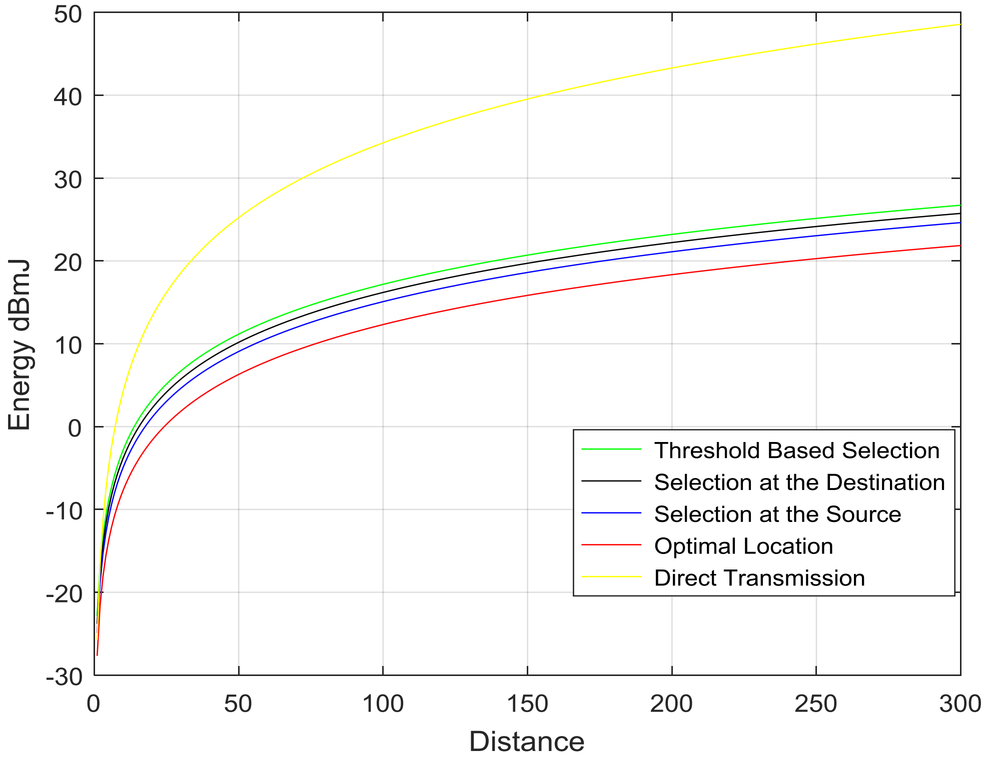


Figure 3.21: Total Energy Cost per Bit vs Distance (Meters), (Rayleigh, uncoded MQAM)

Figure 3.21 illustrates the total energy cost per bit, for three methods in addition of direct transmission mode against the transmission distance. It can be clearly seen the improvement in terms of energy saving by around 30dB at a transmission distance of 300 meters when comparing the optimal location to direct transmission. Moreover, the total energy cost per bit is reduced by minimum 3 dB in optimal location method, compared to other selection methods.

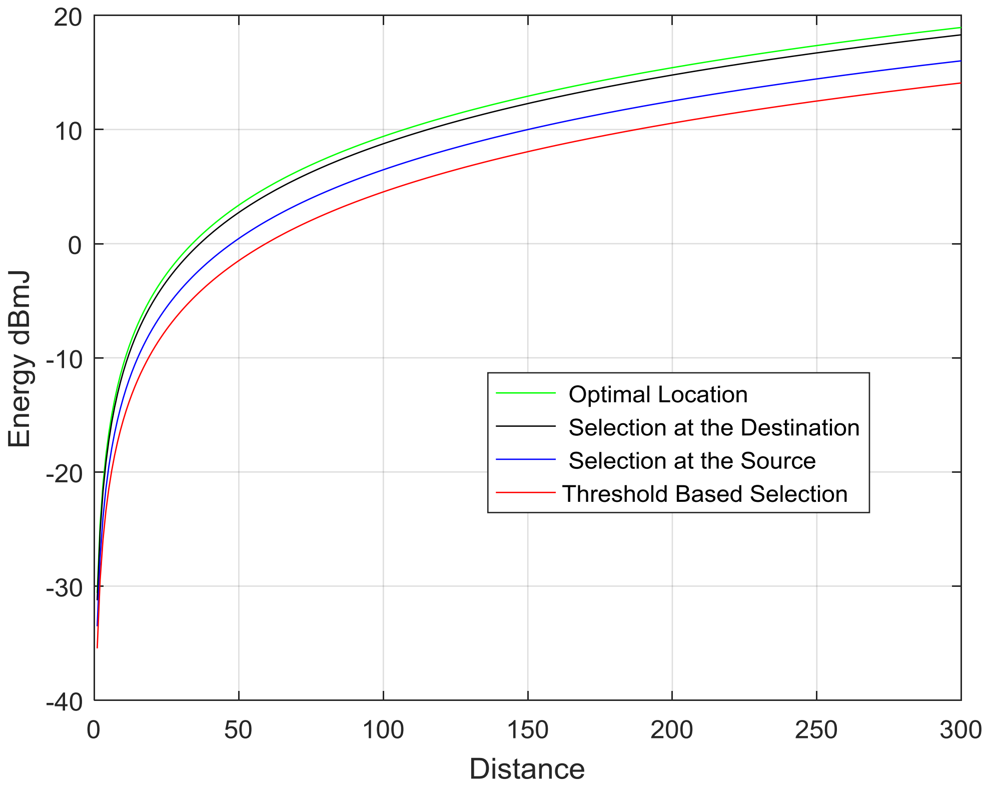


Figure 3.22: Source Energy Cost per Bit at Different Distance (Meters), (Rayleigh, Coded MQAM)

We repeat the same experiment for coded MQAM system in Rayleigh fading channel, and the results in Figure 3.22, Figure 3.23 and Figure 3.24 show the performance in terms of energy consumption per bit at the source, energy consumption per bit at the relay and the total energy consumption respectively. Similar to uncoded MQAM, the proposed algorithm minimizes the energy consumption at the relay, the source and the total energy cost per bit is reduced significantly. However, an increase of energy cost per bit for the other three methods is observed due to the additional energy cost of error correction code. From the above results, it's clear that the proposed algorithm minimises the energy consumption in Rayleigh fading channel compared to other relay selection techniques regardless of the using coded MQAM or uncoded MQAM.

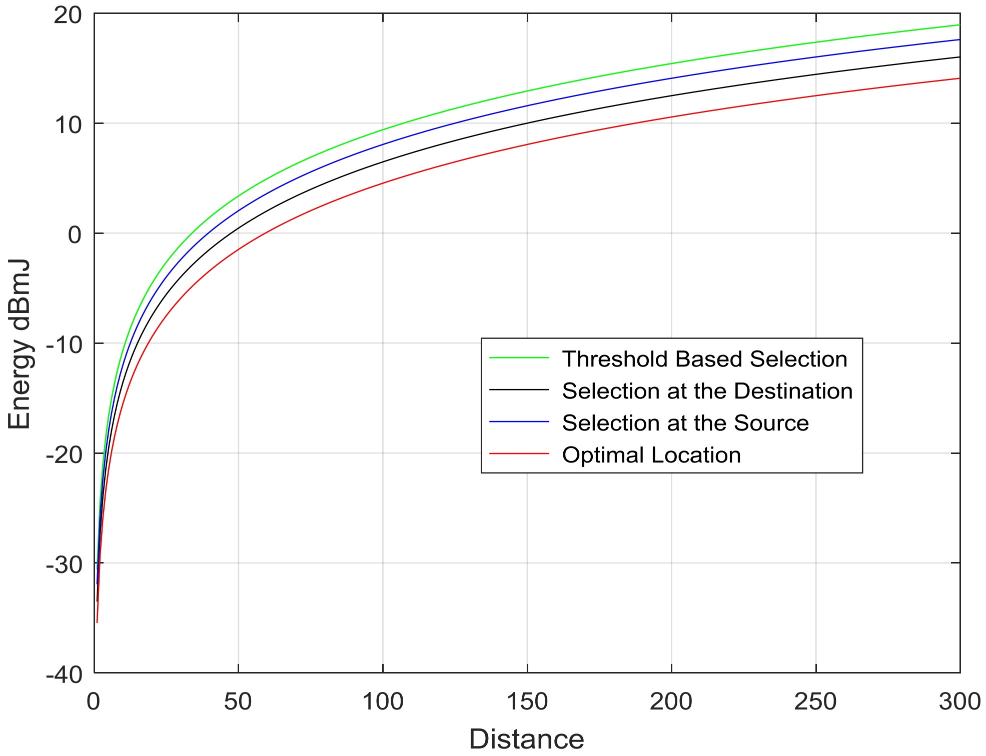


Figure 3.23: Relay Energy Cost per Bit at Different Distance (Meters), (Rayleigh, Coded MQAM)

We illustrate the performance of the proposed algorithm and compare the energy consumption with other selection methods using the same selection policy in AWGN channel. For transmission in AWGN, we consider a maximum transmission distance of 150 meters as for longer transmission range. The energy cost per bit at the source and the relay are illustrated in Figure 3.24 and Figure 3.26 respectively, and the performance is given by plotting the energy cost in dBm mJ against distance in meters.

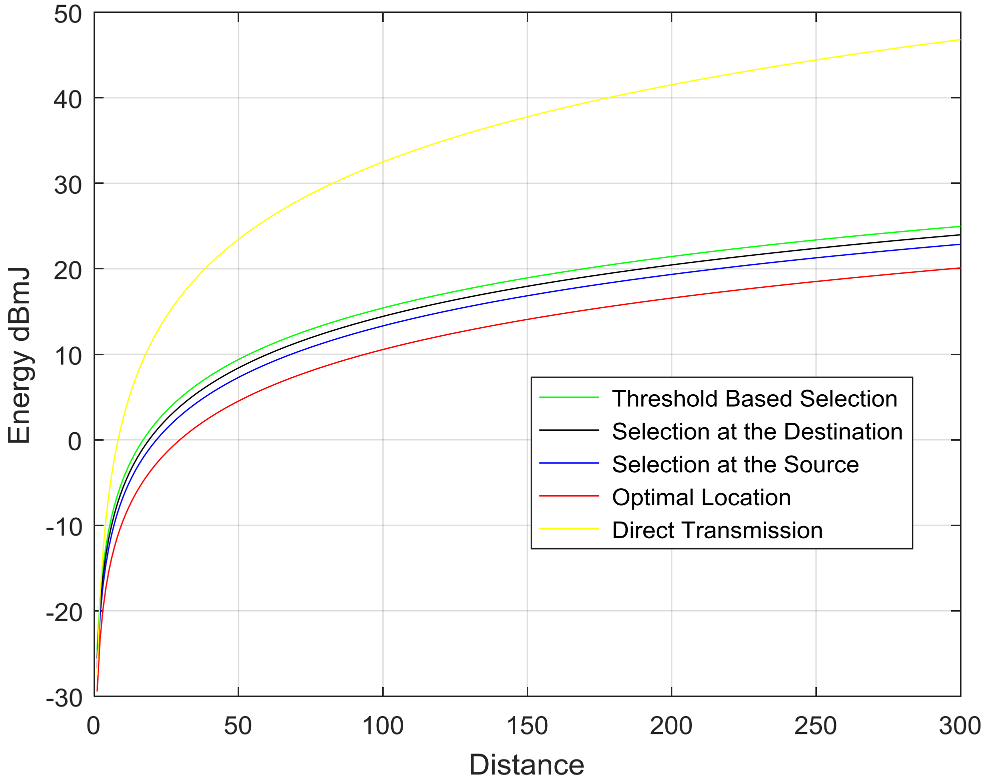


Figure 3.24: Total Energy Cost per Bit at Different Distance (Meters), (Rayleigh, Coded MQAM)

The energy cost per bit at the source is improved be around 7 dB in the proposed algorithm compared to threshold based selection, and around 4 dB compared to other methods. Furthermore, the proposed algorithm improves the energy cost per bit at the relay by an average of 3 dB compared to threshold based selection and source selection. In addition of that, the proposed algorithm outperforms the selection method at the destination in terms of energy consumption at the relay by an average 2 dB at different distance.

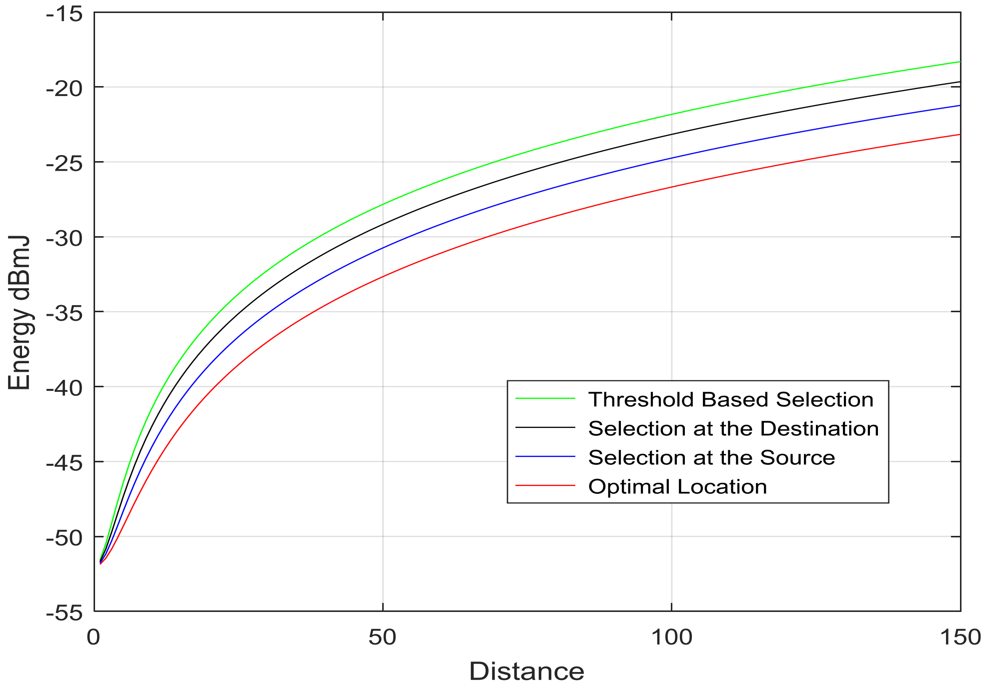


Figure 3.25: Source Energy Cost per Bit at Different Distance (Meters), (AWGN, Uncoded MQAM)

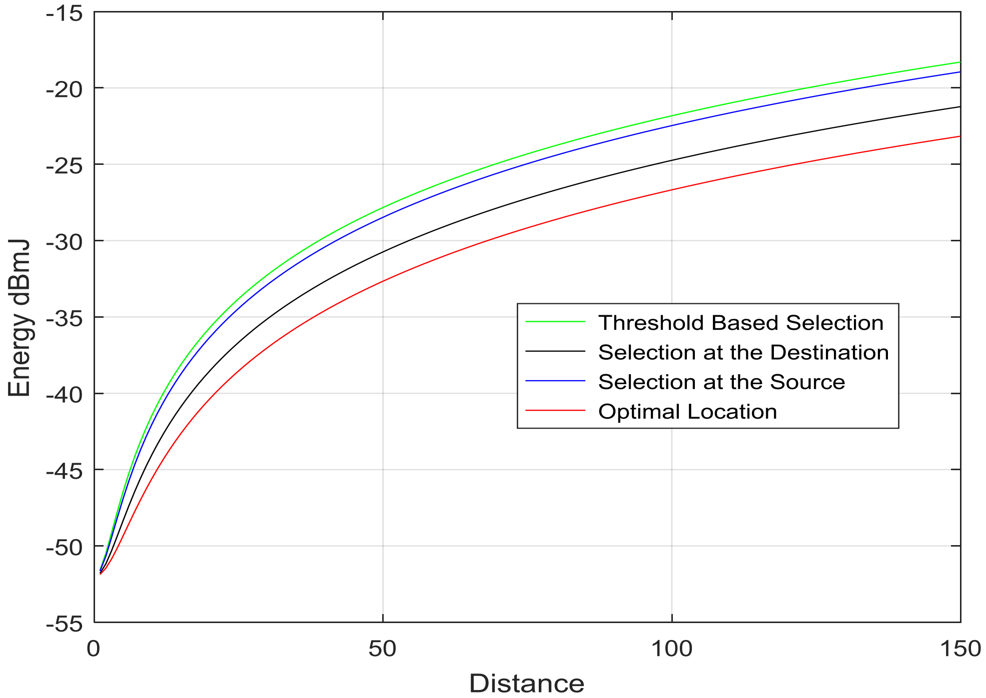


Figure 3.26: Relay Energy Cost per Bit at Different Distance (Meters), (AWGN, Uncoded MQAM)

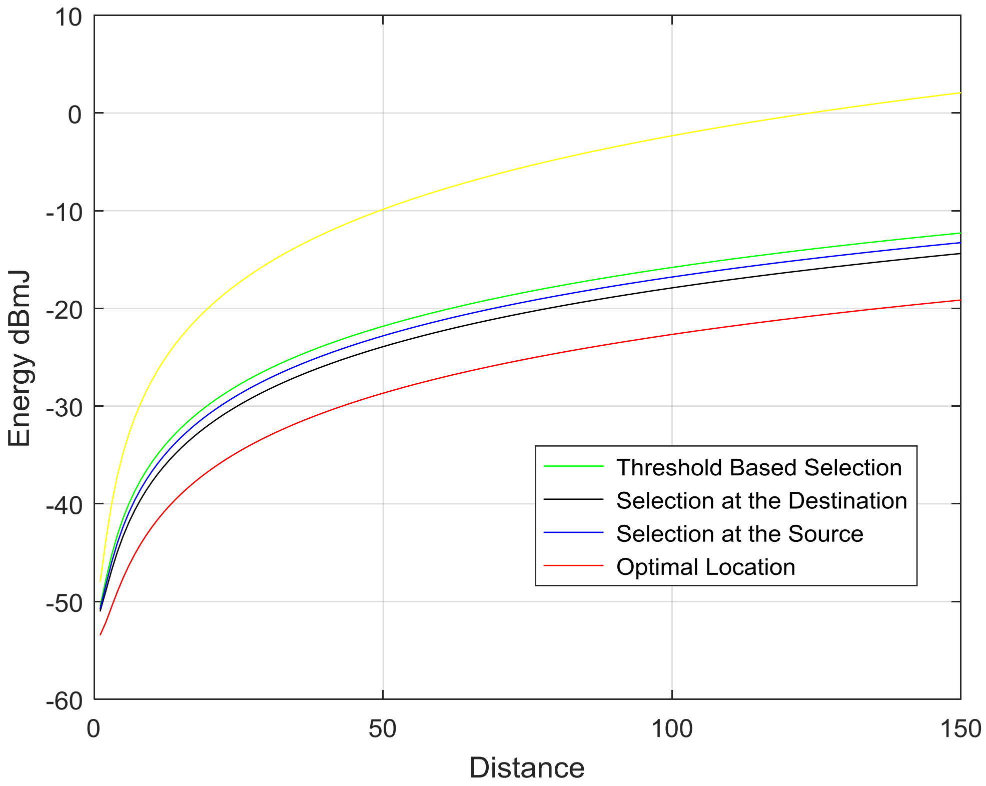


Figure 3.27: Total Energy Cost per Bit at Different Distance (Meters), (AWGN, uncoded MQAM)

From Figure 3.27, an improvement of 20dB in terms of the total energy cost per bit between direct transmission and the proposed algorithm for a transmission distance greater than 50 meters. Moreover, the proposed algorithm outperforms the other three selection methods by an average of 4 dB at different transmission distance. This improvement due to modulation strategy optimization jointly implemented with relay selection approach and switching between coded MQAM and uncoded MQAM. We consider coded MQAM in AWGN channel, and we plot the energy cost per bit at the source and the relay against the transmission path in Figure 3.28 and Figure 3.29. Following the same selection policy in the previous experiments, we compare the performance of the proposed algorithm with threshold based relay selection, source relay selection and destination relay selection for a maximum transmission distance of 150 meters between the source and the destination.

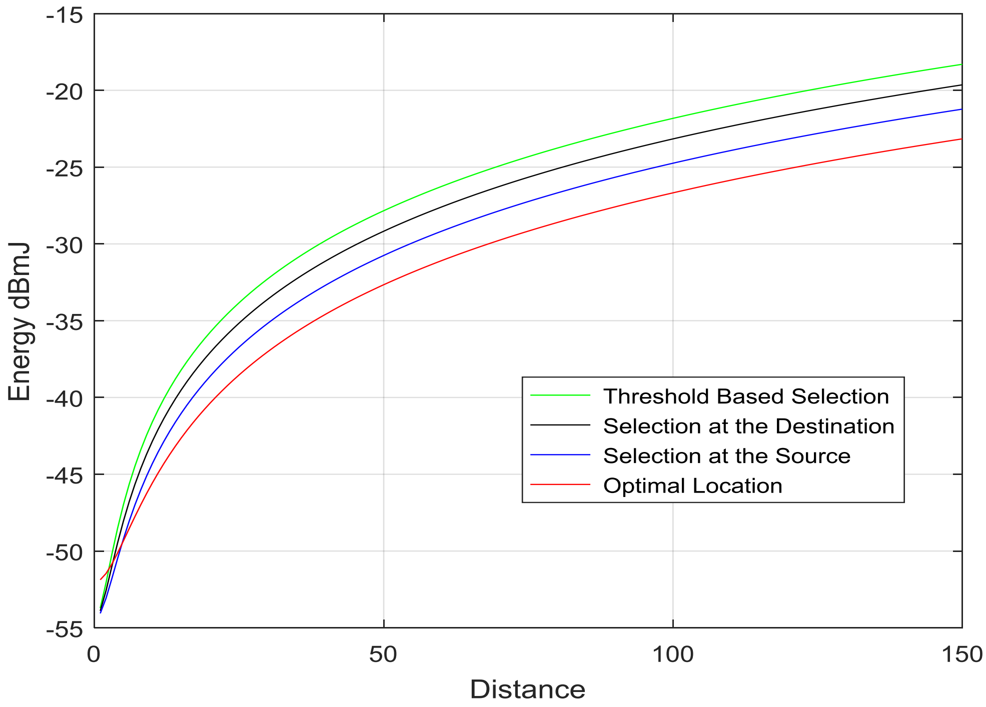


Figure 3.28: Source Energy Cost per Bit at Different Distance (Meters), (AWGN, Coded MQAM)

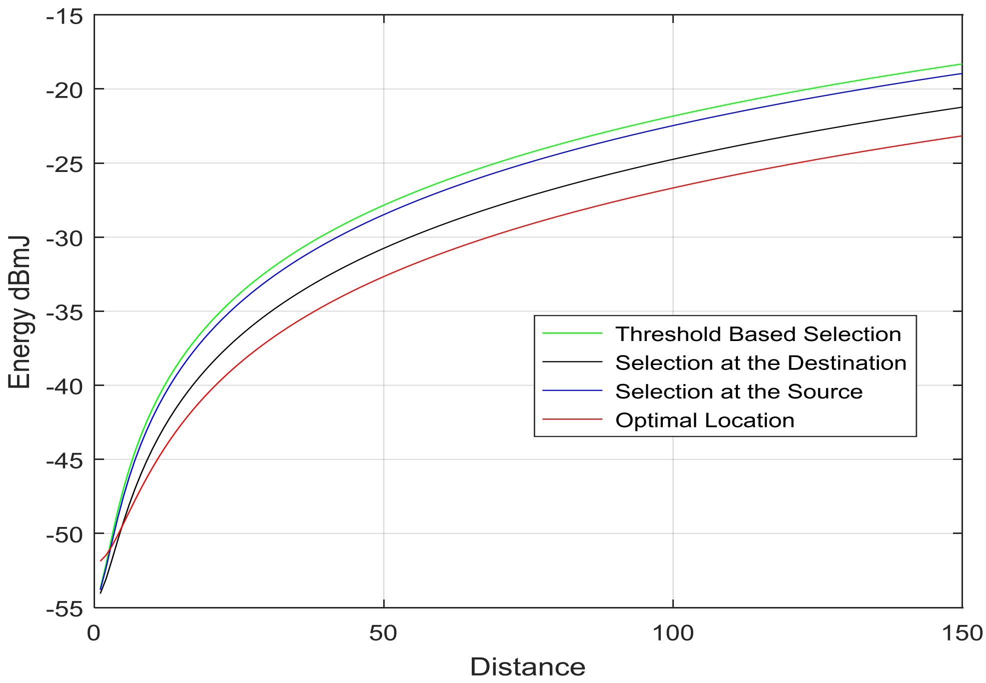


Figure 3.29: Relay Energy Cost per Bit at Different Distance (Meters), (AWGN, Coded MQAM)

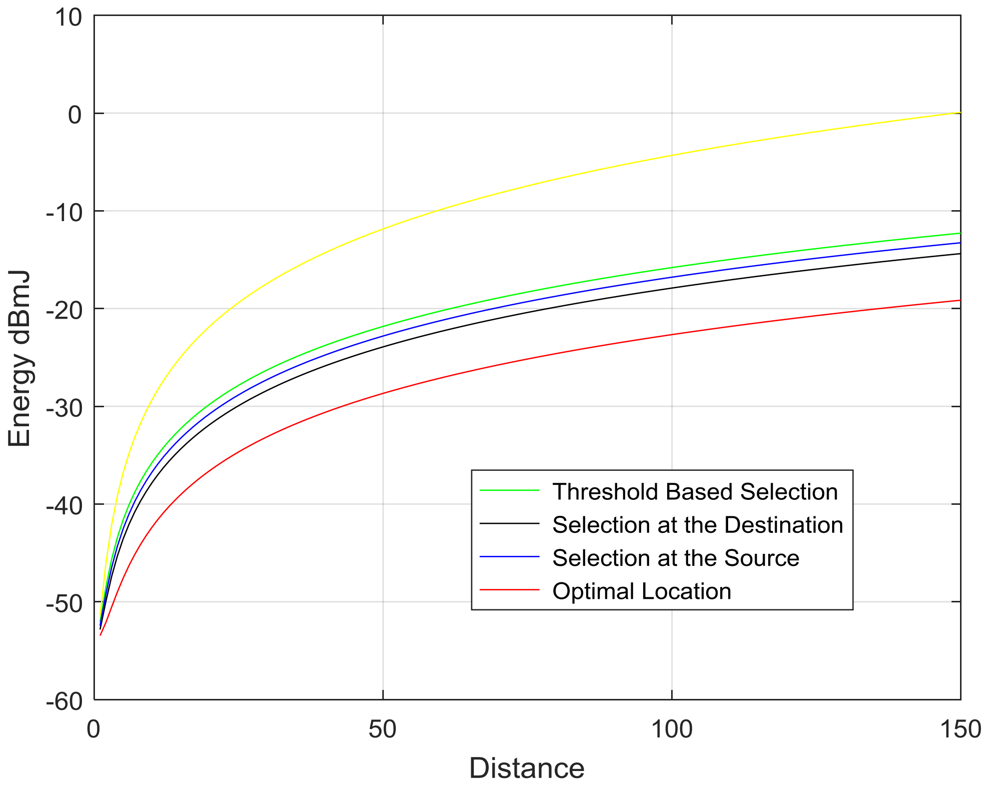


Figure 3.30: Total Energy Cost per Bit at Different Distance (Meters), (AWGN, Coded MQAM)

The total energy cost per bit for all transmission schemes is given in Figure 3.31, in addition of the energy cost in direct transmission mode. The proposed algorithm outperforms the direct transmission by showing an improvement of an average 20 dB when we compare the energy cost at different transmission distance. Moreover, the proposed algorithm consumes less energy per bit by an average of 6 dB less than the threshold selection based, and 5 dB compared to the selection at the source or at the destination. The proposed algorithm benefit from the observation given in section 3.5.2 and section 3.5.3 which illustrate the impact constellation size, coded MQAM and uncoded MQAM on the energy cost for short transmission and long transmission range. Therefore, the adaptive solution employed in the proposed algorithm offer a better energy saving regardless of the communication strategy. The proposed algorithm outperforms other techniques at short and long transmission range due to implementation of relay selection in line with complete selection policy.

3.7 Summary

In this Chapter, an energy efficient relay selection algorithm for cooperative wireless network was proposed. A distance based selection method in line with an SNR threshold are used, whereby nodes that fulfils the criterion of having both links SNR above the required threshold compete to participate in the transmission and the node with minimum distance to source and destination is selected as relay. Consequently, the overall transmission path is minimized, which decrease the energy cost per transmitted bit. The constellation size has been investigated through numerical example for two communications scenarios; coded and uncoded system in AWGN and Rayleigh fading channel and the optimal solution is proposed using analytical analysis. The proposed method outperforms the traditional threshold based selective relaying method, destination relay selection method and source relay selection method in terms of energy cost per bit at the source, the relay and the total transmission energy cost. However, the proposed algorithm use distance based relay selection in addition to the joint optimization policy which is adaptable to any wireless system requirements. Thus, for different delay or BER requirements, the relay and the source apply the proposed policy to meet the target performance subject to the power constraint. Moreover, the proposed algorithm is compatible with variable rate system, as the constellation size is optimized subject to power constraint. Thus, in the next chapter we investigate and present the performance of the proposed algorithm in system where multiple relay cooperate in the transmission.

Chapter 4: Energy Efficient Virtual MIMO

In this chapter, energy efficient relay selection algorithm for cooperative virtual multiple-input-multiple-output (MIMO)is proposed. The proposed algorithm in Chapter 3 is extended to variable and fixed wireless system where multiple relays cooperate in the transmission. The impact of the constellation size and coding on energy consumption are investigated and the optimal cooperation strategy is proposed for different MIMO configuration.

4.1Introduction

Over recent years, virtual multiple-input-multiple-output systems (MIMO) has been intensively studied and have shown to be an efficient technique to overcome the space limitation of deploying multiple antennas in physical size constrained wireless nodes [107]. In these techniques, multiple nodes collaborate to form a virtual antenna array, and jointly cooperate in the signal reception or/and transmission [108 109]. In distributed wireless networks, cooperative virtual MIMO were used to exploit the spatial and temporal diversity gain achieved in MIMO systems, therefore the probability of deep fading is minimized by the different paths created which improve the link reliability [110 111].

Moreover, the concept of virtual MIMO benefits from relaying techniques introduced into those networks, overcome dead-spots, improve data rate, extend coverage and guarantee inter-connectivity [112 113]. The demand for higher data rates communications over longer distances was the primary motivations for the development of MIMO systems used in modern wireless standards, including in IEEE 802.11n, such as in WiMAX systems as they support higher throughput under bad channel conditions, interference, fading environment and multipath [114]. The benefits of MIMO are mainly observed in the channel capacity limits defined by the Shannon theorem given in equation (4.1). It can be clearly seen that an increase in the SNR or the bandwidth results in marginal gains in channel throughput.

$$C = B\log_2(1+SNR) \tag{4.1}$$

As MIMO systems provide multiple signal paths by the spatial dimension of a communications link offered, these systems can achieve significantly higher data rates than the traditional SISO systems. Accordingly, the receiver can recover independent signals from each path and MIMO system produces multiple streams to effectively that increase the data rate achieved in a SISO system. Researchers approximate the channel capacity of a MIMO system as a function of the transmitted streams number, and the MIMO channel capacity is approximated as a function of streams number, bandwidth, and SNR and is given in (4.2) used for various implementations of SISO and MIMO systems

$$C = NB\log_2(1+SNR) \tag{4.2}$$

For Example, following the IEEE 802.11g specification, wireless local area network (WLAN) transmitting using SISO configuration achieve a maximum coded data rate of 54 Mb/s using 64-QAM modulation estimating a25 dB SNR in 20-MHz bandwidth. By contrast, 4*4 MIMO system achieves a bit rate of 4 x 94 Mb/s = 376 Mb/s that produce a data rate of 288.9 Mb/s for the same specification, that is slightly comparable to the limit of the Shannon theorem 376 Mb/s. Thus, MIMO systems are more practical for higher throughput. Inspired by MIMO, virtual MIMO have been introduced to cooperative wireless network and shown to be an effective technique to combat the fading nature of the wireless channel and improve the wireless system performance [116 117 118]. Cooperative-virtual MIMO schemes, in which the transmitting and/or receiving wireless nodes does not necessarily have multiple antennas, but it's a group of single/multiple antenna transmitters and single/multiple antenna receivers, grouped together to form a cluster and act as a MIMO system at each side as shown in Figure 4.1[119 120]. Virtual MIMO has several variations, the trivial case SISO, SIMO (a cluster of transmitting nodes sending to a single node), MISO (one single node sending to a cluster of nodes, shown in Figure 4.2) or MIMO (a cluster of several nodes sending to another cluster of several nodes shown in Figure 4.1).Although, virtual MIMO systems provide clear benefits at the application level, the design of virtual MIMO schemes is not without significant challenges such as synchronization to deal with the unknown number of antennas. Moreover, digital signal processing (DSP) require more sophisticated baseband processing algorithms to better interpret the channel model [121 122 123].

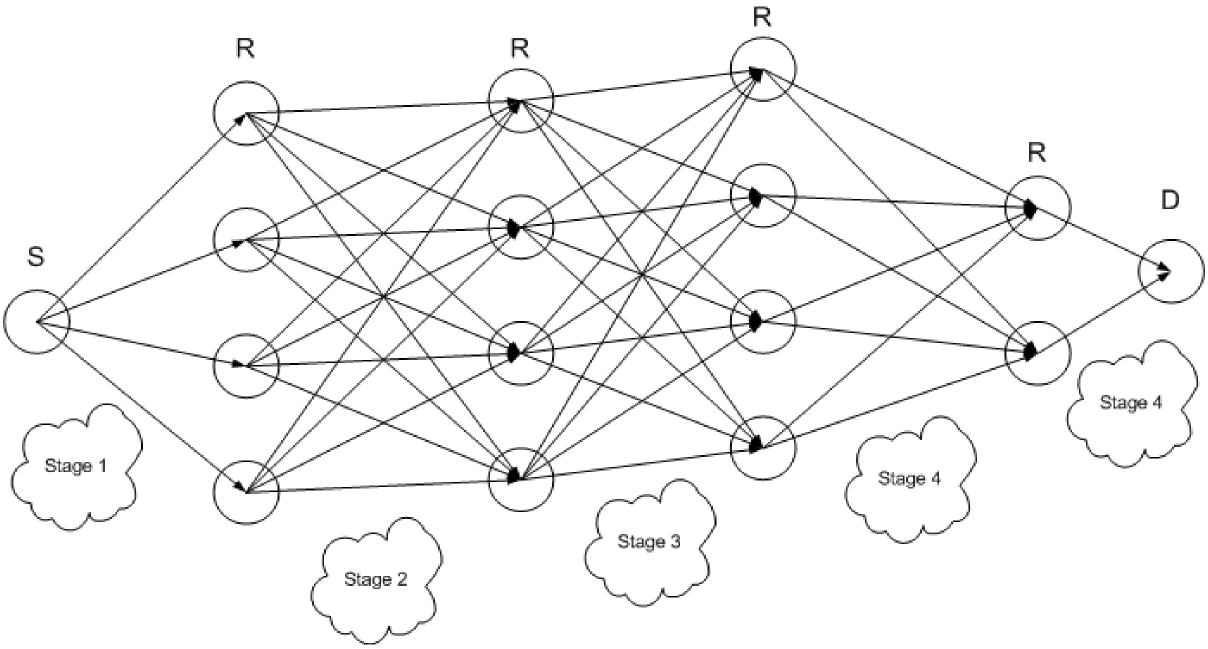


Figure 4.1: Multi stages Cooperative Virtual MIMO in Wirleess Network.

The massive enhancement in the network performance using virtual MIMO, add an energy penalty caused by the additional circuit operations as more nodes are involved in the transmission [124]. Since the pioneer work in [125]and in [126], where the authors derived the energy consumption of virtual MIMO systems, the architecture proposed and the energy consumption affecting factors has been the core several works to illustrate the performance of those schemes in cooperative wireless networks from different perspectives. Hence, virtual MIMO cooperative communication performance in terms of energy efficiency has been studied and investigated for fixed rate or variable rate system [127]. Moreover, routing approach in those schemes and the impact on energy consumption was investigated in [128], showing the necessary of optimizing the system parameters.

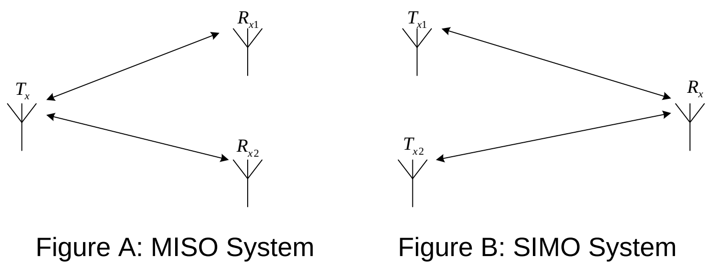


Figure 4.2: A-MISO configuration, B-SIMO configuration.

In [129], it has been proved that MIMO systems require less transmission energy than SISO system for the same throughput requirements. This topic was deliberate in [130], showing that for a critical distance between transceivers, MIMO outperforms SISO in terms of energy efficiency. Consequently, it has been proved in [131] that nodes operating on MIMO structure and employing STBC spend less energy than SISO systems. The most recent progress towards improving virtual MIMO in terms of energy efficiency is introducing relay selection schemes. Hence, under certain selection criteria the system performance in terms of energy efficiency can be improved, and several routing techniques and optimization schemes have been proposed in the literature [132 133 134 135]. Virtual MIMO communication techniques has been intensively studied in the literature as they have shown great improvement of energy efficiency in cooperative wireless networks, and several techniques has been proposed in the literature on various multi-input, mutli-output approach[136 137138].DF and AF energy efficiency performance was analysed in [139], for various relay position subject to SEP at the destination. The authors investigate the coloration between the energy cost and the transmission distance, and results prove that DF outperforms AF at long distance. In [140], cooperative MISO performance in terms of energy efficiency and delay has been investigated using a joint optimization strategy, and the proposed routing methods based on minimizing the end-to-end energy consumption shown better performance compare to SISO system. In [141], the routing protocol selects the optimal transmission path that minimizes the energy cost, and shown better performance compared to SISO transmission in terms of the network lifetime. In [142], a finite feedback rate was used to determine the transmit power in clustered WSN and the performance of the proposed algorithm extend the nodes serving time. In [143], energy efficiency in cooperative MISO was triggered using a selection function that determines the number of cooperative nodes in clustered WSN. The proposed selection function, which combines the channel condition, residual energy and inter cluster distance, have shown to be more energy efficient than SISO or non-selective approach. Moreover, the performance of cooperative MISO in multi-hop network was compared to other transmission techniques, and it was shown that single hop transmission outperforms multi-hop under certain distance threshold [144]. In addition of that, energy efficient for cooperative MISO was approached using power allocation, where the authors proposed determining the transmit power using analytical calculation before the cooperative transmission [145]. In cooperative virtual MIMO, energy efficiency was triggered by proposing node selection for Virtual MIMO formation such as in [146]. However, to the best of our knowledge distance based node selection has not been used a relay selection to optimize the energy consumption in MIMO. To the best of our knowledge, distance haven't been proposed a relay selection metric in cooperative communication. We propose an energy efficient relay selection algorithm for different MIMO configuration.

The relay selection algorithm given in Chapter 3 is extended to virtual MIMO systems where multiple nodes cooperate with a transmitting node.

The contribution of this chapter can be summarized as follow:

- The relay selection algorithm given in Chapter 3 is extended to cooperative wireless network where virtual MIMO is used, and multiple relays are involved in the transmission.
- The constellation size and the impact on energy cost is investigated, thus we propose the optimal modulation strategy jointly with the proposed relay selection algorithm.
- A novel energy calculation approach for fixed rate and variable virtual MIMO system is used which based on MISO configuration.
- An adaptable solution to the channel condition is proposed benefiting from the RTS/CTS packet, thereby the relay(s) adjust the transmit power.
- An adaptive solution for virtual MIMO systems is proposed, as switching between different operation mode is implemented.

The rest of the chapter is organized as follows: In Section 4.2, the system of the proposed scenario, MIMO different configuration and the communication model are given. In Section 4.3, communication scenario using DSTBC is given. In Section 4.3, the energy consumption per bit in virtual MIMO is derived for different configurations in Rayleigh fading channel, for fixed rate and variable rate system. In Section 4.4, the impact of the constellation size is investigated for fixed rate and variable rate system through simulations. In Section 4.5 analytical analysis of the proposed scenario with problem formulation are illustrated through simulations. In Section 4.6 the proposed relay selection algorithm with link performance is given. In this regard, the impact of relay location is investigated through numerical example and the optimal solution is given. The performance of the proposed algorithm is illustrated and compared to other methods through simulation using numerical values in Section 4.7. Finally, Section 4.8 concludes this chapter.

4.2 System Model

4.2.1 Virtual MIMO Configuration

Consider the wireless network shown in Figure 4.3, where two wireless nodes communicate with the help of N nodes and the communication mode sis MIMO, or SIMO or MISO. In MIMO configuration, the communication consists of three stages. At the first stage the source transmits the message signal to T transmitter's nodes, and those nodes retransmit to R receiver's nodes at stage two. At stage three, the receiver's nodes forward the message to the destination.

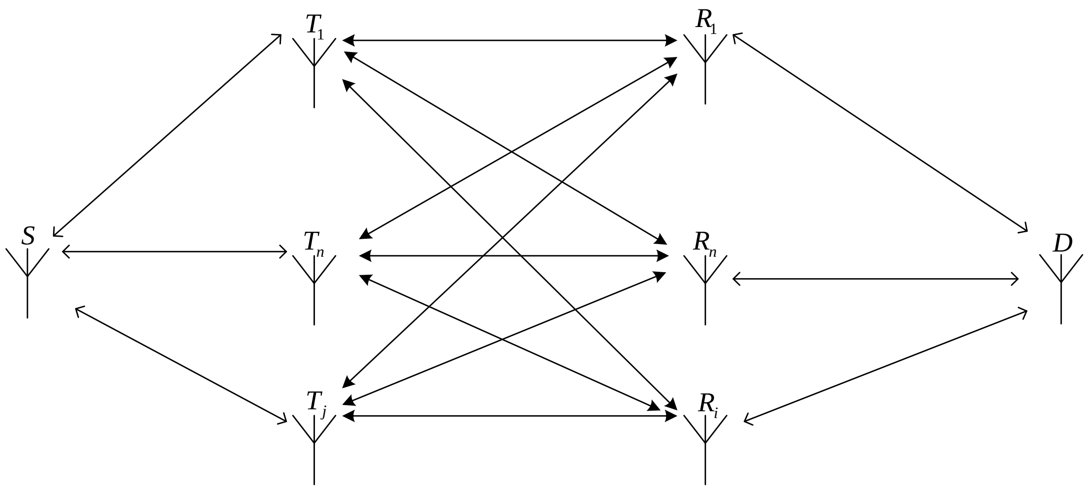


Figure 4.3: Virtual Cooperative MIMO System

At stage one, SIMO configuration is employed, while MIMO is implemented as stage two and MISO is executed at stage three. In MISO configuration, the source transmits at stage one, and N relay nodes forward the message to the destination at stage two. MISO transmission is employed between the relays and the destination as multiple virtual antenna transmits to single antenna terminal. SIMO configuration is a special case, when multiple source transmits at stage one, and single relay forward an aggregated message to the destination at stage two. This scenario can be observed in WSN, such the case when a cluster head (CH) message is received by multiple cluster members, then after forwarded to the next hop or the destination. For the three scenarios, we assume the source packet size is L , and the network support a throughput of L/T packets per second, where T is the transmission deadline. The Communication implement TDMA scheme, and each transmission stage is assigned timeslot, with the total transmission time bounded by T . The transmitter bit rate (number of bit per symbol), and the constellation size (number of modulated bit per symbol) depend on the distance between transmitters and receivers as variable rate system is considered. Using MQAM, the constellation size is given as. We assume a flat Rayleigh fading channel between each transmitter receiver pair, and the power falloff proportional to the distance squared following the path loss equation. We assume all the nodes have perfect channel information from the RTS/CTS packet exchange at the beginning of the transmission.

4.2.2 Distrusted Space Time Block Coding

In the proposed model, the destination receives the source(s) signal via multiple relays, and different MIMO configuration executing Distributed STBC scheme. Through the rest of this chapter we assume 2*2 MIMO, 1*2 SIMO and 2*1MISO which can be expended to superior number subject to system requirements. Let's assume the source transmits the signal sequence S_0 and S_1 to2 transmit relays and the signal received at the i relay is given by

$$T_i = \sum_1^f h_{ij} S_f + N_i \tag{4.3}$$

where f and N_i are the symbol index and the noise captured by the source-relay channel h_{ij} .The transmit relays forwards the signal using equation (4.4) at stage two.

$$S = \begin{pmatrix} S_0 & S_1 \\ -S_1^* & S_0^* \end{pmatrix} \quad (4.4)$$

At the end of stage two, the received signal at the receive relays is given by

$$R_i = \sum_1^t \sum_1^j g_{ij} S_j + N_{ji} \quad (4.5)$$

where j and t are the transmit relay index, and the timeslot index respectively, and N_{ij} is the noised captured between the transmit and receive relay. At stage three, the received signal at the destination is given by

$$D = \sum_1^t \sum_1^j w_j R_j + N_j \quad (4.6)$$

where w_j and N_j are the relay-destination channel coefficient and the noise captured. For MISO configuration the received signal at the relays follow the step given in equation (4.3) and the relays transmit using equation (4.4). Thus, the signal received at the destination is given by

$$D = \sum_1^t \sum_1^j w_j S_j + N_j \quad (4.7)$$

For SIMO configuration we consider a specific scenario, where two nodes receive the source signal, and forward it to the relay. This scenario is mainly found in clustered wireless network, where clusters members form a virtual SIMO within the cluster head, then MISO configuration is used to forward the signal to the destination. Thus, for SIMO configuration the communication procedure at the second stage comprise the same steps of MISO using equation (4.3), equation (4.4) and equation (4.7). DSTBC is not the focus of this work, thus the decoding procedure of the received signal at the relay or at the destination is not covered in this thesis. However, we assume the destination recovers the signal using linear signal combination such as Maximum Likelihood Decoding, and details explanation of this soft decision technique can be found in [147].

4.3 Energy Cost in Virtual MIMO

We assume a Raleigh fading channel for all the links, and the transmit power falloff proportional to the transmission distance following the path loss model, the required transmit power for a target BER is given by

$$P_{ij} = \bar{E}_b R_b G d_{ij}^k \tag{4.8}$$

Where P_{ij} is the transmit power from node i to node j. $\bar{E}_b$, R_b, G and d_{ij}^k are the average energy received per bit, bit rate, the power attenuation factor and the distance between transceivers. k is path loss evaluated based on equation in Chapter 3. According to the Chernoff bound, for a fixed rate system in high SNR y_b regime given in equation (4.9), the average probability of bit error P_e given in Rayleigh channel can be approximated in equation (4.10).

$$y_b = \left(\frac{E_b \left| h_{ij} \right|_F^2}{M_t M_r N_o} \right)^{-M_t M_r} \tag{4.9}$$

$$BER(E_b) = \frac{4}{b}(1 - \frac{1}{2^{\frac{b}{2}}})(1 - \frac{1}{\sqrt{1+\sqrt{y_b}}})^{N_t N_r} \left(\frac{1}{2^{N_t N_r}} \right) \left(\sum_{a=0}^{N_t N_r - 1} \frac{(a + N_t N_r)!}{a! N_t N_r !} (1 + \frac{1}{\sqrt{1+\sqrt{y_b}}})^a \right)$$

(4.10)

where M_t, M_r, $\overline{E_b}$, $\left| h_{ij} \right|_F^2$ and N_0 are the number of transmit antenna, number of receive antenna, energy received per bit, channel Frobenius channel matrix, and the noise spectral density respectively. For SIMO configuration M_r is set to 1, while M_t is set to 1 in MISO configuration. Although, E_b can be computed using numerical technique, different approach to evaluate the required energy per bit are used as minimising the energy consumption is achieved via relay selection implementation. Thus, the energy cost for each MIMO configuration is addressed and evaluated separately using the energy cost per bit for MISO configuration.

4.3.1 Energy Consumption in Fixed Rate System

For a 2*1MISO configuration, the energy required per for a target P_e at the destination is approximated as in [125] and is given in (4.11). As the source and destination are within the relay transmission range, for the same P_e target at both nodes, same E_b is desired at both nodes. Consequently, the source use equation (4.12) to evaluate the required E_b in SIMO configuration, MISO configuration and at stage one and stage two of MIMO configuration. Moreover, in MIMO configuration each potential relay calculates E_b using equation (4.12), to select the optimal relay pair.

$$P_e \approx \varepsilon_h \left\{ Q\sqrt{2y_b} \right\} \approx \left(\frac{E_b}{M_t N_0} \right)^{-M_t} \quad (4.11)$$

$$E_b = \frac{M_t N_0}{P_e^{-1/M_t}} \quad (4.12)$$

where ε_h and N_0 are the channel expectation and the noise spectral density. The SNR is evaluated using equation (4.9) and setting M_r to one.

4.3.2 Energy Consumption in Variable Rate System

For variable rate system, under the same condition P_e is evaluated in equation (4.12) as in [124], and the required is calculated using equation (4.13) for MISO configuration for MQAM modulation. Similar to fixed rate system, we use the same approach to evaluate E_b in SIMO configuration, MIMO stage one, MIMO stage two and at the relay in stage three. The energy cost calculation is correlated to the relay selection algorithm and the described approach is used to evaluate the energy cost for every MISO configuration in the network. Thus, every potential relay estimates the energy cost per bit using equation (4.14) for different MIMO configuration.

$$P_e \le \frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)\left(\frac{1.5E_b hb}{2N_0\left(2^b-1\right)}\right)^{-2} \tag{4.13}$$

$$E_b \le \frac{4}{3}\left(\frac{P_e}{4}\right)^{-\frac{1}{2}}\frac{2^b-1}{b^{\frac{1}{2}+1}}N_0 \tag{4.14}$$

Using equation (4.11) in equation (4.8) the total energy cost per bit for MISO configuration in fixed rate and variable rate system are given in equation (4.14) and equation (4.15).

$$E_t = (1+\alpha)\frac{M_t N_0}{P_b^{-1/M_t}} Gd_{ij}^k + \frac{P_c}{R_b} \tag{4.15}$$

$$E_t = \frac{2}{3}(1+\alpha)(\frac{P_e}{4})^{\frac{-1}{M_t}}\frac{2^b-1}{b^{\frac{1+M_t}{M_t}}} M_t N_0 Gd_{ij}^k + \frac{T_{on}P_c}{L} \tag{4.16}$$

where L , T_{on} and P_c are the packet length, the transmission time and circuit power consumption respectively.

4.3.3 Total Energy Cost

The total energy cost per bit per transmission using different MIMO configuration is given by

$$\begin{aligned} E_{Total} = m\sum_{1}^{M_t M_r+1}(E_T+E_{Rx}+E_{Beacon})+E_{RTS}+E_{CTS} \\ +\sum_{1}^{M_t+1}(E_T+E_{Rx}+E_{Beacon}) \\ +\sum_{1}^{Mr+1}(E_T+E_{Rx}+E_{Beacon}) \end{aligned} \tag{4.17}$$

where E_{RTS}, E_{CTS} and E_{Beacon} are the energy consumption per bit to transmit the RTS, CTS and beacon message respectively. E_{Rx} is the energy cost to receive one bit, and $M_t M_r + 1$ illustrate the number of nodes involved in the transmission. For the MISO and SIMO configuration m is set to zero. In equation (4.16), we omit the receiving energy cost at the destination and sleep mode, idle mode and transient energy cost.

4.4 Constellation Size Impact on Energy Consumption

As discussed in Section 3.5.2, E_b is variable function correlated to the modulation strategy and it can be minimized by selecting the optimal value of b . Thus, the optimal constellation size is vital design parameters to minimize the energy consumption in variable rate system and fixed rate system. Higher modulation minimises the overall transmission time at the price of an increase of the SNR threshold at the receiver side for correct signal recovery. Thus, an energy penalty observed in the transmit power that increase linearly with the transmission range as discussed in Section.3.3.1. Figure 4.4 illustrates the energy cost per bit in dBm mJ against the transmission distance for different MIMO configurations under different modulation strategy in Rayleigh fading channel. The optimal energy solution depends on the constellation size correlated to the transmission distance, whereby for MIMO configuration in fixed rate system, the optimal constellation size is 32, as it minimises the energy consumption at different transmission range as explained in the previous section. Moreover, from Figure 4.4, MISO outperforms SIMO using the same constellation size at different transmission range. Furthermore, the impact of the constellations size in SIMO and MISO is negligible in correlation to the transmission distance compared to MIMO configuration for long range. Thus, subject to system performance requirement the optimal solution to achieve an energy efficient transmission is switching between different MIMO configurations and applying adaptive modulation. For example, MISO configuration using 32 constellation size is the optimal transmission strategy at 100 meters transmission distance. In summary, the optimal energy solution is related to the system performance requirement such as delay, and BER.

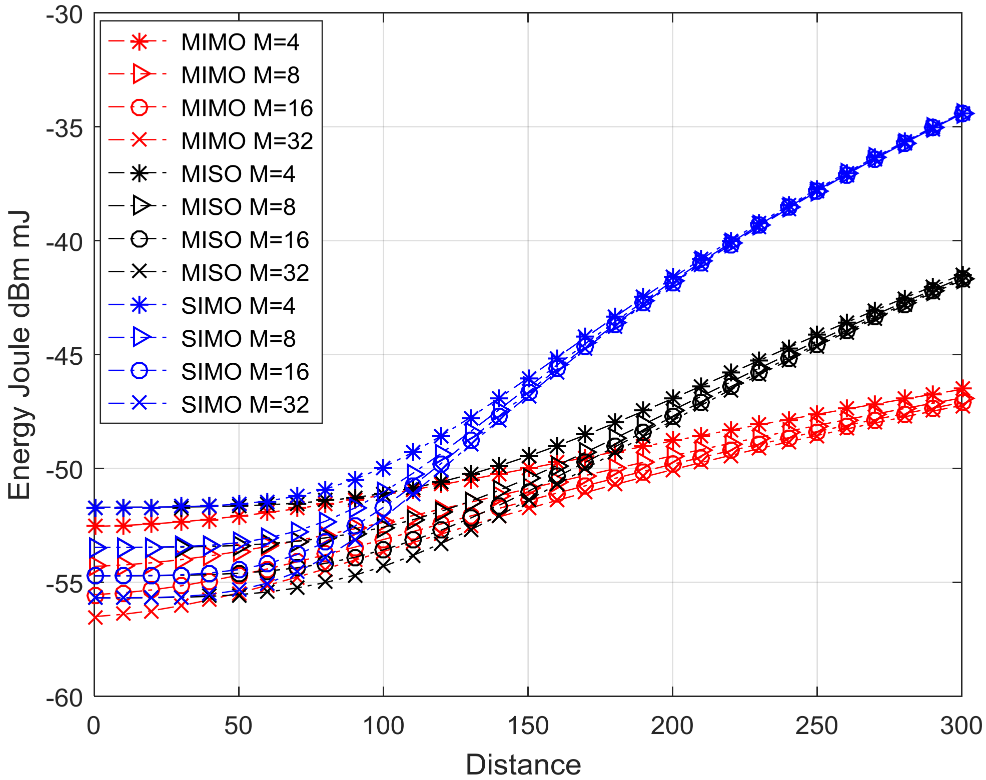


Figure 4.4: Energy Consumption using Different Constellation Size at Different Distance (Meters), (Fixed Rate System)

We repeat the same experiment for variable rate system, and we use equation (4.16) to plot the energy consumption in dBm mJ against the transmission distance in meters for different MIMO configuration in Rayleigh fading channel. The performance is given in Figure 4.5 for different constellation size, where 2*2 MIMO configuration outperforms SIMO and MISO in terms of the energy consumption over 50meters transmission distance. Due to the fact that at short communication range, MIMO configuration consists of three transmission stages in which the distance between nodes is very short and in the ratio of 3 compared to the overall distance. Thus, the transmission energy is dominant compared to the circuit energy. However, the optimal transmission strategy is MIMO configuration with constellation size of 4 for transmission range above 45 meters. Furthermore, SIMO configuration shown to be non-practical solution as it has the worst performance in terms of energy consumption under different constellation size.

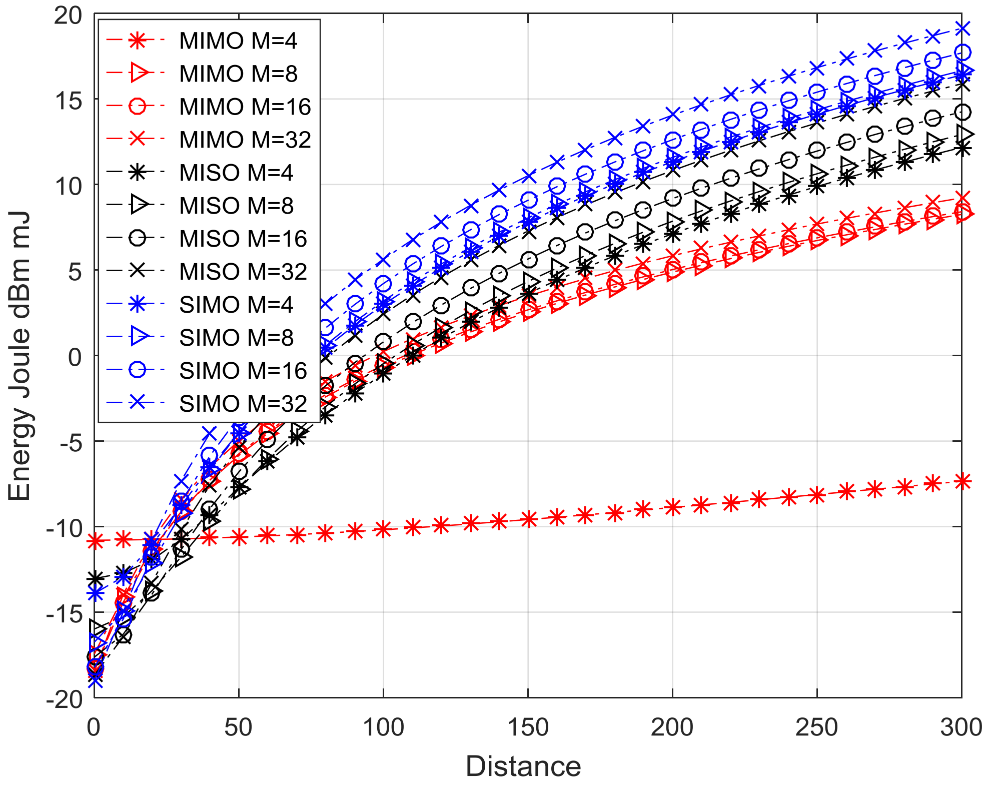


Figure 4.5: Energy Consumption using different constellation seize at Different Distance (Meters), (Variable Rate System)

From the results in Figure 4.4 and Figure 4.5, the optimal transmission strategy for fixed rate system is MIMO or MISO configuration with optimized constellation size. However, this depends on the number of relays available in addition of the system requirements. For example, under certain delay constraint, a higher constellation size for short transmission range is the desired solution at the price of an escalation in the energy cost. Thus 2*2 MIMO using constellation size of 32 at 150 meters transmission distance minimize the energy consumption, with a penalty in terms of delay as more transmission time is required due to bigger number of relays. For variable rate system, MIMO is the most energy efficient solution over 40 meters transmission distance subject to the availability of relays.

4.5 Proposed Relay Selection Algorithm

We propose a distance based energy efficient multiple relay selection algorithm to minimize the energy cost per bit while achieving a target system performance in terms of BER at the destination. We study the impact of the relay location for different MIMO configuration, and prove by numerical example that minimizing the sum of all path link length leads to lower energy consumption under the same performance requirement for MIMO, MISO and SIMO configuration. The core of proposed relay selection methods is selecting the node set that minimize the overall path lengths. For SIMO and MISO communication mode consists of two stages and we use two relays in the cooperative approach. In MIMO configuration, the communications process differs significantly as it consists of three stages, and more relays are involved in the transmission. Therefore, we use a modified relay selection technique for each stage with the same context of selecting the relays with minimum sum of path lengths.

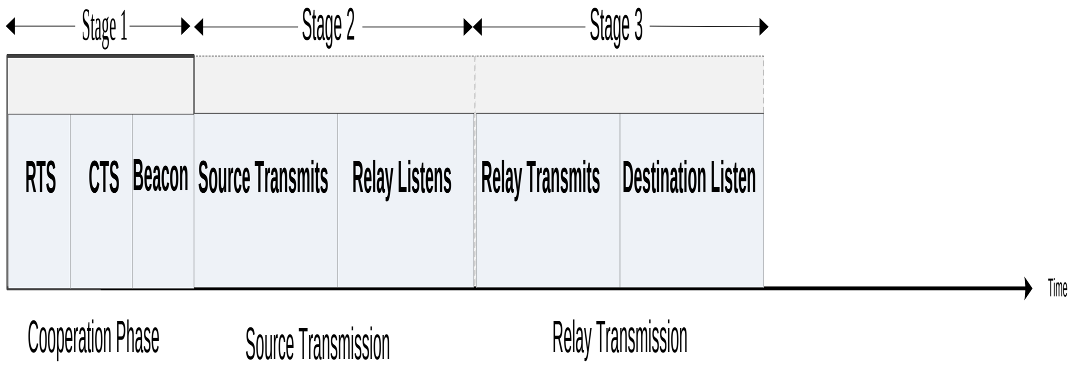


Figure 4.6 : Cooperative Virtual MIMO TDMA Communication

The communications mode for MISO and SIMO given in Figure 4.2, consists of two stages where the source broadcast the signal in the first-time slot and relay transmit in their allocated time slots following the implemented TDMA cooperative scheme given in Figure 4.9 Candidates relays aware from their location on the network grid, estimate the partial channel gain from the RTS/CTS packet exchange. The total transmission power is fairly allocated between the source and relays subject to maximum power constraint as given by

$$p_s + \sum_{1}^{n} p_i \le p_{tot} \tag{4.18}$$

where P_{tot} is estimated based the source-destination path length. For MISO and SIMO configurations, the distance based relay selection policy is given by

$$\begin{aligned} &\min imize \quad E_b \\ &subject\,to \;\sum\nolimits_{1}^{i} d_i^{\alpha} \le d_t^{\alpha} \\ &\qquad d_i \ge d_{\min} \\ &\qquad d_i \le d_{\max} \end{aligned} \tag{4.19}$$

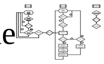
4.5.1 MISO Relay Selection Algorithm

For MISO configuration, we define the decoded relay set as the set of nodes that correctly decode the source and destination messages, and this set is given as

$$D_1 = \left\{ P_{\max} \overline{y}_i(D) \ge y_{th}(b_{SR}) \right\} \tag{4.20}$$

Where $P_{\max}, \overline{y}_i(S)$ and $y_{th}(b_{SR})$ are the maximum transmit power at the source, the average received SNR at the node, and the SNR threshold for a target BER, and i is the node index. From the RTS message, nodes within the source transmission range estimate $\overline{y}_i(S)$ and if the condition in equation (4.20) is satisfied, nodes listen to CTS message otherwise switch to sleep mode. At this stage, we define the second relay set that correctly decode the CTS message and its given by

$$D_2 = \left\{ P_{\max} \overline{y}_i(D) \ge y_{th}(b_{DR}) \right\} \tag{4.21}$$

Where $P_{\max}, \bar{y}_i(D)$ and $y_{th}(b_{DR})$ are the maximum transmit power at the destination, the received SNR at a node, and the SNR threshold for the target BER. The destination transmits using the  evaluated using (4.12) or (4.14). The relay selection is completed in un-centralized manner and nodes set their timer using (4.22) and the node with minimum sum distance of both links has the smaller timer and has the priority to send the flag.

$$\Delta = \frac{d_i^1 + d_i^2}{d_l} T \tag{4.22}$$

where d_i^1, d_i^2 and d_l are the relay-source path length and relay-destination path length, while T is the transmission timeslot allocated for each node to send the Flag message initiating itself as a successful relay. We implement 2*1 MISO configuration that can be expended to larger number of relays, and the relay selection algorithm is given in Table 4.1.

Table 4.1:Relay Selection Algorithm for 2*1 MISO Configuration

1. ***Candidates relay, switch to idle mode, at the beginning of each transmission.***
2. ***The source sends the RTS initiating data to transmit.***
3. ***Candidate relays satisfying (3.27) compute (4.20).***
4. ***The destination sends CTS.***
5. ***Candidate relays compute (4.21).***
6. ***Nodes satisfying (4.20) and (4.21) set their timer using (4.22).***
7. ***Candidate relay use (4.15) or (4.16) to evaluate the modulation strategy.***
8. ***Candidate relays, use (4.12) or (4.12) and send Beacon message.***
9. ***The source and the relays transmit following the TDMA procedure.***

4.5.2 SIMO Relay Selection Algorithm

The SIMO communication mode is a special case, where single relay forward multiple source signal to the destination. In this scenario, we define the decoded relay set as the set of nodes that correctly decode the sources messages, and this set is given as

$$D_1 = \{P_{\max}^{j} \overline{y}_i(S_j) \geq y_{th}(b_{SR})\} \tag{4.23}$$

where $P_{\max}^{j}, \overline{y}_i(S_j)$ and $y_{th}(b_{SR})$ are the maximum transmit power at the sources, the average received SNR at the node, and the SNR threshold for a target BER. While i and j represent the receiving node index and the transmitting node index. We modify the TDMA scheme such as all the sources transmit the RTS messages simultaneously, from which candidate relays execute equation (4.22) at stage two. Thus, similar to MISO communication mode, the decoding set of relays satisfying the condition in equation (4.25) listen to the destination CTS message and the decoding set of nodes is minimized following the condition given in (4.26), and nodes satisfying the condition compete for the relay role. The selection is competed in non-centralized manner, and the successful relay set their timer based on equation (4.25), and the node with minimum timer value has the priority to send the Flag message initiating itself as the successful relay.

$$D_2 = \left\{P_{\max} \overline{y}_i(D) \geq y_{th}(b_{DR})\right\} \tag{4.24}$$

$$\Delta = \frac{d_i^1 + d_i^2 + d_i^3}{d_l} T \tag{4.25}$$

The relay selection algorithm is given in Table 4.1.

Table 4.2: Relay Selection Algorithm for 1*2 SIMO Configuration

1. Candidates relay, switch to idle mode, at the beginning of each transmission.
2. The source sends the RTS initiating data to transmit.
3. Candidate relays satisfying (4.19) compute (4.23).
4. The destination sends CTS.
5. Candidate relays compute (4.24).
6. Nodes satisfying (4.23) and (4.24) set their timer using (4.25).
7. Candidate relay use (4.15) or (4.16) to evaluate the optimal modulation strategy.
8. Candidate relays, use (4.12) or (4.12) and send Beacon message.
9. ***The source and the relays transmits in their following the TDMA procedure.***

4.5.3 MIMO Relay Selection Algorithm

For MIMO configuration, transmission consist of the following stages; the source transmits to the transmitting relay cluster, the transmitting relay cluster transmit to the receiving relay cluster, and finally the receiving relay cluster forward the signal to the destination. Similar to SIMO and MISO communication mode, we identify two decoding set, defined as the source decoding set and the destination set based on equation (5.15) and equation (5.14)

$$D_1 = \left\{ P_{\max} \overline{y}_i(D) \geq y_{th}(b_{SR}) \right\} \tag{4.26}$$

$$D_2 = \left\{ P_{\max} \overline{y}_i(D) \geq y_{th}(b_{DR}) \right\} \tag{4.27}$$

The major difference between the SIMO and MISO relay selection is the communication between relays at stage two. Therefore, potential relays have to estimate the virtual MIMO communication energy cost, to select the best grouping. At this stage the selection policy involve additional signalling overhead between candidate relays as the selection is done in un-centralized manner. To overcome additional signalling, we modify the selection policy such as each potential relay in the decoding sets transmit one bit feedback after the RTS/CTS message exchange. Thus, all the potential relays and the destination have knowledge of the available sets. The source selects the best set to form virtual MIMO at stage two, or request MISO configuration subject to relay availability. The source selects two relays from each set with minimum two path lengths. Similarly, the destination follows the same procedure and predicts the communication strategy. This scenario is spotted in Virtual MIMO, where the source transmits training sequence to the relays for channel estimation. The source transmits redundant bit to inform the successful relay of the communication strategy. Successful relays and the source adjust their transmit power based on the communication strategy using equation (4.12) in fixed rate system, or equation (4.12) in variable rate system. The relay selection algorithm is given in Table 4.1

Table 4.3 :Relay Selection Algorithm for 2*2 MIMO Configuration

1. ***Candidates relay, switch to idle mode, at the beginning of each transmission.***
2. ***The source sends the RTS initiating data to transmit.***
3. ***The destination sends CTS.***
4. ***Candidate relays compute (4.26) and (4.27), and compute (4.19).***
5. ***Relays send one bit Feedback.***
6. ***Source compute (3.31), and ACK.***
7. ***MIMO or SIMO Formation.***
8. ***Candidate relays use (4.15) or (4.16).***
9. ***The source and the relay transmit following the TDMA procedure.***

4.6 Performance Analysis

As the source transmit subject to energy constraint, the probability of finding k nodes out of n to correctly decode the source signal follow the Bernoulli distribution and is given by

$$P_n(k) = \binom{n}{k} P^k (1-k)^{n-k} \tag{4.28}$$

Where $P = {r_0}/{R_0}$ represent the probability of finding a successful relay within the source transmission range subject to a transmit desire power approximated based on the transmission range r_0 and the network radius R_0 . Figure 4.7 consider the number of available relay sets, for MIMO, MISO and SIMO configuration against the total transmission distance, and its clearly observed that the decrease in the set number relatively to the distance.

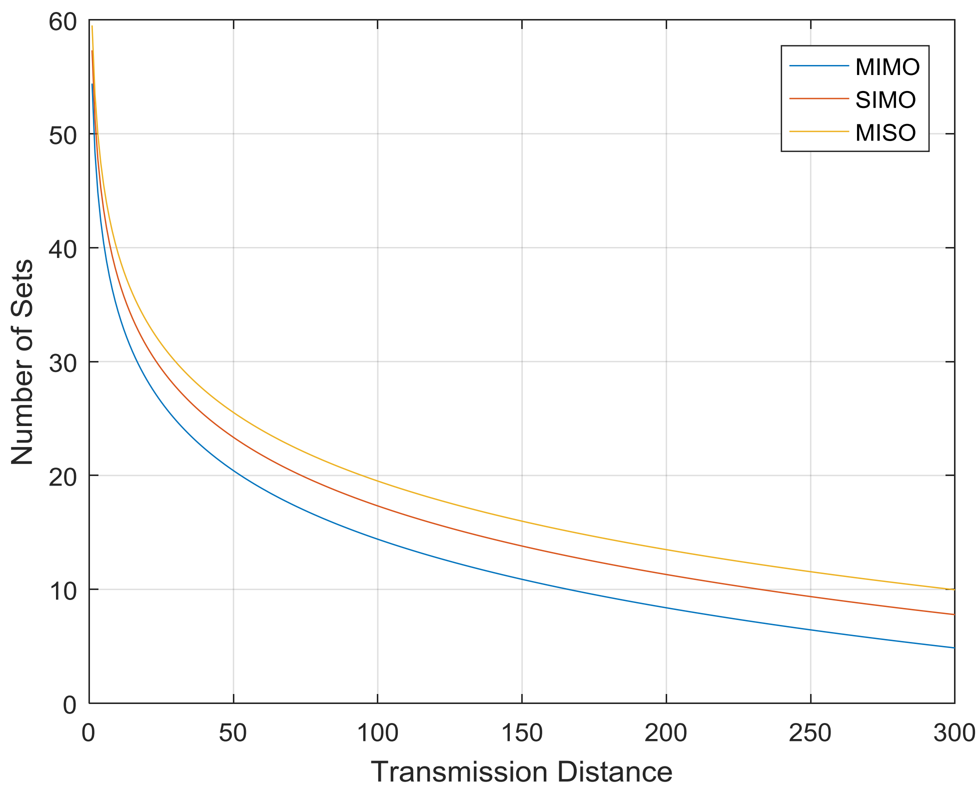


Figure 4.7: Number of Relays Set vs Distance (Meters)

For SIMO, MISO and MIMO configuration the probability of finding K_i nodes out of n to correctly decode the message at stage i is given in equation (4.19) which is used to evaluate the probability of successful transmission given in Figure 4.7 in respect to the transmission distance. We plot the probability of successful transmission for SISO configuration by setting i to one which is the case of direct transmission.

$$P_n(k) = \prod_0^i \binom{n}{k} P^k (1-k)^{n-k} \tag{4.29}$$

We consider two cases, optimized and non-optimized system for all configurations, and it can be clearly seen that MIMO has the highest probability of successful transmission for optimized system and non-optimised system as the overall path is divided into shorter links. Thus, under the same power constraint the number of potential relay within the source transmission range increase which is due to the reduce in power level at the receiver side.

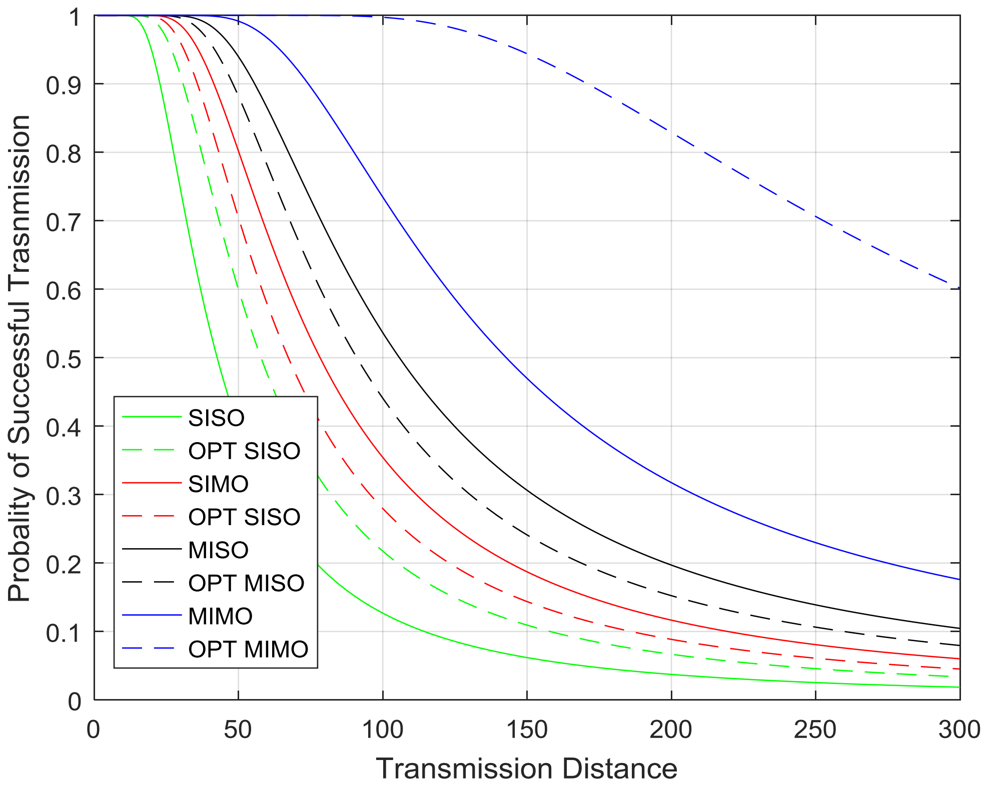


Figure 4.8: Probability of Successful Transmission vs Distance (Meters)

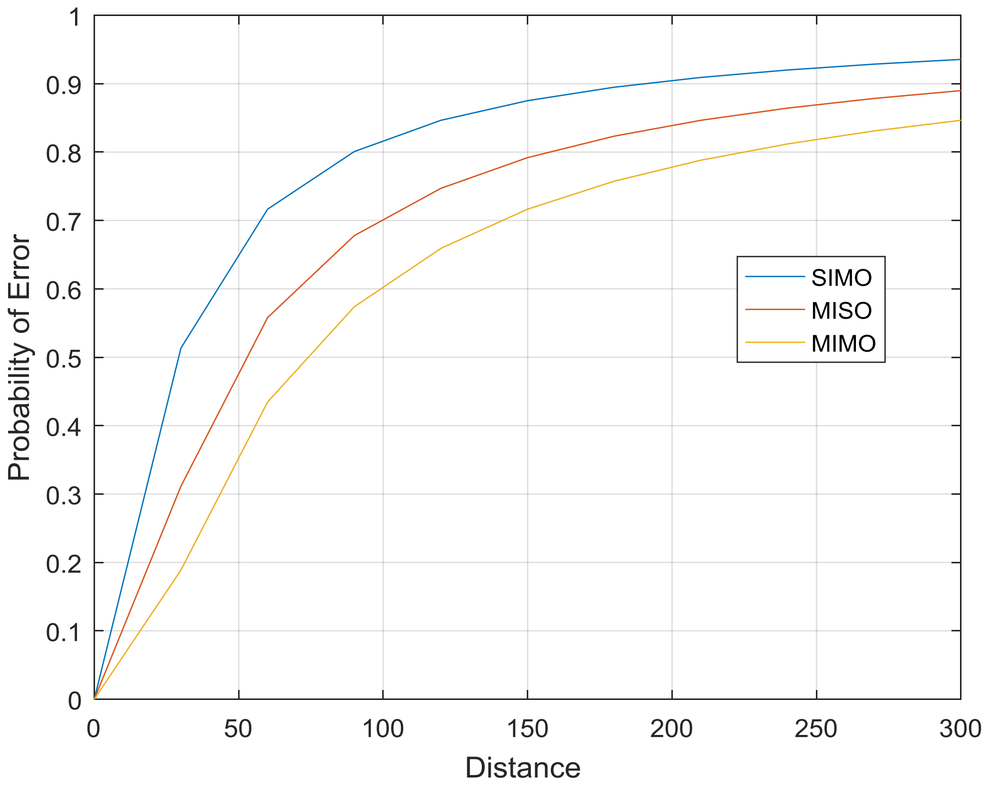


Figure 4.9: Probability of Error vs Distance (Meters)

Furthermore, Figure 4.8 consider the performance of different MIMO configuration in an ideal scenario, where all the nodes involved transmit using unit power per unit distance calculated based on the direct transmission scenario and without applying relay selection. In other worlds, using equation (4.12), the source estimates the required energy cost per bit for direct transmission and the power is allocated between the source and the relays using the ratio of each link length. Assuming the destination drops the packet with BER above the required threshold, we plot the probability of error at the destination against the overall transmission distance in meters to illustrate the performance of all the configuration which degrade with the increase in the path length. Figure 4.8 shows that MIMO outperforms SIMO and MISO at different transmission range, where a 0.1 and 0.2 better error probability is observed at 100 meters transmission distance compared to MISO and SIMO respectively. Moreover, SIMO shown the worse performance at different transmission distances.

4.7 Simulations Results

To evaluate the performance of the proposed algorithm, two scenarios are considered. First, a fixed rate system with MQAM constellation and a symbol rate equal to the system bandwidth. We compare the energy consumption per bit for 2*2 MIMO, 1*2 SIMO and 2*1 MISO systems. We investigated the performance of wireless network through numerical example and we use the parameters given in Table 4.4. In this regards we consider a source node transmitting data to the destination using SIMO configuration, or MISO or MIMO configuration with distance based relay selection using Algorithm 1, or Algorithm 2 or Algorithm 3 respectively. we compare the performance of the proposed algorithm with non-optimised MIMO, and MIMO without relay selection for different configuration.

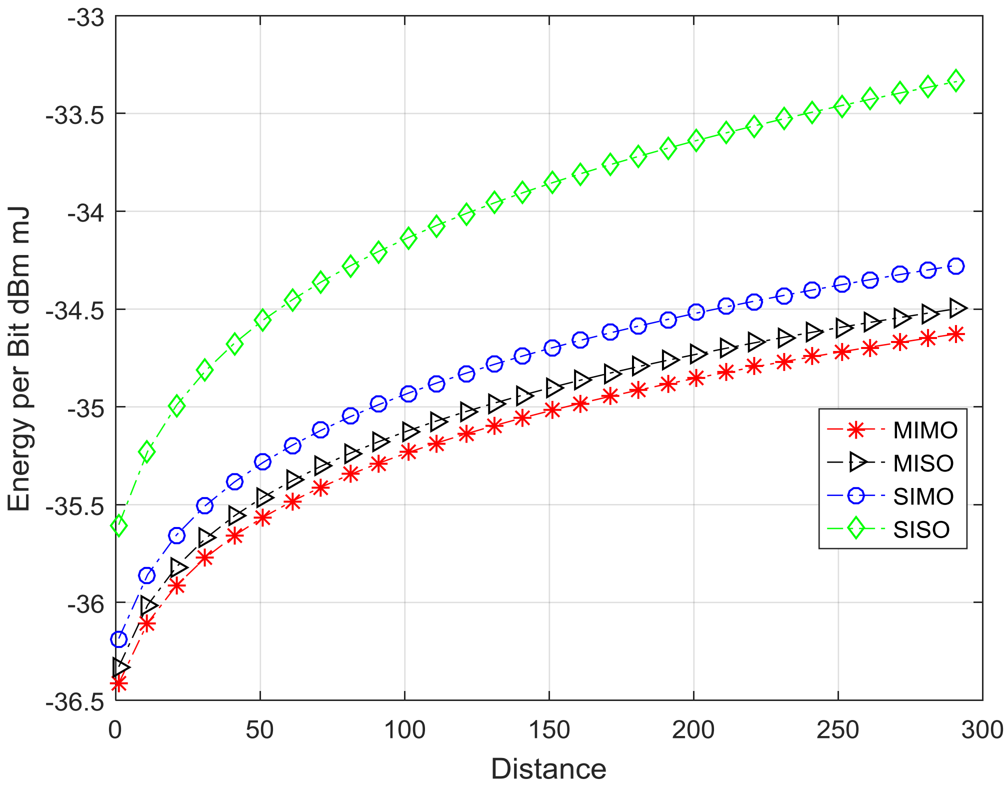


Figure 4.10: Energy Consumption per Bit vs Distance without Relay Selection at Different Distance (Meters)

Table 4.4: Simulation Parameters

Parameters	Annotation	VALUE
Drain Efficiency	η	0.35
Thermal Noise PSD	N_0	-171dBm / Hz
Target Bit Error Rate	P_e	10^{-3}
Carrier Frequency	f_c	2.5GHz
Bandwidth	B	$1MHz$
Packet Length	L	$200Kb$
Link Margin	M_l	$40dB$
Transmission Deadline	T	$100ms$
Mixer Power	P_{MIX}	$30.3mW$
ADC & DAC Power	P_{DAC}, P_{ADC}	$15.4mW$
LNA Power	P_{LNA}	$20mW$
Active Filter Power	P_{FILR}, P_{FILT}	$2.5mW$
Frequency Synthesizer Power	P_{SYN}	$50mW$
Receiver Noise Figure	N_f	$10dB$
Intermediate Frequency Amplifier Power	P_{IFA}	$3mW$

For every transmission distance we evaluate the average of energy consumption per bit using 100000 iterations. Figure 4.10 illustrates the performance of different MIMO configuration in terms of energy consumption per bit against the transmission distance in meters. Different MIMO configurations outperforms SISO in terms of the energy consumption at different transmission distance even though the communication is implemented without relay selection. We repeat the same experiment for different MIMO configuration, using the relay selection technique given in Algorithm 1, Algorithm 2, and Algorithm 3 for MISO, SIMO and MIMO configuration. and the results is illustrated in Figure 4.11 using equation (4.17).

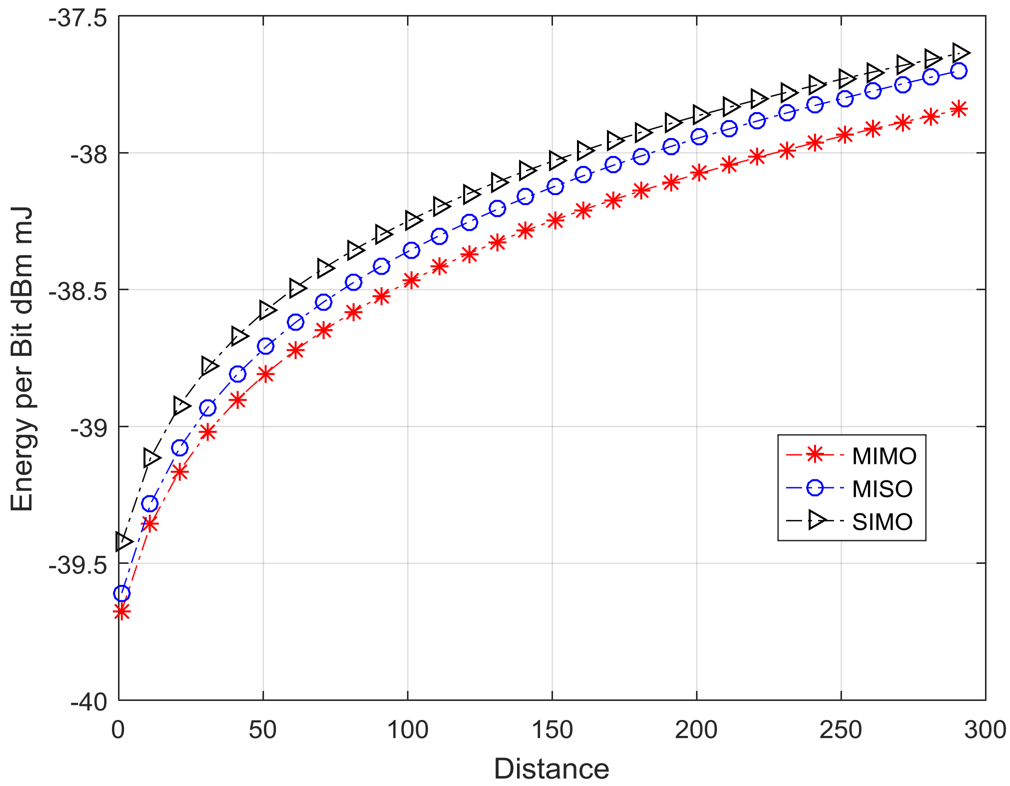


Figure 4.11: Energy Consumption per Bit vs Distance (Meters) with Relay Selection

In this experiment we assume 16-QAM fixed rate system without optimizing the constellation size. MIMO outperforms MISO and SIMO with less than 1 dB at different transmission distances. This slightly comparable performance is due additional energy cost of the overhead required as more relays cooperate in the transmission. However, the optimal energy solution is MISO as it provides the same performance in terms of total energy cost per bit with less complexity. We repeat the same experiment using the proposed Algorithms for different MIMO configurations, and the result is shown in Figure 4.12. The Constellation size optimization improves the performance in terms of total energy consumption per bit for different configuration. Moreover, 2*2 MIMO (CON-MIMO) outperforms SIMO, and MISO by 2 dB at different transmission distance when switching between MISO and MIMO is applied. Thus, optimized MIMO is the optimal solution for energy problem in fixed rate system. In this configuration mode, further energy saving is achieved due to the relay number reduction by switching between MISO and MIMO subject to the system performance requirements. In other words, for short transmission range MISO achieve the same performance in terms of BER consuming less energy as less circuit operations and signal receiving signal is required.

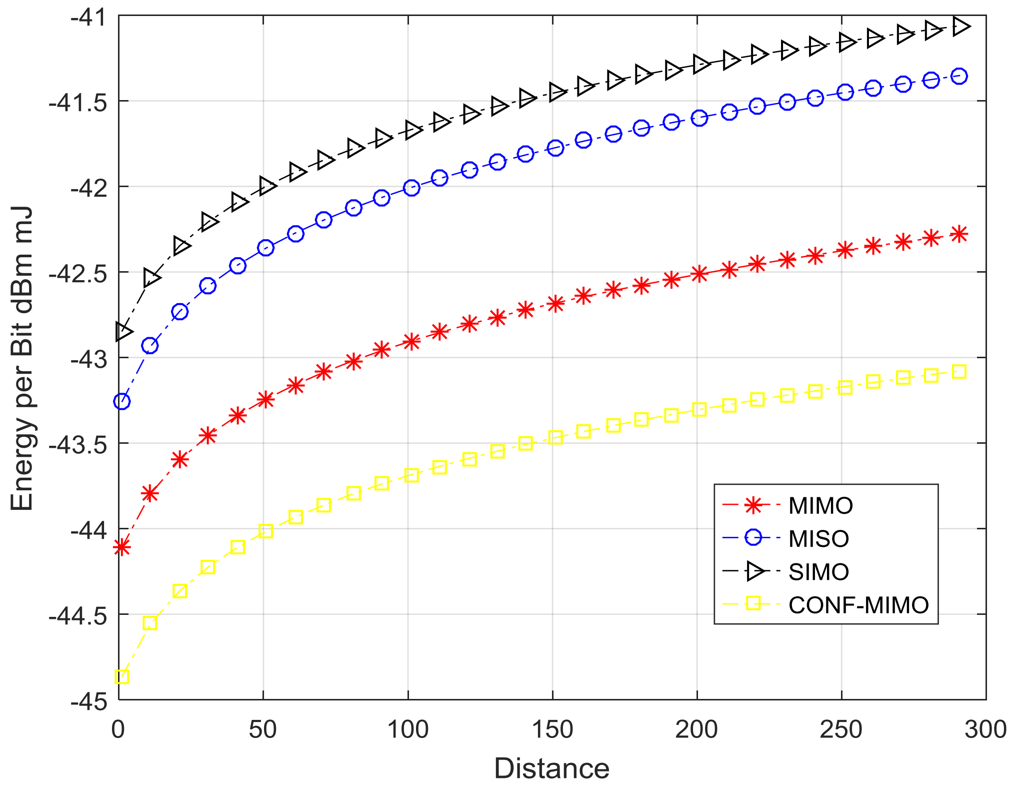


Figure 4.12: Energy Consumption per Bit vs Distance (Meters), Optimized System.

The performance of different MIMO configurations in a fixed rate system of 10Kb/s was compared in the previous section, while the performance of different MIMO configuration in variable rate system where adaptive modulation is employed is investigated. Thus, the performance of 2*2 MIMO, 1*2 SIMO and 2*1 MISO systems is evaluated by plotting the total energy cost per bit against the transmission distances using the same parameters given in Table and transmission deadline of 1 second for 10 Kb packet. We assume Rayleigh fading channel, and we use equation (4.14) and equation (4.16) to calculate the energy cost per bit for different configurations using the appropriate algorithm. Figure 4.13 considers the performance the performance of three different configuration without relay selection, where the optimal energy solution is MISO configuration as it outperforms MIMO and SIMO in terms of energy cost per bit. However, comparing MISO performance in Figure 4.10, in fixed rate system MISO outperforms by 1dB.

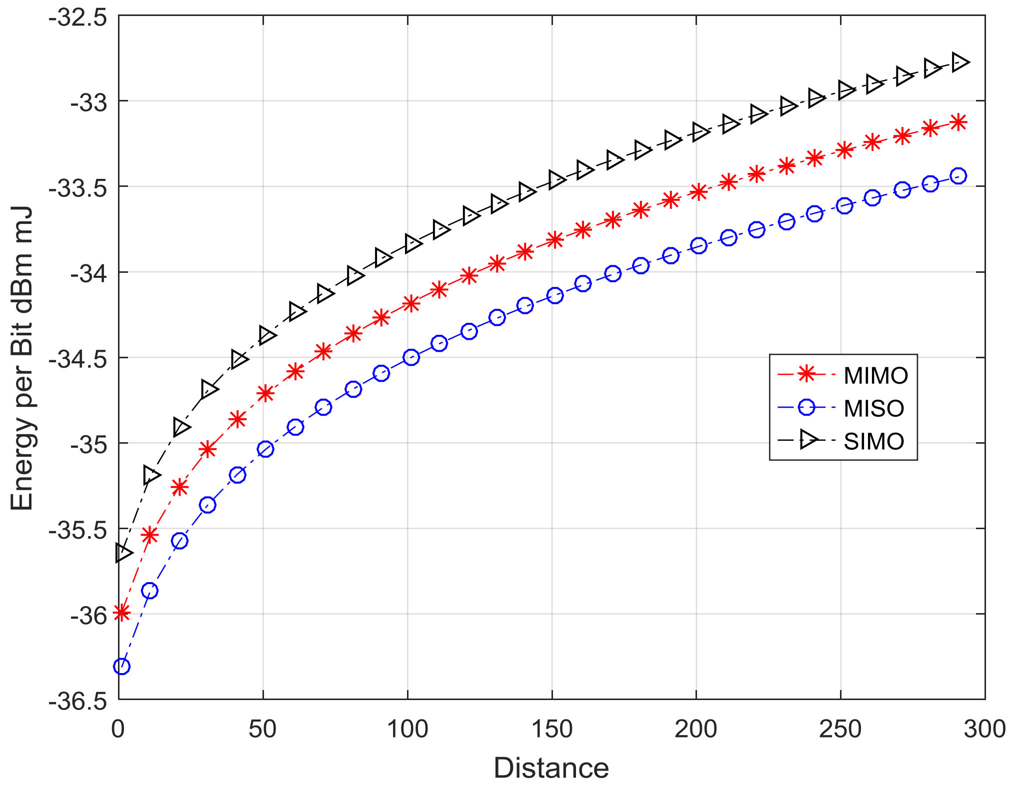


Figure 4.13: Energy Consumption per Bit vs Distance without Relay Selection

We repeat the same experiment using the distance based relay selection technique without optimizing the constellation size for the same systems parameters. From Figure 4.14, 2 dB improvement in terms of energy consumption per bit is observed for transmission distances above 100 meters. Moreover, MIMO and MISO show the same performance in terms of the total energy consumption per bit at the same transmission distance. Hence, the optimal energy transmission strategy is MISO with relay selection regardless of the transmission distance.

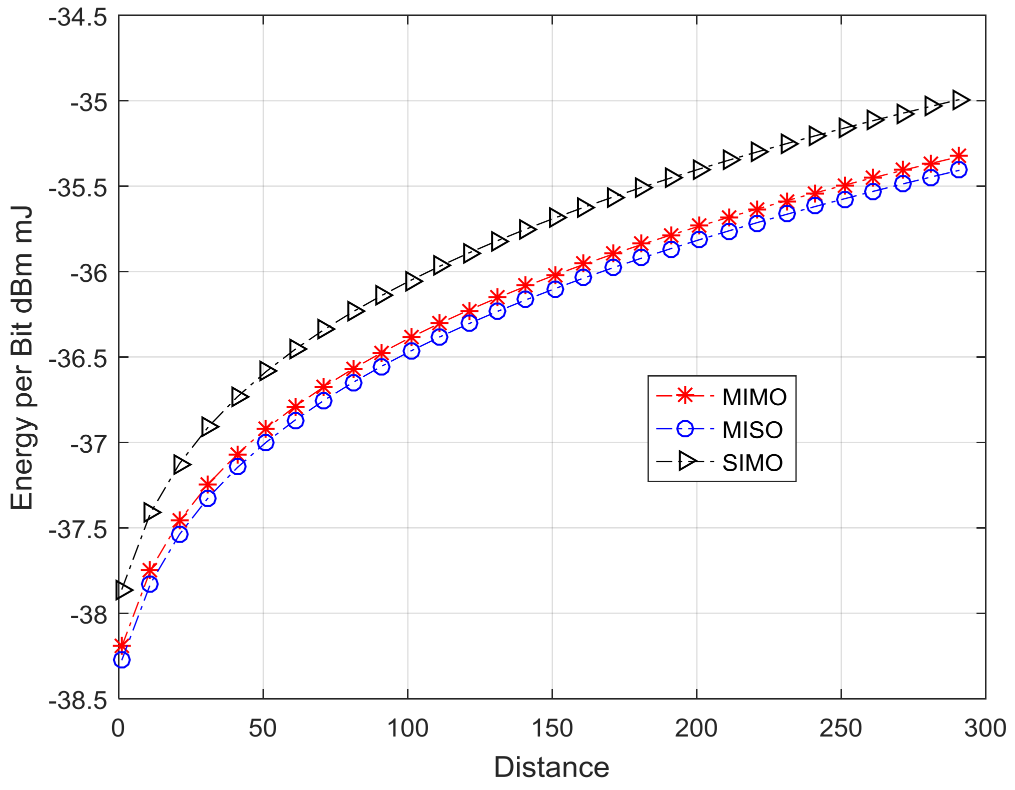


Figure 4.14: Energy Consumption per Bit vs Distance (Meters)with Relay Selection

We evaluate the performance of MIMO, MISO and SIMO using the same parameters for variable system rate, when the constellation size is optimized. Figure 4.15 shows the performance of Configured MIMO, MIMO, MISO and SIMO under the same system performance requirements. Compared to fixed rate system, an energy penalty around 2 dB can be seen at different transmission range.

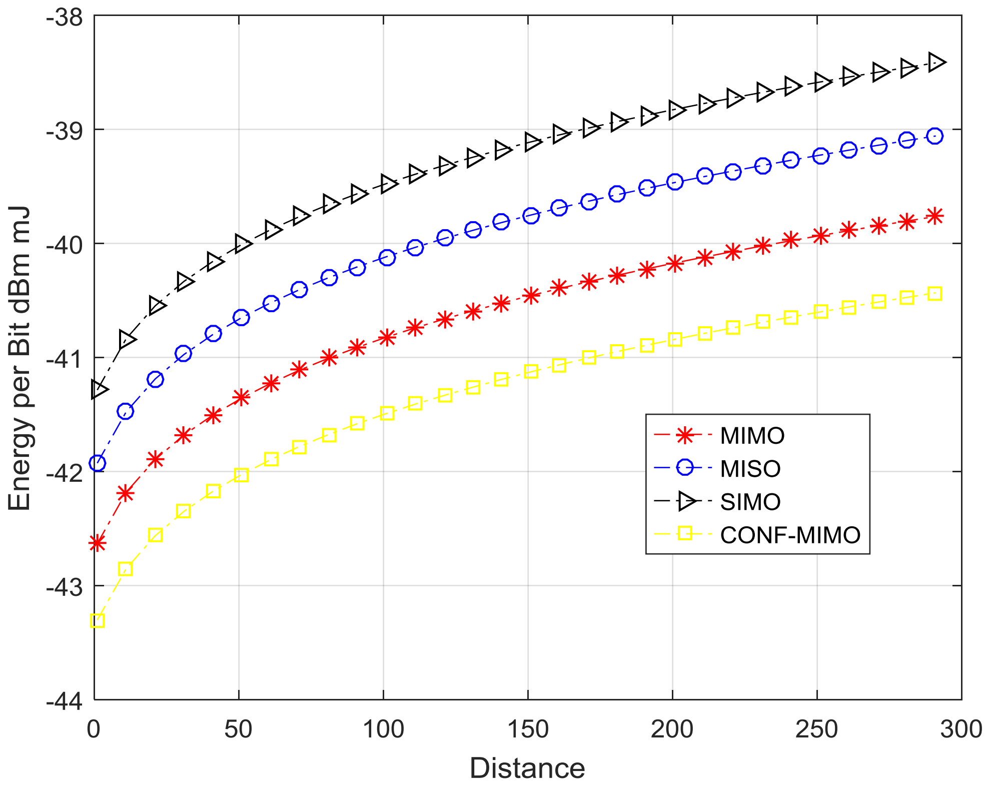


Figure 4.15: Energy Consumption per Bit vs Distance (Meters)(Optimized system)

The CONF-MIMO transmission strategy given in Algorithm 3 is the more energy efficient compared to other MIMO configurations as seen in Figure 4.15. An improvement of 1.5 dB and 2dB compared to MISO and SIMO performance in terms of the total energy consumption per bit at transmission distance above 100 meters. This is achieved by implementing switching between 2*1 MISO and 2*2 MIMO subject to the total transmission path length evaluated based on the available relays. An interesting conclusion from the results given in this section, validate the hypothesis given in Chapter 2 that persist on the necessity of resource allocation to achieve the most energy efficient transmission strategy. Thus, implementing relay selection jointly with constellation size optimization is an obligation in cooperative wireless networks. Moreover, the general belief that MIMO systems are more energy efficient can be misleading if the circuit energy consumption is not considered, as over short distance circuit energy is more dominant than transmit energy as seen in Figure 4.4. To evaluate the energy efficient performance, total energy consumption for different system with different code rates. We consider that all the nodes are transmits the data size packet of 2kb. The simulation is performed under the same system condition for same MIMO configuration for two different code rates r = 1/2 and r = 3/4. In Figure 4.16 the total energy consumption over distance is given for 2*2MIMO, and clear that the cooperative MIMO is more energy efficient than SISO transmission. The simulation is taken. When the code rate increases, the ratio of redundant bits compared to message bits is reduced. Therefore, total energy consumption is reduced as the code gain increase which minimize the SNR threshold. Consequently, the transmit energy per bit at the transmitter side is reduced.

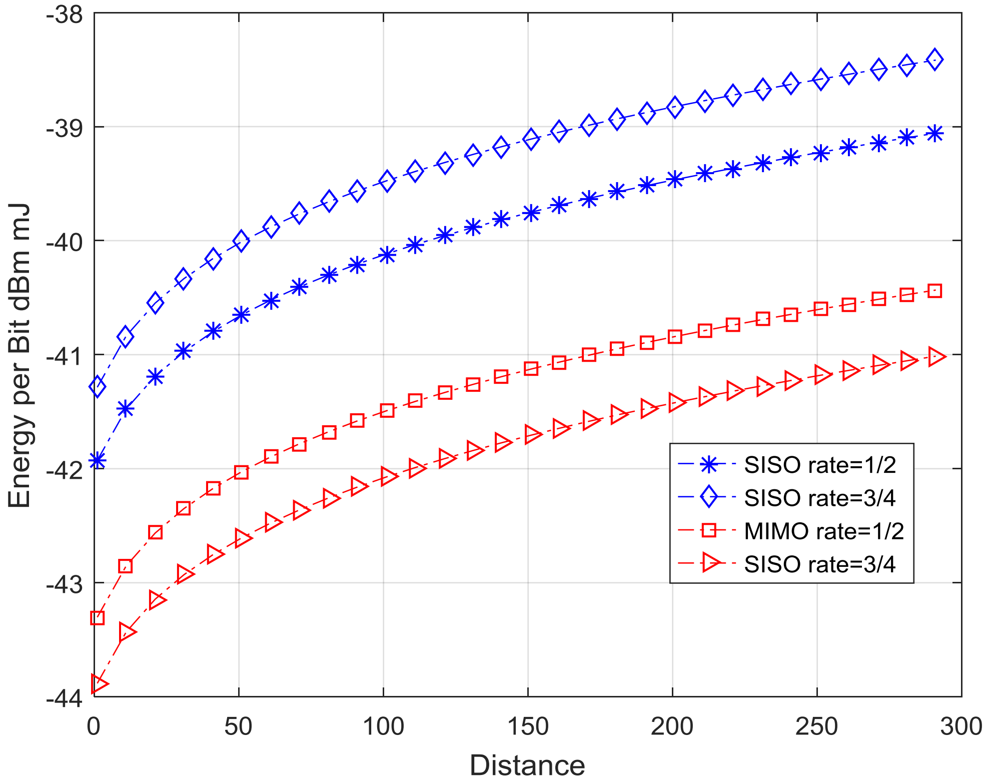


Figure 4.16: 2*2 MIMO and SISO Performance for different Code Rate Different Distance (Meters)

Energy efficiency is another major key to illustrate the performance in terms of energy saving. Thus, we define the energy efficiency for different MIMO configuration as amount of energy saved compared to SISO transmission, and we illustrated the energy saving using the equation (4.30) which is a ratio of SISO energy cost E_{SISO} to MIMO energy cost EE .For a code rate =1/2 and code rate=3/4 illustrated in Figure 4.17 and Figure 4.18 respectively against different transmission distances.

$$EE = \frac{E_{SISO} - E_{MIMO}}{E_{SISO}} \tag{4.30}$$

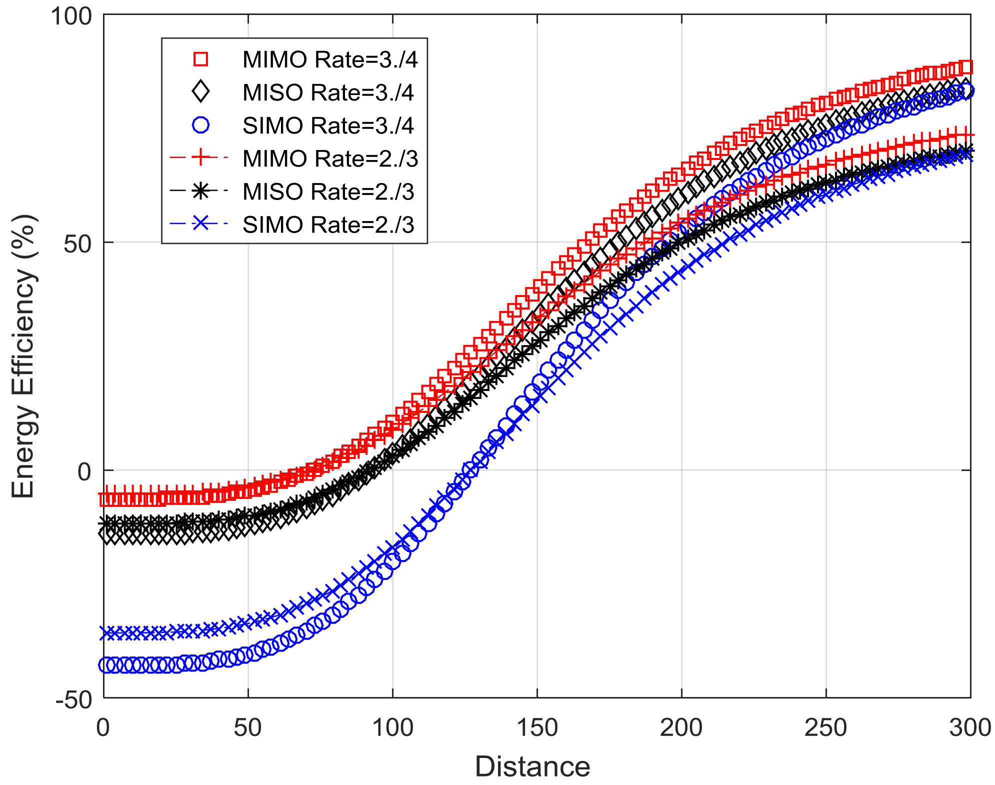


Figure 4.17: Energy Efficiency of Different MIMO Configuration vs Distance (Meters)

It obvious that energy efficiency of different MIMO configuration increases with higher code rate. However, from the results we can see that MIMO outperforms SISO around 75 meters transmission distance and above, while SIMO and MISO achieves positive value for around transmission distance above 120 meters and 100 meters respectively. Thus, cooperative virtual MIMO supports higher data rate at the lower energy cost for the same BER requirement at the receiver side at long transmission range. Switching between MIMO and SISO at short transmission range offer better energy efficient communication. In the literature it has been point that MIMO lead to better performance in terms of delay. Thus, the performance of different MIMO configuration in terms of end-to-end transmission delay with respect to different transmission distances is investigated. We assume the symbol period T_s is equal to the inverse of the bandwidth, and the total delay T_{SISO} in SISO is given in equation (4.31), and for MIMO configuration the delay is given in equation (4.32).

$$T_{SISO} = \frac{L}{bB} \tag{4.31}$$

$$T_{MIMO} = \frac{1}{B}\left(\frac{L}{b_s} + \sum_{1}^{M_t}\frac{L_r}{b_t} + \sum_{1}^{M_r}\frac{L_r}{b_r} + \frac{L_d}{b_d}\right) \tag{4.32}$$

where M_t and M_r are the number of transmitters and receivers for different MIMO configurations. L, L_r are the packet size the source and receiving cluster, L_d is total number of symbol received at the destination. b_s , b_t b_r and b_d are the number of bits depending on the constellation size of each stages. The delay efficiency T_{delay} is given by

$$T_{delay} = \frac{T_{SISO} - T_{MIMO}}{T_{SISO}} \tag{4.33}$$

We plot the delay efficiency for different MIMO configuration against the transmission distance in meters. We use specific numerical example for a 20Kb packet and the result is given in Figure 4.18. For long transmission distances, SISO offers betters performance in terms of delay as T_{delay} has negative value for transmission distance above 50 meters compared to SIMO configuration, and the distance margin is around 55 meters for MIMO configuration and MISO configuration. This is due to the small constellation size over short distance to reduce circuit energy consumption. Hence, reducing energy consumption can cause a delay penalty.

However, a trade-off between energy saving and delay depends on the application requirements and the small window at distance between 50 meters to 70 meters is the margin of delay efficiency and energy efficiency.

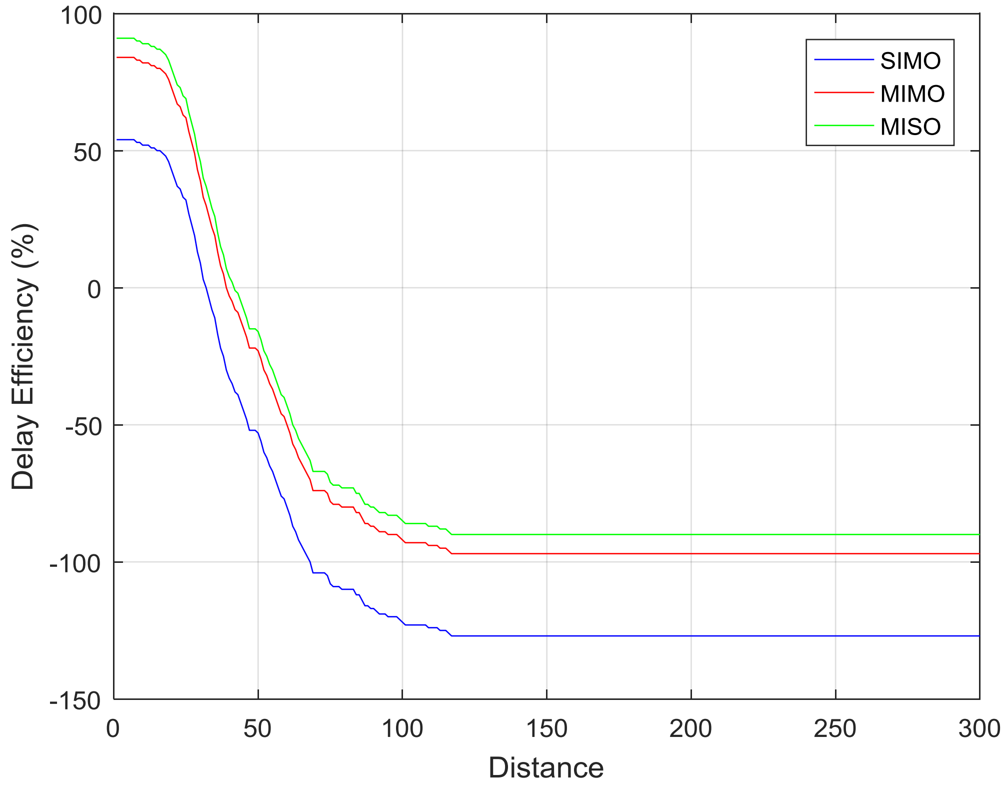


Figure 4.18: Delay Efficiency for Different MIMO configuration vs Distance (Meters)

4.8 Summary

In this chapter, an energy efficient relay selection algorithm for cooperative virtual MIMO was proposed. The relay selection algorithm proposed in Chapter 3 is extended to variable and fixed wireless system where multiple relay cooperate in the transmission. Thus, we extend the distance based relay selection technique for different MIMO configuration. Similar to the single relay selection algorithm, we investigate the impact of the constellation size on energy consumption and the optimal cooperation strategy is proposed for different MIMO configuration. For MIMO, SIMO and MISO the nodes that minimize the overall transmission path length are selected as relay. Moreover, we jointly optimize the constellation size with relay selection to achieve the optimal transmission strategy. Furthermore, for MIMO configuration we employ switching between MIMO and SIMO based on the overall energy cost. We compare the performance of MIMO, SIMO and MISO in terms of energy consumption and we present the results in terms of energy cost per bit against transmission distance. The proposed algorithm outperforms non- optimised MIMO, and traditional virtual MIMO communication in terms of energy consumption in fixed rate system and variable rate system.

Chapter5: Energy Efficient Relay Selection Energy Efficient Clustering

In the literature, cooperative relay selection methods are proposed for Ad-hoc networks such as wireless sensor networks (WSNs) taking into consideration the characteristics of those networks in terms of energy consumption. However, to ensure the cluster heads (CHs) have variety of relay candidates without adding extra signalling energy cost, an energy efficient relay selection method based on clustering is proposed for clustered WSNs.

5.1 Introduction

Inspired by the early work of network performance such as coverage and capacity, in respect to the network deployment strategy, the optimal cell size was investigated. heterogeneous networks formed of a mix of macrocells, microcells, picocells and femtocells was considered [148]. In these techniques receivers are brought close together thereby the energy cost is reduced by effectively reducing the penetration loss and path loss. Thus, macrocells were investigated and the impact of inter-site distance and the average of micro-sites on power consumption were addressed from energy efficiency prospective. Inspired by this trend clustering technique have been proposed and implemented in wireless sensor networks as those networks suffer from scalability [149 150]. Clustering prove to be an energy efficient technique as neighbor nodes are grouped into small size cluster and work jointly, along with an elected leader node transmit the cluster member data to a far located base station. Clustering techniques are mainly adopted in WSN, where by nodes organize them self and work in non-centralized manner. Wireless sensor networks (WSNs) are composed of densely deployed huge number of tiny low power sensor nodes deployed for various applications purposes [151]. In WSNs, each node is required to collect data’s and reports periodically to the central base station (the Sink) and serves without access to back-up charger or maintenance. However, the feature of the small size of these nodes raises the challenge of energy conservation as those nodes are powered by small battery and are expected to work for long period. Benefiting from the distributed random deployment and the un-centralized architecture of these networks, multi-hop transmission is mainly adopted to overcome the transmission range limitation due to power constraint, by reducing transmission distance whereby the distance between transceiver is divided into shorter links [152 153]. Those strategies benefit from the broadcast nature of wireless channel by using adjacent nodes as relay to forward the signal toward the destination. The focus of several works is improving those exciting strategies to be more energy efficient. Thus, clustering has been proposed where the network is divided into sub-regions in which nodes are grouped together, and leader node, the cluster head (CH), are elected to forwards the received data from cluster member toward the Sink using multiple, single or direct transmission as shown in Figure 5.1.

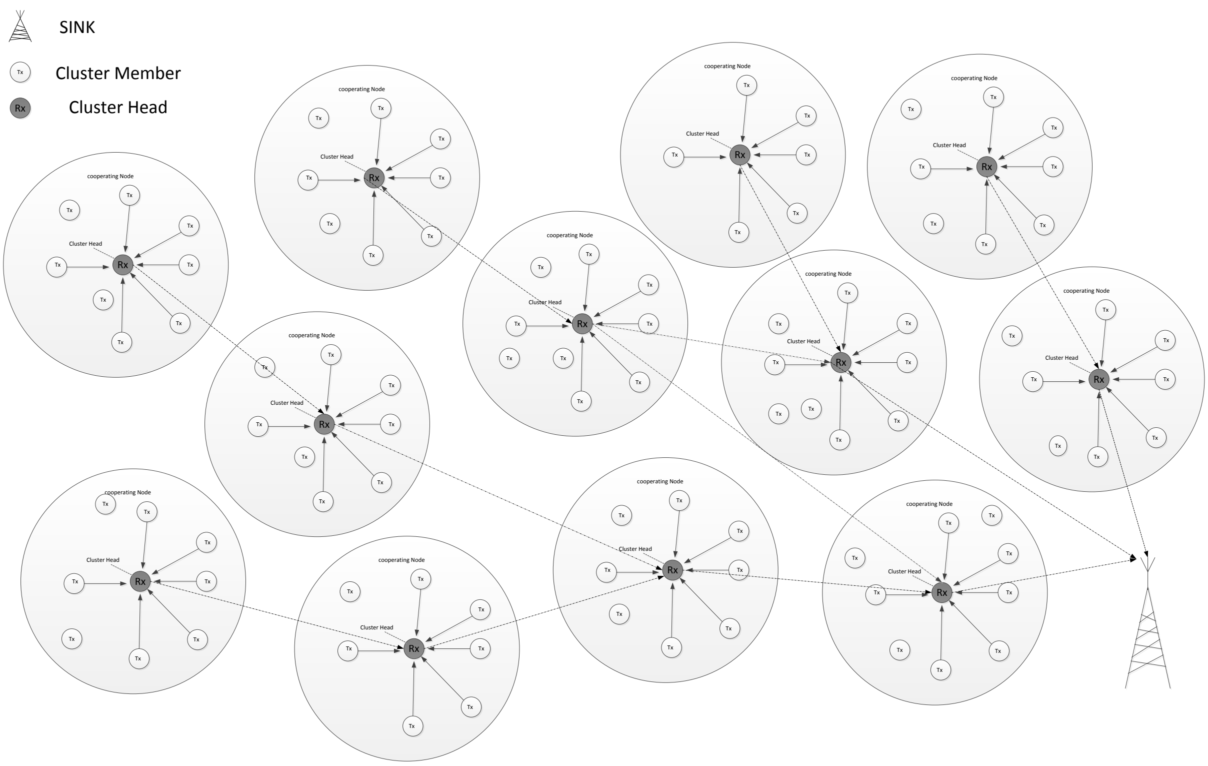


Figure 5.1: Clustered Wireless Sensor Networks

In this Chapter, a specific energy efficient relay selection method for clustered WSNs is proposed. The aim is minimizing the total transmission path length from the source toward the sink, by relaying the signal using the node with minimum two paths length. Thus, the transmission energy per bit at the source and the relay is minimized and the total transmission energy cost is reduced by selecting the optimal path. The fundamental of the proposed method is defining virtual clusters formed around the base station, in addition to the exiting cluster in each sub-region yielding to higher number of relay candidates for each CH. The basic of the novel method is electing the relay with the optimal location from virtual circular clusters defined at the Sink. Therefore, the base station selects the relay with minimum two link lengths, which minimizes the total energy cost per transmission. Simulation results are presented for different transmission range and the performance of the proposed method is evaluated in terms of energy cost per bit at the source, energy cost at the relay, total transmission energy cost and the network lifetime. Results show that the proposed method outperforms random relay selection method, conventional multi-hop transmission in terms of energy efficiency.

The contribution of this chapter can be summarized as follow

- Combining relay selection and clustering to achieve higher energy efficiency with less complexity.
- Balance the overall network energy consumption, as the relay role is not limited to CH due to the implementation of relay rotation.
- Minimizing the overhead energy cost, as relay is selected from predefined cluster at the destination.
- Minimize the energy cost per bit by using the optimal path with minimum length.
- Minimize the total transmission cost, by minimizing the energy cost at the source and the relay.
- Offer adaptable energy efficient solution to the channel condition, as the channel gain impact on energy consumption is considered.

- Minimizing the energy consumption by implementing the optimal modulation strategy jointly with relay selection

The rest of this chapter is organized as follows. In Section 5.2, a brief overview of clustering techniques, energy efficiency approaches in WSN are given. In Section 5.3, the system model is presented. In Section 5.4, the energy cost in the proposed scenario is presented. In Section 5.5, the modulation strategy impact on energy consumption is investigated through numerical example and the optimal policy is proposed. In Section 5.6, the energy consumption problem in clustered scenario is presented through analytical analysis as a base to the proposed algorithm and the proposed algorithm is given. In Section 5.7, the performance of the proposed method is compared with different techniques and performance in terms of energy cost per bit, total energy cost and network lifetime are given. Finally, Section 5.8concludes this chapter.

5.2 Clustering Concept

Wireless sensor networks (WSN) are composed of densely deployed tiny low power nodes (infrared, magnetic, acoustic and are deployed for various purpose such as health monitoring, military application, home automation, traffic control, environmental research, and forecast [154]. The physical size limitation, low cost and low complexity of WSN nodes raise the challenge of energy conservation as they are powered by battery and are expected to work for long period. Benefiting from the distributed deployment, and the broadcast nature of the wireless channel, multi-hop transmission schemes are mainly adopted to overcome the limited transmission range in WSN, by dividing the path into several shorter links. In this regard, NON-Hierarchical protocols such as Spin, Rumor-routing, Cougar and Direct Diffusion has been utilised, and proved to be more energy efficient than conventional transmission [155 156]. However, these protocols sever scalability as specific nodes belonging to certain path deplete their energy faster leading to a strayed connection with the destination. Therefore, Hierarchical protocols such as LEACH, PEGASIS,TEEN and hierarchical PEGASIS has been proposed to further minimize the energy consumption. In those schemes, clustering has been adopted to prolong the network lifetime by dividing the network region into sub-regions as shown in Figure 5.1. In consequence, nodes collaborate and organize themselves into cluster, based on the received signal strength, and elect a leader node, the cluster head CH. In those protocols, probabilistic approaches are used for electing CH responsible for forward the aggregated data to the final destination using multiple, single or even direct transmission [157]. Current Clustering techniques have been intensely studied in the literature from energy efficiency prospective, that has been addressed through different methods such as CH rotation, CH election metric, the optimizing clusters size [158]. Those protocols shown to be more energy efficient, but they severe from several drawbacks such as the delay, impractical and scalability as only CHs communicate with the base station. Different CH election metrics and adaptive clustering have been proposed to improve that protocol performance in terms of energy consumption. In[159] energy efficiency has been addressed by proposing a CH election algorithm, where the performance in term of network lifetime show significant improvement compared to LEACH. Thus, the threshold equation of LEACH has been multiplied with a factor representing the energy remaining in the node. Moreover, two clustering protocols, for single and multi-hop transmission toward destination, have been proposed for heterogeneous WSN in [160]. In this purpose, the threshold equation in[161], is multiplied by the ratio of the node residual energy to the network energy. Hence, the network energy consumption is balanced as the rotation of CH is based on energy weighted probability evaluation. From energy efficiency prospective the authors in [162], proposed a distance based CH election algorithm such as the CH to destination distance and the residual energy are the election metric showing an improved performance over LEACH in term of network lifetime. Moreover, to balance energy consumption in the network, sink as CH was proposed in [163] to relieve nodes near to the sink from being over utilized as they are more prone to relay data. Optimal clustering by minimizing the distance between nodes in the purpose of prolonging the network lifetime has been proposed in[164]. Adaptive clustering based on residual energy was proposed in [165]. Furthermore to overcome the problem of isolated node in network, that communicate directly with the sink consuming intense amount of energy, energy weighted CH election was proposed in[166] to prolong the network lifetime. Accordingly, inspired by MIMO technique [167],cooperation approaches were introduced to WSN such as nodes collaborate and exchange information to transmit cooperatively by forming a virtual MIMO antenna array. Moreover, the performance of cooperative Virtual MIMO in WSN has been studied and analysed in [168] showing that MIMO technique is more energy efficient than traditional SISO for long haul transmission, and short range if constellation size is optimized. In this regard, the total energy consumption expression of distributed cooperative WSN derived in [160], which is based (MIMO), and proved that virtual MIMO is more energy efficient compared to the traditional Single input single output (SISO) transmission in those networks. This phenomenon has been intensively studied in the literature from energy efficiency perspective[169]. Furthermore, as adopting this transmission scheme, prolong network lifetime as nodes use segment of the energy cost of non-cooperative scheme[170], several energy efficient cooperative protocol have been proposed for WSN based on residual energy [171], channel state information[172]. Furtherer, with the impact of the transmission strategy on the energy efficiency [173] as cooperative incur additional overhead and circuit processing cost, relay selection has been introduced to enhance the system performance. Conversely, to the energy efficiency protocols in the literature, we combine relay selection and clustering to tackle the energy conservation issue in WSN. We address the energy problem through the relay selection and the cluster formation as they are considered the essential methods to achieve energy efficiency in

Clustered WSN where inter cluster transmission adopt MISO communication. We propose an energy-efficient relay selection algorithm based on multi-clustering for WSN. Therefore, additional virtual clusters centred at the bases station are formed. In contrast to mutli-hop scenarios, the fundamental of the proposed method is to select a node from a set of relay candidates, from the virtual cluster within source transmission range, subject to correct decoding of the signal. Hence, the successful selected relay location is within the minimum required distance from both the source and the destination. Hence, the source and relay adjust their transmit power subject to the path length and required BER at the destination. Consequently, the network lifetime is extended by balancing the overall energy cost per transmission due to the diversity of relay candidates and minimizing the required energy per bit. To overcome the power limitations in WSNs, multi-hop routing has been employed, where transmitted signals are forwarded by adjutant nodes.

5.3 System Model

Consider a clustered WSNs shown in Figure5.1, where N nodes report their data to the CH responsible for forwarding the aggregated message to the Sink. The communication consists of four stages; setup phase, local communication, cooperation stage and long-haul transmission respectively. It's assumed that each node has a unique ID and the information of its location with respect to the network grid and cluster members, through the base station 'HELLO' message sent at the setup phase. Moreover, at this stage cluster formation is completed where nodes are grouped into local clusters based on their geographical location, CH election are performed, then after rotation is applied to balance the energy consumption as in [169]. Likewise, circular cluster initiated at the Sink is completed at this stage, and the optimal number k of circular cluster is calculated using equation (5.1), with the d_{BS} as the distance of the nearest node to the Sink. While the value of M is 500 as circular cluster are formed and the virtual network grid is $500\,X\,500$ although nodes are spread over a $200\,X\,200$

$$k = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{d_0} \frac{M}{d_{BS}^2} \tag{5.1}$$

After the virtual cluster formation, nodes are acknowledged of their virtual cluster index and the serving time slot in which they cooperate and forward the CH signal. For local communication, Time division multiple access (TDMA) is implemented, where each node is allocated a time slot as shown in Figure 5.2. CH aggregated the received data and transmits to the Sink using intermediate node, the relay, and the signal received at the CH is given by

$$S_C = \sum_1^n h_i S_i + n_i \tag{5.2}$$

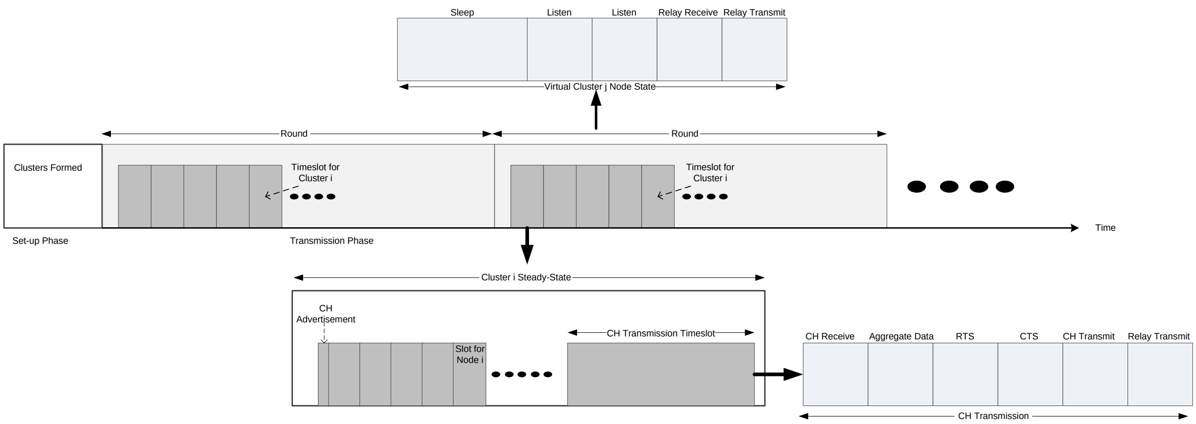


Figure 5.2: TMDA Cooperation Procedure.

For long haul communication, the transmission occurs over two-time slots. In the first-time slot, the source (S) transmits the message while in the second-time slot the successful relay transmits re-encoded version of the received signal toward the destination (D). The signal received at the relay (R) and D in the first and second timeslot are expressed as follow

$$\begin{aligned} S_R &= h_{SR}\sqrt{E_S}\,S + n_{SR} \\ S_D &= h_{RD}\sqrt{E_S}\,S + n_{RD} \end{aligned} \tag{5.3}$$

where h_{SR}, h_{RD} are the channel gain of the source-relay and relay-destination link respectively, and n_{sr}, n_{rd} are the additive white Gaussian with average power spectral density N_0. And S, S are the original source message and the re-encoded message signal transmitted at the relay. While E_S, E_S are the energy per symbol for a target BER at the destination. We consider different modulation strategy; coded MQAM, uncoded MQAM, uncoded MFSK and coded MFSK. For local transmission, the probability of error in AWGN channel calculated as in [170]. For local communication and long-haul communication, we assume uncorrelated AWGN channels fading that experience additive white Gaussian noise, and each link exploit different channel gain. We consider a cooperative scenario, with the CH as a source (S) transmitting to a destination (D) the Sink, through the aid of single relay node (R) selected at the destination from a set of N available candidates as shown in Figure 3. The CH send the RTS message, then after the Sink transmit the CTS message, and finally the ACK message which includes the ID of the selected relay. At this stage, S and R adjust their power to achieve the required target BER at the destination. The proposed virtual clustering technique and the energy efficient relay selection algorithm are given in Section 5.6.

5.4 Energy Consumption in Clustered Networks

As given in [60] the energy consumption in a typical RF receiver consists of the power amplifier P_{PA}, and the circuit power P_C and it is given by

$$E = \frac{(P_C + P_{PA})}{R_b} \tag{5.4}$$

where R_b and P_C are the system bit rate and the circuit power consumption respectively, and P_{PA} is given by

$$P_{PA} = (1+\alpha)P_{out} \tag{5.5}$$

where α is the amplifier drain efficiency, and P_{out} is the required transmit power which can calculated using the link budget equation given by

$$P_{out} = \frac{(4\pi)^2 d^{\alpha} M_t N_f}{G_r G_t (\lambda)^2} \overline{E_b} R_b \tag{5.6}$$

where M_t, N_f, R_b, G_r, G_t and λ are the link margin, receiver noise figure, bit rate, receiver antenna gains, transmitter antenna gain and wavelength respectively. α and $\overline{E_b}$ are the path loss factor and required energy per bit at the receiver for the target BER. And α depend on the distance between transceivers and is evaluated by

$$\begin{aligned} \alpha &= 2 \; if \; d \le d_0 \\ \alpha &= 4 \; if \; d \ge d_0 \end{aligned} \tag{5.7}$$

and the threshold distance d_0 is calculated by

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{5.8}$$

where $\varepsilon_{fs}, \varepsilon_{mp}$ are the free space and the multipath model transmit amplifier circuit energy consumption parameters subject to free path loss or two ray model respectively, and $\overline{E_b}$ is correlated to the modulation strategy as explained in Chapter 3. MQAM and MFSK modulation in AWGN channel are considered and the energy required per bit based on BER requirement at the destination for coded and uncoded system are evaluated. For uncoded MQAM and coded MQAM, the energy per bit is evaluated using the same approach given in Section 3.5. The total energy per bit for uncoded MQAM and coded MQAM are given in equation (5.9) and equation (5.10) respectively.

$$E_b = ((1+\theta)\frac{4}{3}N_f B\sigma^2(2^b-1)\ln(\frac{4(1-\frac{1}{\sqrt{2^b}})}{bP_e})G_d T_{on})/L + (P_c T_{on})/L \quad (5.9)$$

$$E_b = ((1+\theta)\frac{4}{3G_c}N_f B\sigma^2(2^b-1)\ln(\frac{4(1-\frac{1}{\sqrt{2^b}})}{bP_e})G_d T_{on})/L + (P_c T_{on})/L \quad (5.10)$$

The data aggregation energy cost per bit E_a and E_{Rx} are set to 0.005 nanoJoule per bit. n and f are the transmitting node number within the cluster and frame length, and d_l is distance between the node and the CH. While d_1 and d_2 are the distance from the CH to the selected relay and the distance from the relay to the Sink respectively. Therefore, the total energy cost per transmission is given by

$$E_{total} = E_{Rx}(S_1 + S_2 + S_3) + E_{Tx}S_1 \quad (5.11)$$

where S_1, S_2 and S_3 are the RTS, CTS and Beacon message frame length respectively.

5.5 Optimal Modulation Strategy

For MFSK modulation the probability of error is derived as in (4.11), since most of practical MFSK receivers use non- coherent detectors.

$$P_e = 2^{b-2} e^{-\frac{\gamma b}{2}} \quad (5.12)$$

The instantaneous SNR y_b at the receiver side is calculated using equation (5.12).Raising equation (5.11) to logarithm 2, and using equation (5.12) in the modified (5.11), the energy per bit is given in equation (5.13).

$$y_b = \frac{bE_b}{2\partial^2 N_f} \quad (5.13)$$

$$E_b = 2\partial^2 N_f \ln\frac{2^{b-2}}{P_e} \quad (5.14)$$

Following the same derivation Chapter 3, the transmission power and the transmission energy are given in equation (5.14) and equation (5.15) respectively [103].

$$P_t = 4\partial^2 N_f \ln \frac{2^{b-2}}{P_e} G B_e \quad (5.15)$$

where G is given by

$$G = \frac{(4\pi)^2 d^{\alpha} M_t}{G_r G_t (\lambda)^2} \quad (5.16)$$

and B_e follow the bandwidth efficiency in MFSK modulation given by

$$B_e = \frac{2b}{2^b} \quad (5.17)$$

Following the same derivation in Section 3.5, the total energy cost per bit is given by

$$E_t = (1+\theta) 4\partial^2 N_f \ln \frac{2^{b-2}}{P_e} G B_e + \frac{P_c}{L T_{on}} + \frac{2 P_{syn} T_{tr}}{L} \quad (5.18)$$

where T_{on} is given by

$$T_{on} = \frac{2^b L}{2bB} \quad (5.19)$$

For coded MFSK modulation, we follow the same approach in Chapter 3, using a convolutional code rate of 2/3 with code gain $C_g = 2.6$ [103]. Thus, the total energy cost per bit is reduced and given by

$$E_t = (1+\theta) 4\partial^2 N_f \ln(\frac{2^{b-2}}{P_e}) \frac{G B_e}{C_g} + \frac{P_c}{L T_{on}} + \frac{2 P_{syn} T_{tr}}{L} \quad (5.20)$$

The energy cost for local communication E_{loc}, and the energy cost for long haul communication E_{lon} are given in equations (5.20) and (5.21) respectively.

$$E_{loc} = n(E_t(d_l{}^{\alpha}) + E_{Rx}) + E_a \tag{5.21}$$

$$E_{lon} = E_t(d_1{}^{\alpha}) + E_{Rx} + E_t(d_2{}^{\alpha}) + E_{loc} + E_{cop} \tag{5.22}$$

where E_{cr} and E_{Rx} are the Cooperation energy cost per bit, receive energy cost per bit, E_t is calculated based on the distance between transceivers. Following the observation in Chapter 3, where uncoded modulation outperforms coded modulation in short transmission range, E_t is evaluated using equation (4.17) for local communication. For long haul transmission, between the CH and the relay, and Relay to the destination E_t is evaluated using equation (4.17) or equation (4.18). We use the same approach used for MQAM modulation in Chapter 3, and we consider the energy consumption of uncoded MSFK and coded MSFK for different constellation size. As seen in Figure 5.1, at short transmission range (1 meter), where the circuit energy is dominant, the total energy cost slightly increases with the raise in b. Besides, at 30 meters transmission distance, the total energy cost and the transmit energy cost curves almost intersect at b=6. Thus, considering the circuit energy cost, the optimal constellation size for distance below 30 meters is $M = 2^b$ =4, as for b=2 the total energy is minimized, while b=3 is the optimal choice for short range, such as within the cluster.

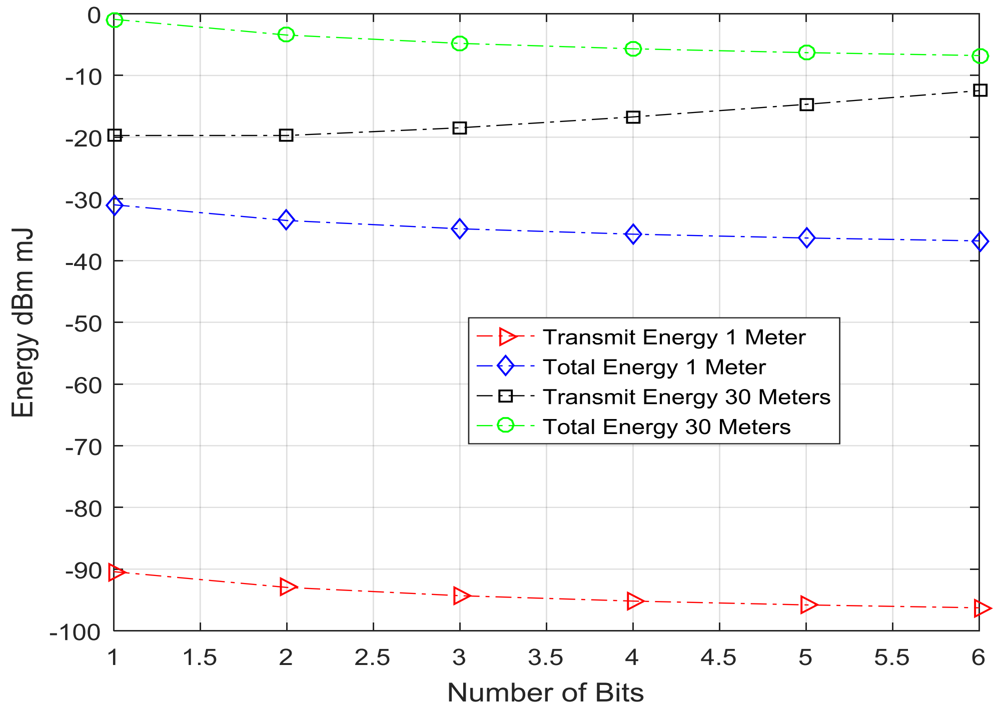


Figure 5.3: Transmit Energy Cost vs Total Energy Cost at different Distance (Meters)

To illustrate the performance assuming a transmission deadline T of 1second in uncoded system, which is expended to $T/C_g = 3/2$ in coded system due to the additional redundant bits, with code rate of 3/2. From Figure 5.2, coded MFSK start outperforming the uncoded MFSK for transmission distance above 50 meters. From the observation in Figure 5.2, for transmission distance over 50 meters, coded MFSK is used otherwise uncoded MFSK is utilized. The same experiment under the same delay requirement is repeated and the performance in terms of energy consumption per bit, for coded MFSK, uncoded MFSK, coded MQAM and uncoded MQAM for optimized system in is shown in Figure 5.3 for the energy consumption per bit (dBm mJ) against the transmission distance in meters. The optimal constellation size for coded MQAM and uncoded MQAM is derived following the same approach given in Section 3.5.3.

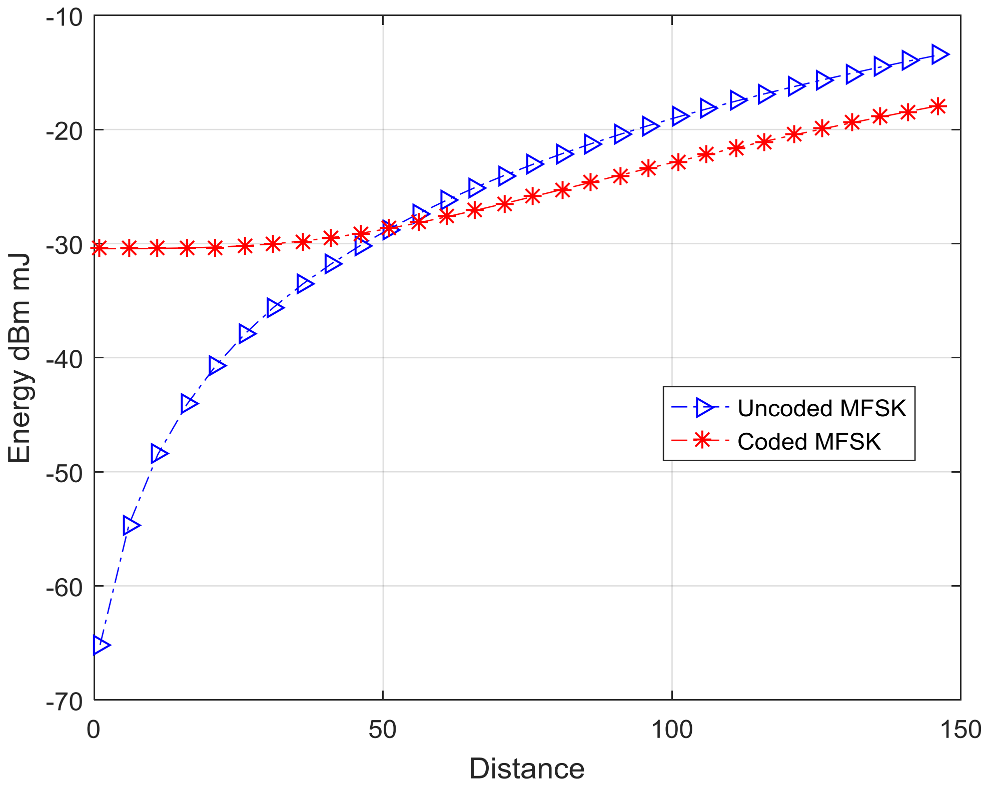


Figure 5.4: uncoded MFSK vs coded MFSK under Delay Constraint at different distances (Meters)

From Figure 5.3, uncoded MQAM performance in terms of energy consumption is the worse compared to other strategies, and it shows 20dB increase in energy cost at 50meters transmission distance compared to coded MFSK and uncoded MFSK. In contrast, coded MQAM shows the best performance for transmission range above 10 meters where it outperforms uncoded MFSK. At transmission range of 50 meters and above the most energy efficiency transmission strategy is coded MQAM which has slightly similar performance to coded MFSK for 100 meters transmission distance and above. Thus, from the result given in Figure 5.3 the optimal modulation strategy for local communication is uncoded MFSK and for transmission distance above 50 meters, while for transmission distance interval of [10-50] uncoded MFSK is in use.

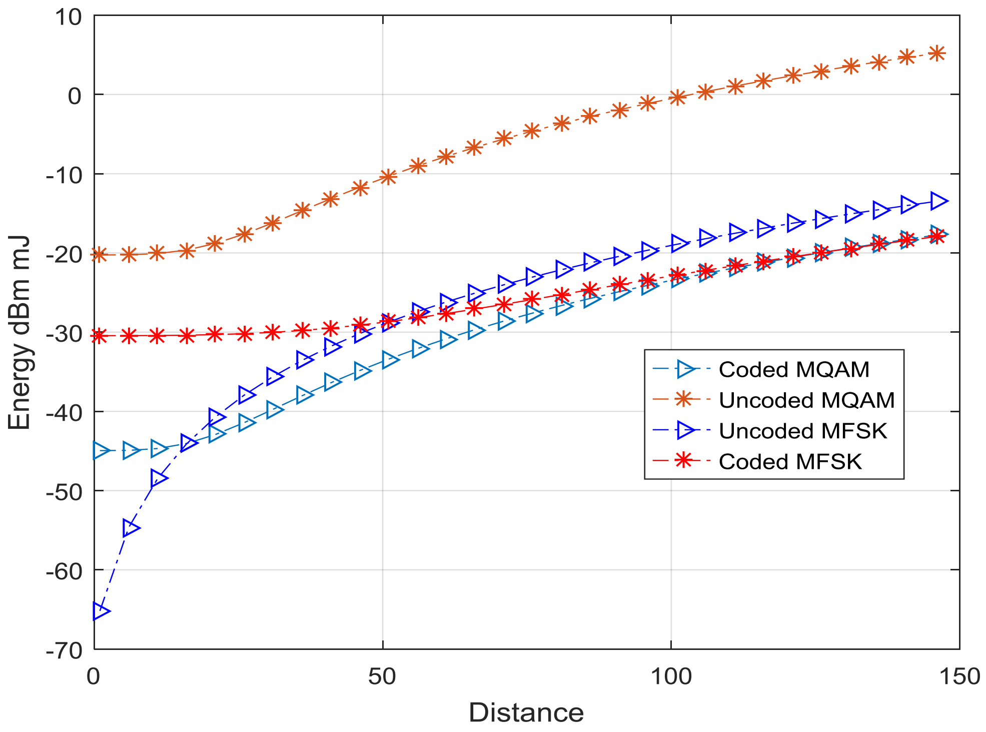


Figure 5.5: Modulation Strategy Performance under Delay constraint at different distances (Meters)

The optimization policy at the node (Relay or Source) is given by

$$\begin{aligned} &\min imize \quad E_t \\ &subject\ \ to\ \ b - b_{\min} > 0 \\ &\qquad\qquad\quad b_{\max} - b > 0 \end{aligned} \tag{5.23}$$

where the node compute all the values of b under the time deadline constraint, and the maximum energy budget correlated to the transmission range. Using a convex optimization, the optimization problem is solved by the interior point method in the format given in (4.24).

$$\begin{aligned} &\min imize \quad E(b) \\ &subject\, to \quad E^i(b) > 0 \end{aligned} \tag{5.24}$$

where i represents different energy cost for different b. The node start with minimum b, calculates the energy cost, and update b in case the cost is minimized. Minimum and maximum value of b are evaluated based on the transmission deadline requirements.

5.6 Problem Formulation

5.6.1 Clustering Performance Analysis

As discussed in previous chapters, wireless nodes are limited to certain transmission range due to power constraint, thus the implementation of relay channel evades the necessity of higher power at a transmitting node to attain a desired power level at the receiver to meet the SNR threshold. Although clustering schemes shown to be effective approaches to achieve a target performance without escalating the energy cost, they suffer from a major drawback which is limitation of relay candidates as only CHs participate in the transmission. As a result, the performance is stringent to the link quality of available CH. A potential solution is adopting relay schemes whereby increasing the diversity of relay candidates. However, the benefits achieved in clustering schemes in terms of delays, synchronization can be omitted by the implementation of relay schemes as non- CH nodes are put into sleep mode for energy saving. The benefit of clustering schemes where the network is divided into smaller sub-region is easing the synchronization that evades an additional energy cost in term of signalling. This benefit can be eliminated due higher of nodes involved in the transmission from outside a transmitting cluster. In addition of that, balance power consumption overall the network achieved from CH rotation implementation can be omitted as potential relays task might spend long periods in the idle mode. To sustain the benefit of clustering schemes and reap the benefit of relay schemes, we propose a relay selection based on multi-clustering. The core of this method is increasing the number of candidate relays for transmit node, where by the node that minimize the energy transmission cost forward the source message. The relay candidate's limitation is illustrated in equation (3.39) as the probability of finding n nodes from k node to perform the relay task is correlated to number of CH, in addition of the desired transmit power at the source. Thus, increasing k, raise the probability of higher number of candidate relays. Consequently, the probability of successful transmission given in equation (5.25) is raised.

$$P(R) = P(\gamma_1 > T)P(\gamma_2 > T) \tag{5.25}$$

where γ_1 and γ_2 are the instantaneous SNR of the source-relay link and relay-Sink link. The predefined SNR threshold T for a target BER in AWGN channel evaluated using equation (5.26) or equation (5.27).

$$T = \ln \frac{2^{b-2}}{P_e} \tag{5.26}$$

$$T = \frac{2^b - 1}{6P_e} \tag{5.27}$$

The relay selection policy at the Sink is given by

$$\begin{aligned} &\text{Minimize} \quad E_1, E_2 \\ &\text{Subject} \quad P_e \le P_{req} \\ &d_1 \le d_{Max}^1 \; and \; d_2 \le d_{Max}^2 \\ &d_1^2 + d_2^2 \le d^{\alpha} \\ &P_{Total} < P_{Max} \end{aligned} \tag{5.28}$$

where $E_1, E_2, P_e, P_{req}, d_{Max}^1, d_{Max}^2$ and d are the energy cost per bit at the source, the energy cost per bit at the relay, the achievable BER, the target BER, the maximum threshold distance for the source-relay link, the maximum threshold distance for the relay-Sink link and the distance between the source-Sink link length. P_{Total} and P_{Max} are the total power and maximum power evaluated using equation (5.9) or (5.10).

5.6.2 Proposed Algorithm

The Sink performs the Virtual cluster formation and broadcast the cluster indexes at the setup phase using equation (5.1). We the required power to reach the Sink as bench to set the upper bound of the transmit energy cost, and we assume no direct link between the source and the Sink, while the Sink messages reach all the nodes in the network. Moreover, it's not necessary that RTS message reach the Sink, while potential relay candidates listen to the RTS/CTS packet exchange in addition of the Beacon message sent by the Sink to estimate channel gains and the successful relay ID. This is because the Sink transmits with unlimited power, and potential relay fall within the source transmission range. The energy per bit at the source and relay for a target BER is calculated using equation (5.9) or equation (5.10). The Propose algorithm consists of the steps given in Table 5.1

Table 5.1:Energy Efficient Relay Selection Algorithm for Clustered Wireless Networks

1. The Sink execute Virtual Cluster formation, and send the necessary information
2. Candidates relay, switch to idle mode, at the beginning of each transmission based on virtual cluster index.
3. The transmitting CH sends the RTS initiating data to transmit.
4. The SINK sends CTS with sufficient power to reach all relay candidates, and the CH.
5. Candidate relays, estimate the partial channel gain and the desired transmit power for the target BER to satisfy the condition in equation (5.25).
6. The Sink use (5.28) to evaluate the optimal modulation strategy, and sends the Beacon message, including the successful relay ID considering residual energy
7. The CH and the successful relay transmit in their allocated time slot following the TDMA subject to satisfy the condition in equation (5.25)

5.7 Simulation Results

In this section, we evaluate the performance of the proposed relay selection algorithm through simulation results, and the performance in terms of energy cost per bit (dBm mJ) is given against the transmission distance in meters. Through this section we refer to the proposed method by Relay Selection and the performance is compared to the multi-hop, random relay selection and direct transmission. Moreover, the network lifetime is considered by showing the performance of all the methods in terms of the number of alive nodes after a certain number of rounds. Consider a network of 200 nodes randomly spread over a network grid of 100meters square with the Sink coordinates are $x = y = 200$ therefore the nearest node to the Sink is at least 50 meters far. The receiving power is set to 100 mW, while the power consumption for sleep mode and transient between different stats is negligible. The wavelength is set to 0.12 meter and data aggregation cost at the CH is set to 5 Nanojoule per bit and other simulation parameters are given in Table 5.2. In Multi-Hop method, the nearest CH forwards the source signal to the Sink, while in random relay selection method, the relay is selected randomly from a set of nodes within the source transmission range subject to correct signal decoding. In the proposed method. the successful relay is selected with the minimum total two links lengths following the policy given in (5.28) and adjust their transmit power based on equation (5.9) or (5.10). In multi-hop and random relay selection the source use $P_{M\,\mathrm{ax}} / 2$ evaluated from (5.9) or (5.10) for the value of equal the total path length similar to the direct transmission scenario. Likewise, the relay adjusts its transmit power using (5.9) or (5.10) based on their path length to the Sink. To illustrate the performance, we examine the energy cost per bit at the source and the relay, total cost per bit and per message for three methods for different path length. Then we present the performance in terms of the network lifetime by plotting the number of alive nodes against the number of round. For coded MFSK system and uncoded MFSK system we plot the energy cost per bit in dBm mJ against the transmission distance in meters for Multi-Hop, Random Relay and optimized Relay Selection. We run 100000 iterations to average the channel gain and the average energy cost per bit for random nodes deployment and the results are given in Figure 5.6 and Figure 5.7.

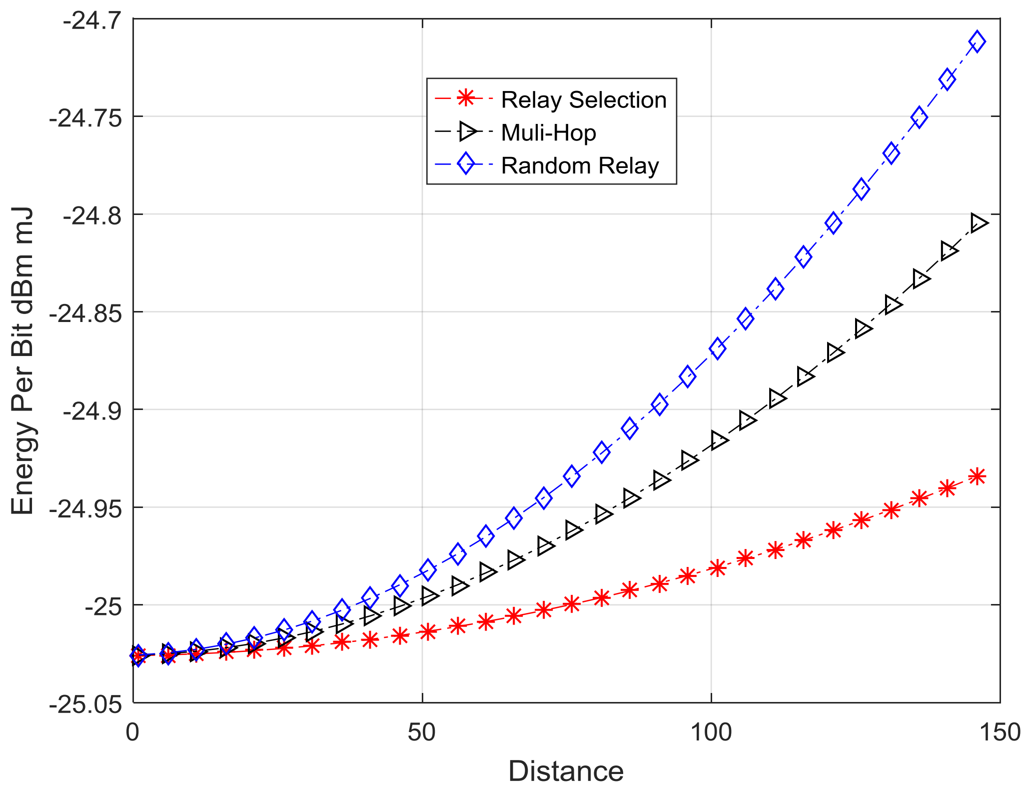


Figure 5.6: Energy Cost per Bit vs Distance (Meters)for uncoded MFSK in AWGN

From the results it can be seen that the optimised algorithm shows an improvement in terms of the energy cost per bit at different transmission range. The optimized algorithm outperforms Random Relay method and Multi Hop method by less than 0.8dB at 150 meters transmission distance. However, an unimpressive improvement of less than 1 dB is due to of adding the RTS, CTS energy cost to the total energy cost per bit for the proposed algorithm and receiving energy cost at the candidate relays, while circuit and energy cost where considered for other methods to evaluate the additional energy penalty in terms of signalling energy cost.

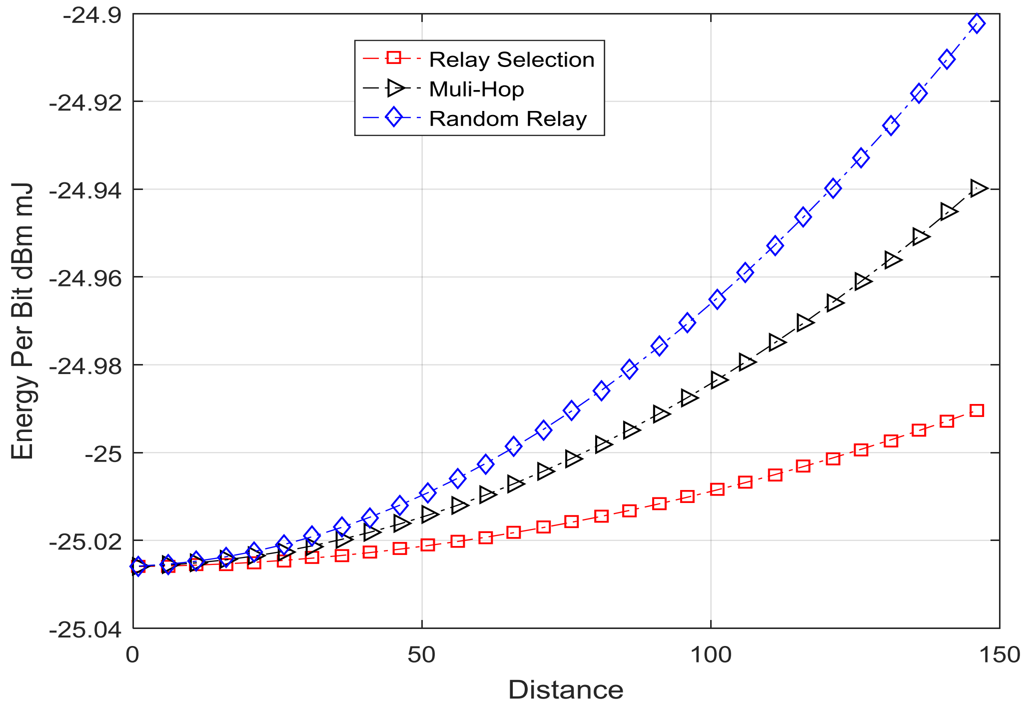


Figure 5.7: Energy Cost per Bit vs Distance (Meters), (coded MFSK, AWGN)

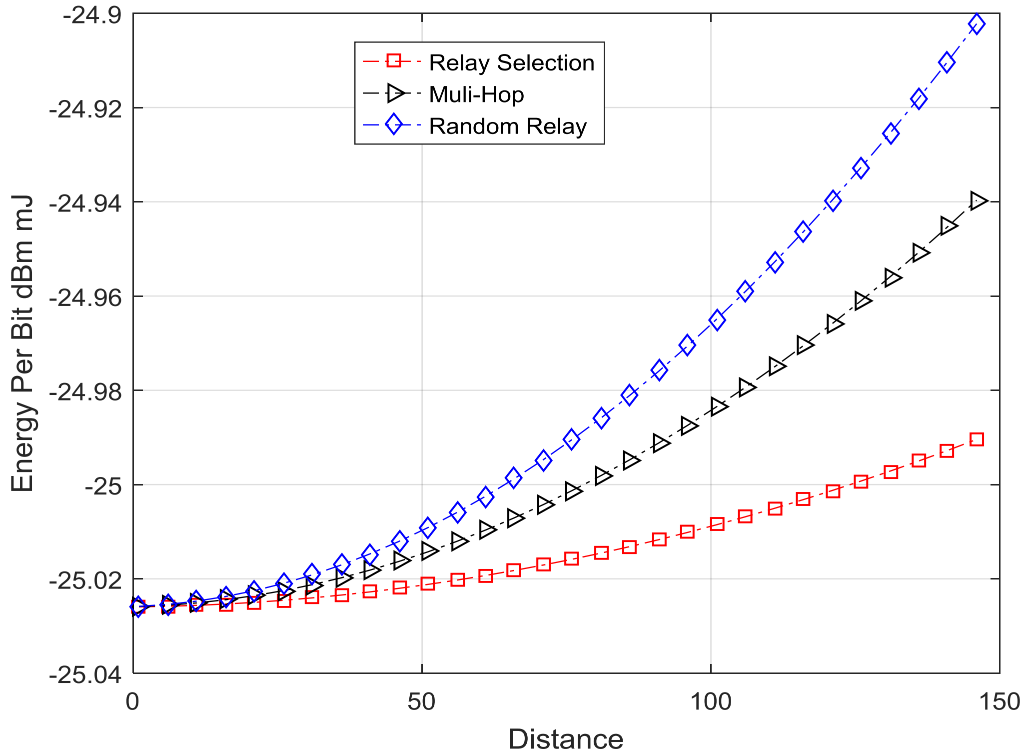


Figure 5.8 : Energy Cost per Bit vs Distance (Meters), (uncoded MQAM, AWGN)

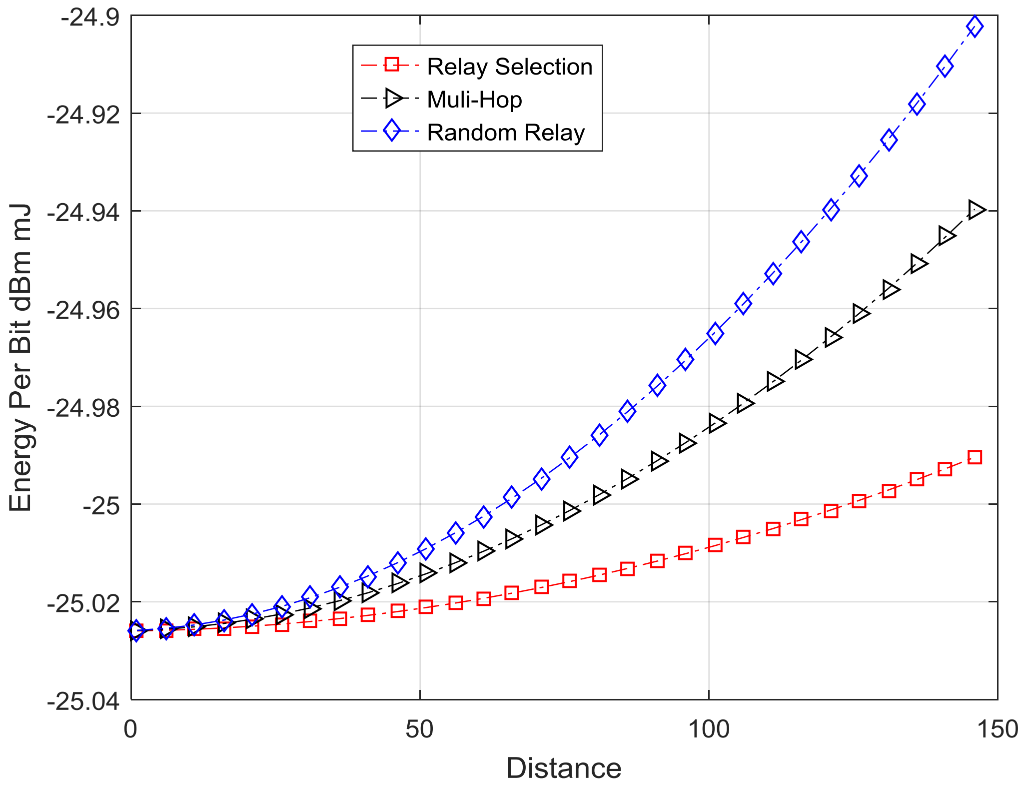


Figure 5.9: Energy Cost per Bit vs Distance (Meters), (coded MQAM, AWGN)

We repeat the same experiment for coded and uncoded MQAM systems using the same parameters and same evaluation approach. Therefore, we run 100000 iterations and average the total energy cost per bit for different transmission distances. The energy cost per bit in dBm mJ is plot against the transmission distance in meters for uncoded MQAM and coded MQAM in Figure 5.8 and Figure 5.8 respectively. From the results we get the same unimpressive improvement less than 1 dB in the best scenario. Therefore, to acquire an unambiguous comparison, we consider different approach where all the methods use the same transmission strategy under the same communication environment. Thus, calculating the total cost per transmission is more precise, therefore we use equation (5.22) and equation (5.23) to calculate the total energy cost per packet. Thus, we perform relay selection in Random Relay selection method and Multi-Hop method using the full optimization policy given in equation (5.24) in line with random relay selection technique.

Table 5.2: Virtual Clustering Algorithm Simulation Parameters

Parameters	Value
Drain Efficiency	0.35
Thermal Noise PSD	-171 dBm/Hz
Target Bit Error Rate	10^{-3}
Carrier Frequency	2.5 GHZ
Bandwidth	1 MHZ
Packet Length	200 Kb
Link Margin	40 dB
Transmission Deadline	100 ms
Mixer Power	30.3 mW
ADC & DAC Power	15.4 mW
LNA Power	20 mW
Active Filter Power	2.5 mW
Frequency Synthesizer Power	50 mW
Receiver Noise Figure	10 dB
Intermediate Frequency Amplifier Power	3 mW

Thus, the same experiment for the optimised scenario is repeated, where by the source and relay use the optimal modulation strategy in Random Relay method, Multi-Hop transmission and the proposed algorithm. The performance in terms of energy consumption is evaluated by plotting the total energy cost in dBm mJ against the distance in meters.

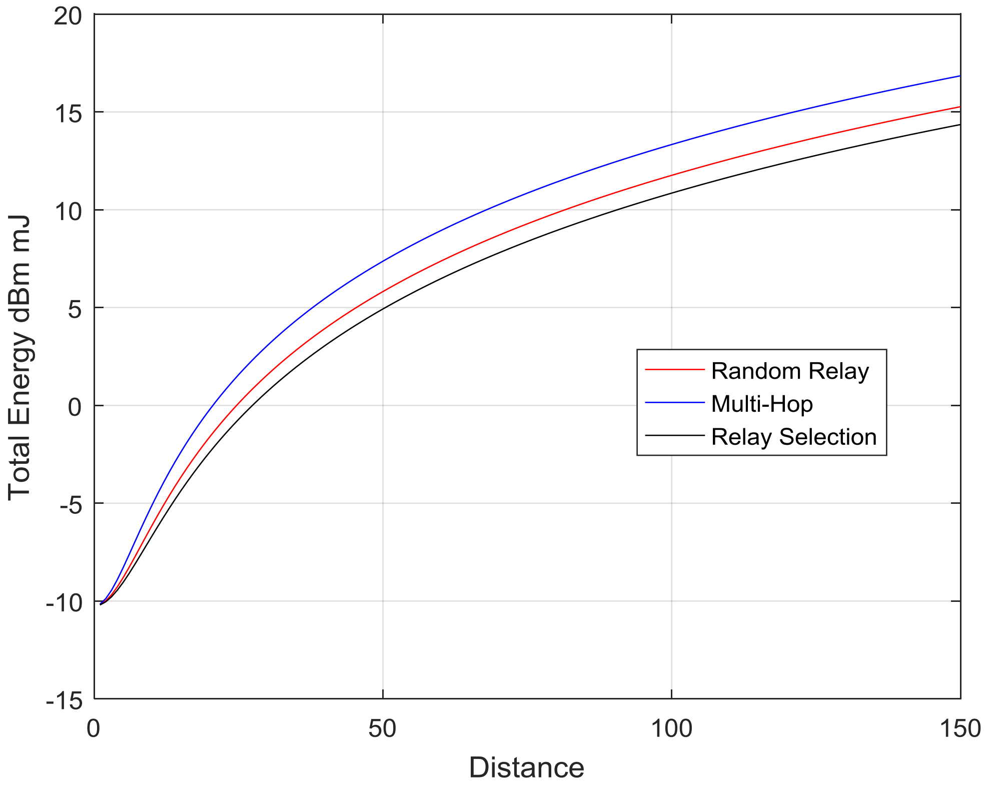


Figure 5.10: Energy Cost per Bit at the Source Different Distance (Meters)

10000 iterations for each distance were conducted, under different condition using random nodes deployment and the average energy cost is used. Figure 5.6 and Figure 5.7 consider the energy consumption at the source and relay respectively, assuming a 2 Kb packet length at CH. The proposed algorithm outperforms Random Relay method and muli-Hop transmission, where an improvement of 3dB and 2dB at the source and relay is observed for different distances. At the relay, the proposed algorithm shows better performance of 10dB average at different transmission distances. This difference in terms of the energy cost improvement at the source compared to the energy cost improvement at the relay is due to the power constraint. As random relay selection is performed in Multi-hop method and Random Relay method doesn't benefit from the system optimization in contrast to the source. The source transmit power is minimized, while a random relay without considering the relay-Sink path length escalate the total energy cost.

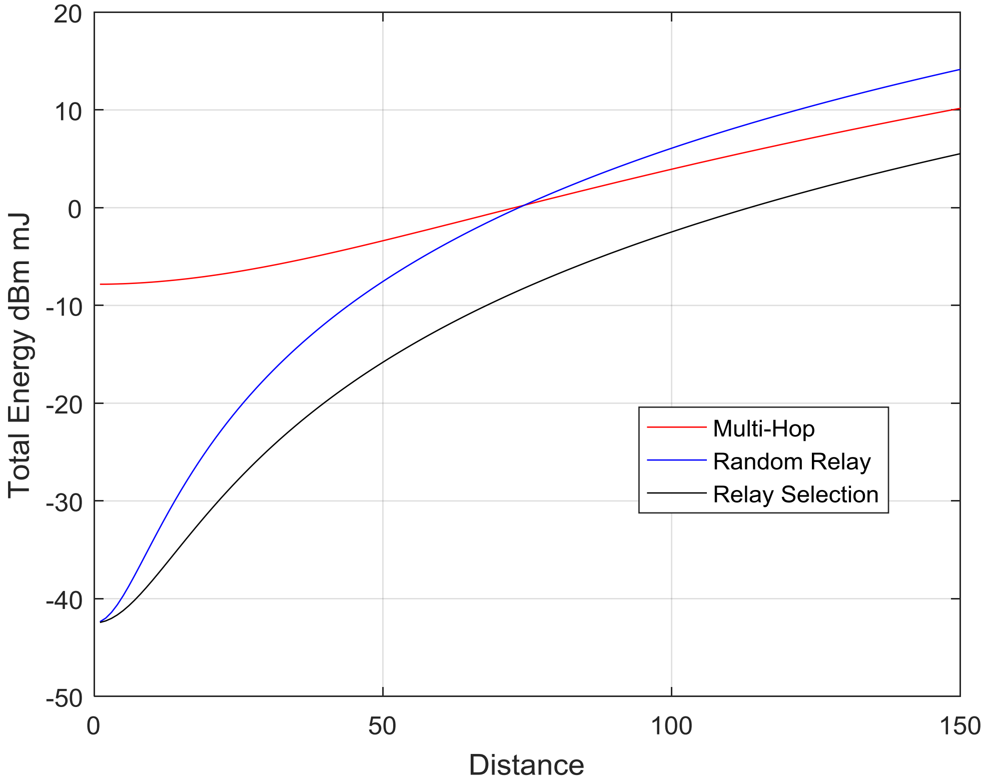


Figure 5.11: Energy Cost per Bit at the Relay vs Distance (Meters)

We plot the total energy cost dBm mJ against transmission distance of the three methods in addition of the Optimized direct transmission. From the obtained results given in Figure 5.8, it can be seen that at variant transmission distances the proposed algorithm outperforms Multi-hop by 2 dB, Random Relay by 3.5 dB, and Optimized direct transmission by 5 dB. To exhibit the performance improvement the network lifetime in terms for all the optimized methods is considered as a performance metric using the following scenario. Its assumed that the CH of local cluster send a packet at each round and cluster rotation is applied. Therefore, at each round different CH performs the task of the source, with different channel condition through candidate relays in the appropriate virtual cluster. The performance of the optimized system is evaluated and compared to Random Relay method, Multi-Hop method.

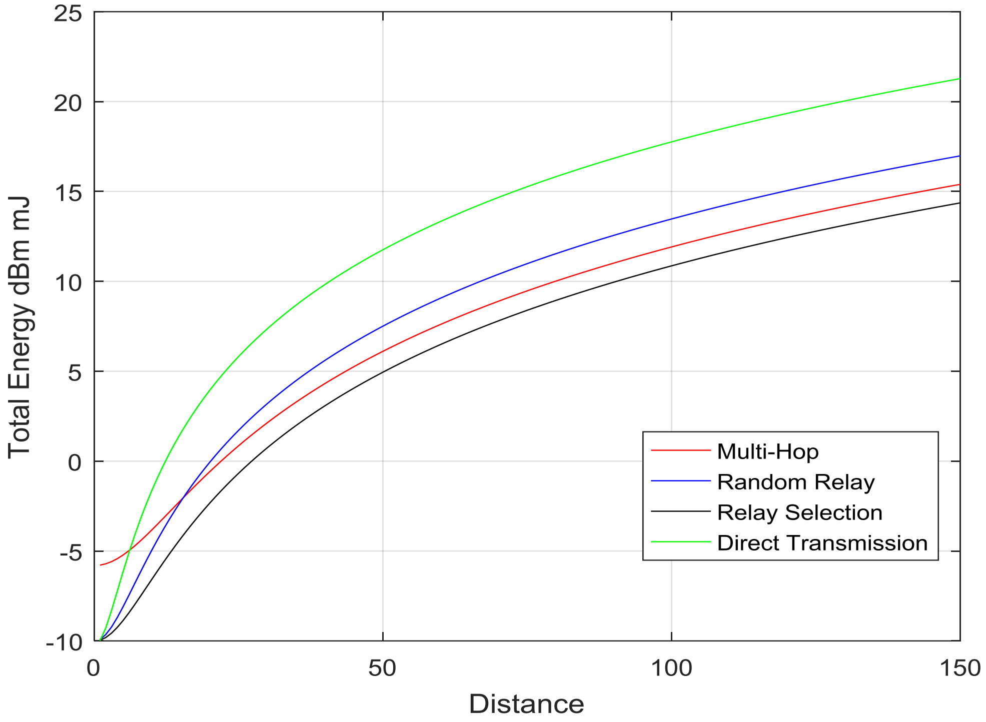


Figure 5.12: Total Energy Cost per Bit vs Distance (Meters)

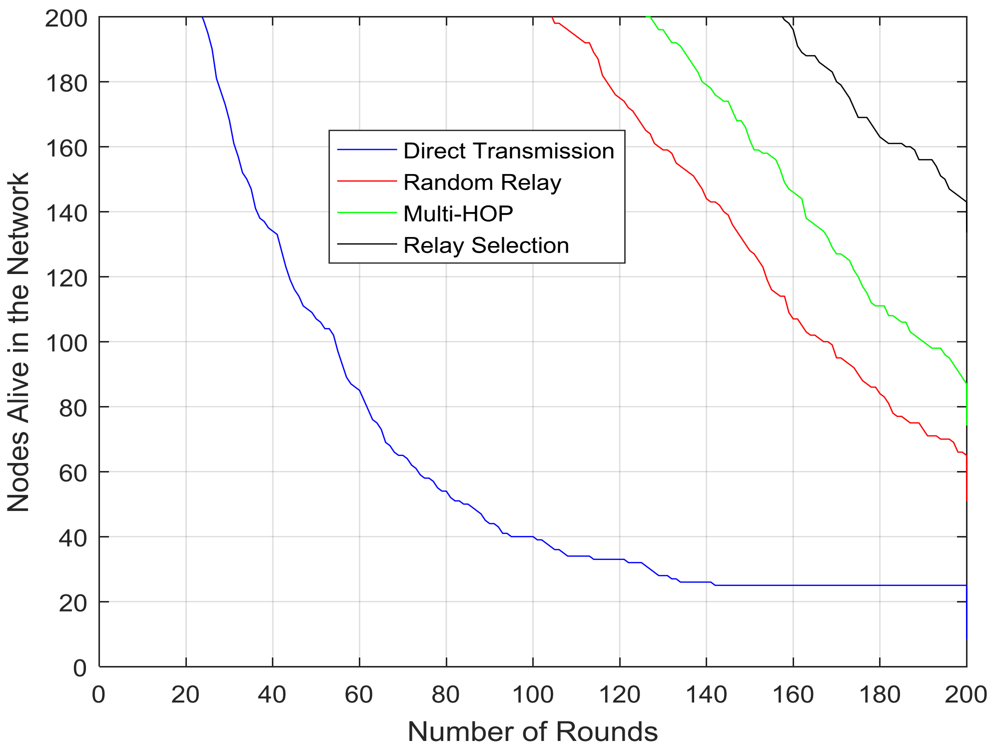


Figure 5.13: Nodes Alive Versus Number of Round (coded MQAM, AWGN)

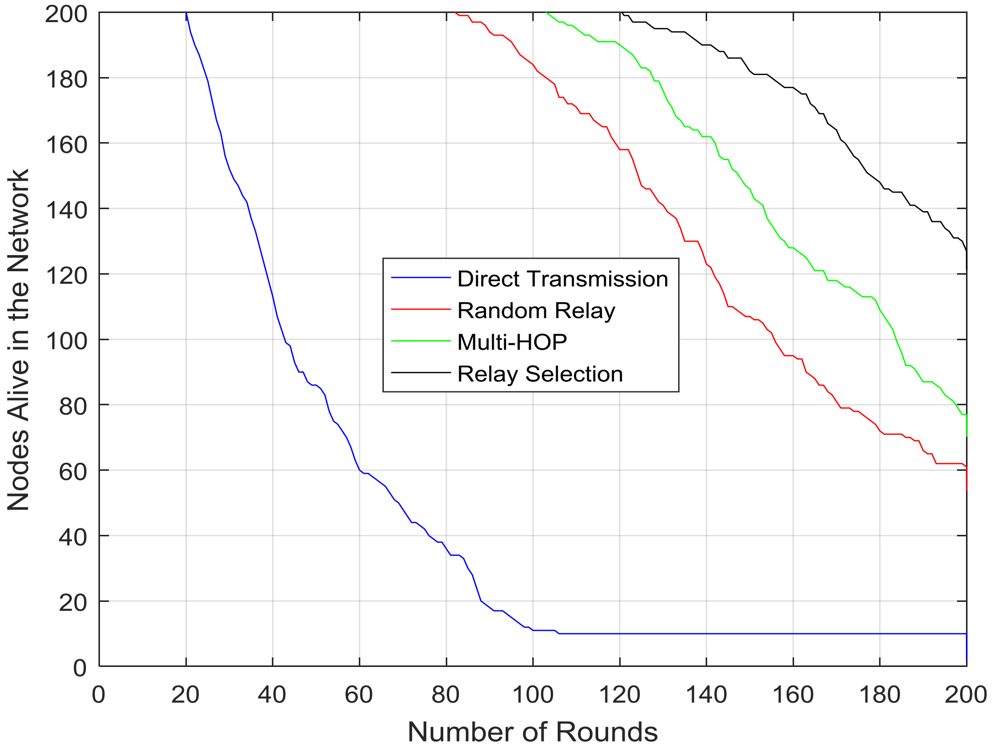


Figure 5.14: Nodes Alive vs Number of Round (coded MFSK,AWGN)

100000 iterations are conducted whereby the channel gain is averaged for random nodes placement, and the energy cost for every distance is averaged. Its assumed that each node has an initial energy of 2 J. Figure 5.10 and Figure 5.11 show the performance of all methods for coded MQAM and coded MFSK. The proposed algorithm uses the optimal modulation strategy outperforms other transmission methods after 200 rounds, as the results show 140 nodes alive. However, the slight difference of alive nodes number is due to the random variation of the channel gain and random nodes deployment. This can be seen by the number of rounds required until the first node depletes the total energy. The proposed algorithm shows a better performance in this aspect as around 130 nodes are alive after 120 rounds. The experiment is conducted for all the transmission methods, using the same parameters for uncoded MFSK and uncoded MQAM and the results are given in Figure 5.12 and Figure 5.13 respectively. Similarly, 100000 iterations are conducted to average the energy cost at each distance.

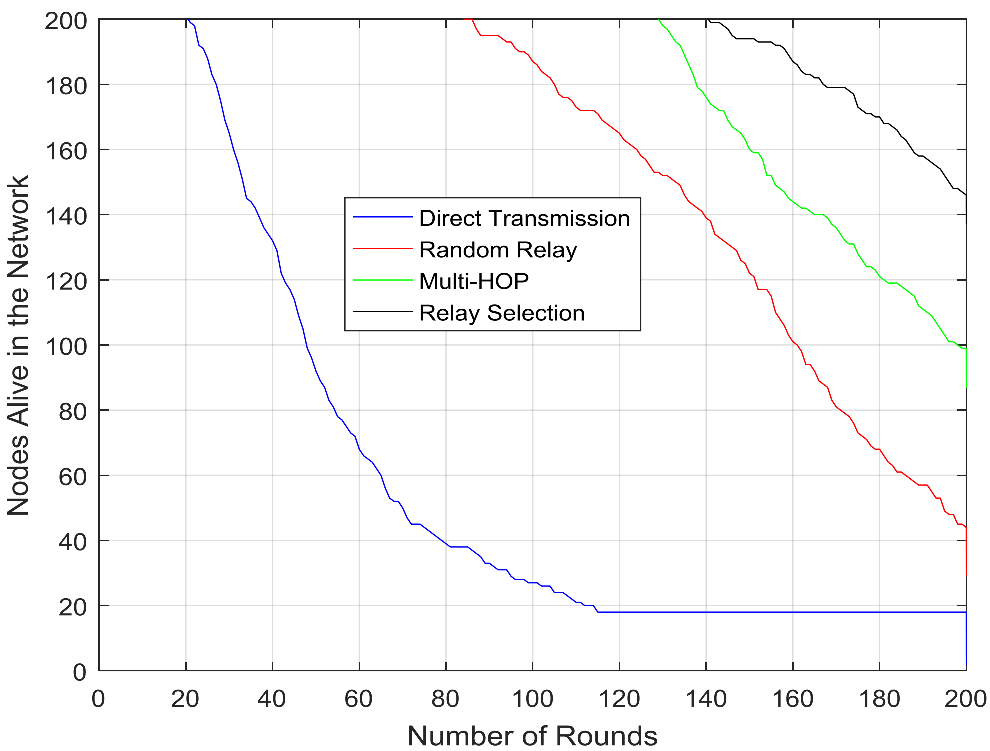


Figure 5.14: Nodes Alive Versus Number of Round (uncoded MFSK, AWGN)

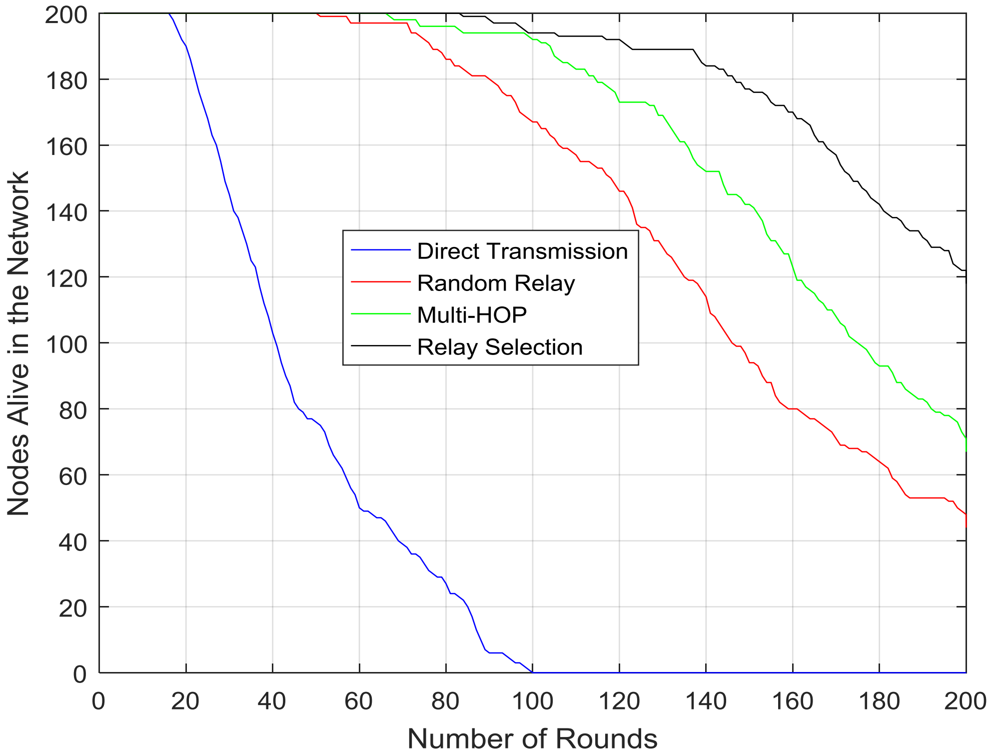


Figure 5.15: Nodes Alive Versus Number of Round (uncoded MQAM, AWGN)

The proposed algorithm outperforms Multi-Hop method, Random Relay Method and Direct Transmission in terms of the number of alive node at different rounds for uncoded MQAM and uncoded MFSK. For uncoded MFSK and uncoded MQAM, the proposed algorithm shows around 140 nodes alive after 200 rounds and the first node deplete the total energy after 140 rounds and 90 rounds. Again, this difference is due to the random nature of deployment and channel variation. Although, Direct Transmission, Multi-Hop and Random Relay use the optimal constellation size, they show inferior performance compared to the proposed algorithm due to random relay selection or the drastic escalation in the transmit energy cost relatively to the transmission distance. Hence, from the observation in this section, the proposed algorithm shows better performance in terms of the energy cost compared to different optimized and non-optimized transmission techniques. This proves the necessity of applying relay selection jointly with resource optimization to achieve and energy efficient transmission strategy.

5.8 Summary

In this chapter, an energy efficient relay selection algorithm combining clustering technique and relay selection was proposed. In contrast to most proposed works in the literature in clustered WSNs, where only CH cooperates in the transmission and forwards the source message, relay is selected from predefined virtual cluster formed at the Sink based on their path length toward the source. The core of the proposed method is minimizing the total transmission energy cost by selecting the relay with minimum two path lengths, which decrease the energy required per transmitted bit. In this regard, the impact of the modulation strategy for coded MFSK, coded MQAM, uncoded MFSK and uncoded MQAM through were investigated through numerical analysis. Hence, the optimal modulation strategy was proposed and implemented in correlation to the transmission distance. The proposed algorithm outperforms the traditional multi-hop, random relay selection and direct transmission in terms of the energy consumption per bit at the source, the energy consumption per bit at the relay and the total energy consumption cost. Moreover, it can be clearly observed from results that the proposed algorithm offers substantial better performance in terms network lifetime.

Conclusion and Future Work

6.1 Conclusion

Cooperation in wireless network is a promising technique to combat the fading nature of channel and improve the overall system performance without extra cost and complexity. Implementing relay selection methods shown to be a potential candidate for achieving an energy efficient cooperative wireless communication. By splitting the communication link into shorter links, significant power conservation can be achieved without scarifying a target performance requirement. The replacement of direct link communication with several shorter paths has been intensively investigated and studied from energy efficiency perspective. Thus, different energy efficient relay selection methods were proposed from energy saving prospective, in contrast to traditional relay selection methods where the aim was enhancing the system performance from different prospective. Moreover, to achieve the optimal energy efficient cooperative communication, the wireless system resources need to be optimise.

However, it has been identified that in attempting to completely optimise the energy consumption in wireless networks, relay selection should be jointly implemented with an adaptive power control mechanism at the physical layer subject to the wireless system performance requirement. Thus, optimised power distribution among cooperating nodes can further reduce the overall transmit energy cost without sacrificing quality of services in wireless systems. In this regard, a detailed literature review has been undertaken in this thesis. To understand the basic principles and implementation, advantages, drawbacks of cooperation communication schemes in wireless networks, the review covers the nature of wireless channel, cooperative communications protocols, energy efficient relay selection methods, impact of modulation strategy and power control methods at the physical layer in cooperative wireless networks.

Moreover, the main cooperative protocols (DF and AF) performance in terms of energy consumption was presented and analysed as a platform for the proposed energy efficient relay selection algorithm for cooperative wireless networks. The core of the proposed algorithm is minimizing the energy cost per bit using a distance based relay selection method in line with the optimal modulation strategy. The proposed algorithm has been extended to different cooperative scenarios; virtual MIMO system and clustered wireless networks. For virtual MIMO system, distance based multiple relay selection is implemented in line with optimal modulation strategy for different MIMO configuration to minimize the energy cost per bit. For clustered network, virtual clustering is implemented jointly with the distance based relay selection algorithm. Simulations (using MATLAB) have been carried out to illustrate and compare the performance of the proposed algorithms with different techniques and results showed an improvement in term of energy cost for different wireless networks scenarios.

In this thesis, the concept of cooperation in wireless networks and protocols, relay selection techniques were presented in Chapter 2, in addition of the fundamentals of the energy consumption in cooperative wireless networks. In Chapter 3, the impact of coding, the modulation strategy and relay location impact on the system performance in terms of energy cost per bit were investigated. Hence, the optimal cooperative solution was proposed based on numerical analysis and presented in terms of energy cost for transmission range. The optimal modulation strategy jointly used with the distance based relay selection method shown to be more energy efficient compared to different transmission techniques in cooperative wireless networks. In Chapter 4, the proposed algorithm was extended for cooperative wireless networks where virtual MIMO system is employed. The proposed methods, system model and the selection metric used for different MIMO configuration were given. Results including comparison with different transmission techniques have been presented. The proposed method outperforms the traditional and random relay selection in terms of energy consumption as shown in simulation results. It has been examined that the energy efficiency achieved is at the cost of effective data rate by introducing an additional signalling message. A further improvement can be achieved by minimizing the Beacon message size based on the cluster size. In Chapter 5, the single relay selection algorithm was implemented in clustered network, by combining virtual clustering and relay selection. The proposed clustering technique, energy cost formula and system models were given. Simulations results show that the proposed method outperforms the traditional multi-hop and random relay selection in terms of energy consumption and network lifetime. Finally, Chapter 6concludes this thesis by presenting a work summary and given the future work plan to be carried out.

6.2 Future Work

6.2.1 Hybrid Schemes

Recent researches focus proposed Hybrid schemes which employ both DF and AF [174]. In these schemes the relay uses either DF or AF based on an SNR threshold. Incorporating Hybrid schemes with the proposed algorithm can be implemented with a feedback so the relay switches between DF or AF. Moreover, for multiple hops transmission, Hybrid schemes can be more energy efficient than selective DF. AF amplify the noise at the relay offering low complexity compared to DF. Thus, the approach is to find a trade-off between the number of hops and the circuit energy cost, whereby the source forward the signal through multiple hops using AF, or single/multiple hops using DF.

6.2.2 Energy Harvesting

Cooperative communication schemes in wireless network shown to be a promising solution for an energy efficient communication. Proposed techniques such as relay selection, clustering considered as low complexity and low-cost solution and have been addressed at different layers. In cooperative wireless networks, relay selection has been implemented jointly with network resources optimization to improve the performance in terms of energy consumption. However, cooperative communication schemes suffer from a drawback which the signalling overheads and switching between different modes considered as energy waste. For example, in most of the relay selection methods proposed in the literature, candidate relays listen and/or exchange message with the source and destination. In consequence the energy consumed on receiving signal, and in idle mode is considered as redundant energy cost. This drawback can be tackled at the battery level that shows an unimpressive improvement. Charging the nodes from unwanted RF signal, turn this disadvantage into advantage, and can be approach using energy harvesting. Energy harvesting schemes can be a potential solution to turn cooperation drawbacks into benefits [175]. The concept revolves around, extending the idle or listen mode of unsuccessful relay if the received signal power fall above a charging threshold. Moreover, in WSN increasing the transmit power at the Sink, or even within cluster transmission improve energy efficiency in terms the network lifetime. However, interference is major design concern and a trade-off between interference and maximum power level should be considered.

References

[1] T. Mshvidobadze, "Evolution mobile wireless communication and LTE networks," in 2012 6th International Conference on Application of Information and Communication Technologies (AICT), pp. 1-7, 2012.

[2] L. D. Olavarrieta and A. A. Nava, "Wireless communications: a bird's eye view of an emerging technology," in IEEE International Symposium on Communications and Information Technology, vol.1, pp. 541-546, 2004.

[3] C. Lichung, R. Fagg, T. Klingenbrunn, L. Mortensen, and B. Vejlgaard, "GSM and AMPS coexistence in the US cellular band," in IEEE 55th Vehicular Technology Conference, vol.4, pp. 1980-1984, , 2002.

[4] A. Kumar;, D. Y. Liu;, D. J. Sengupta;, and Divya, "Evolution of Mobile Wireless Communication Networks: 1G to 4G," in International Journal of Electronics & Communication Technology, vol. 1, pp. 68-72, 2010.

[5] P. G. Blanken, R. Karadi, and H. J. Bergveld, "A 50MHz bandwidth multi-mode PA supply modulator for GSM, EDGE and UMTS application," in IEEE Radio Frequency Integrated Circuits Symposium, pp. 401-404, 2008.

[6] F. Adachi;, "Wireless Past and Future - Evolving Mobile Communications Systems," Institude of Elecctronics, Information, and Communications Engineers (IEICE Transaction), vol. E84-A, pp. 55-60, 2001.

[7] B. Bangerter, S. Talwar, R. Arefi, and K. Stewart, "Networks and devices for the 5G era," IEEE Communications Magazine, vol. 52, pp. 90-96, 2014.

[8] T. Mshvidobadze, "Evolution mobile wireless communication and LTE networks," in 6th International Conference on Application of Information and Communication Technologies (AICT), pp. 1-7, 2012.

[9] T. Koon Hoo, T. Zhifeng, and Z. Jinyun, "The Mobile Broadband WiMAX Standard [Standards in a Nutshell]," IEEE Signal Processing Magazine, vol. 24, pp. 144-148, 2007.

[10] G. Kbar, W. Mansoor, and A. Naim, "Voice over IP Mobile Telephony Using WIFI P2P," in 6th International Conference on Wireless and Mobile Communications (ICWMC), pp. 268-273, 2010.

[11] S. Basagni, D. Turgut, and S.K. Das,"Mobility- adaptive protocols for managing large ad hoc networks," Proc. IEEE Int. Commun. Conf. (ICC), pp. 1539-1543, June 2001.

[12] N. Bambos, "Toward power-sensitive network architectures in wireless communications: Concepts, issues, and design aspects," IEEE Pers. Commun. Mag., pp. 50-59, June 1998.

[13] F. Daquan, J. Chenzi, L. Gubong, L. J. Cimini, Jr., F. Gang, and G. Y. Li, "A survey of energy-efficient wireless communications," IEEE Communications Surveys & Tutorials, vol. 15, pp. 167-178, 2013.

[14] A. F. Naguib, V. Tarokh, N. Seshadri, and A. R. Calderbank, ''A space-time coding modem for high data rate wireless communications", IEEE Journal on Selected Areas in Communications, vol.16, pp.1459-1478, 1998.

[15] J. Yindi and H. Jafarkhani, "Distributed differential space-time coding for wireless relay networks," IEEE Transactions on Communications, vol. 56, pp. 1092-1100, 2008.

[16] A. Sendonaris, E. Erkip and B. Aazhang, "User Cooperation Diversity–Part I: System Description", IEEE Transactions on Communications, vol.51, no.11, pp.1927-1938, November 2003.

[17] A. Sendonaris, E. Erkip and B. Aazhang, "User Cooperation Diversity–Part II: Implementation Aspects and Performance Analysis", IEEE Transactions on Communications, vol.51, no.11, pp.1939-1948, November 2003.

[18] JJ. Gozalvez, "Green Radio Technologies", IEEE Journals and Magazines on Vehicular Technology, vol.5, no.5, pp.9-14, March 2010.

[19] W. Xiaoyan, L. Jie, and W. Kui, "Transmission Rate Enhancement of Cooperative Communications in Wireless Networks," in 31st International Conference on Distributed Computing Systems Workshops (ICDCSW, pp. 345-349), 2011.

[20] M. Vajapeyam and U. Mitra, "Performance analysis of distributed space-time coded protocols for wireless multi-hop communications," IEEE Transactions on Wireless Communications, vol. 9, pp. 122-133, 2010.

[21] A. Fehske, G. Fettweis, J. Malmodin and G. Biczok, "The Global Footprint of Mobile Communications: The Ecological and Economic Perspective", IEEE communications Magazine, vol.49, no.8, pp.55-62, August 2011.

[22] C. Yan, Z. Shunqing, X. Shugong, and G. Y. Li, "Fundamental trade-offs on green wireless networks," IEEE Communications Magazine, vol. 49, pp. 30-37, 2011.

[23] C. Comaniciu, N. B. Mandayam, and H. V. Poor, "Radio Resource Management for Green Wireless Networks", Proc. IEEE VTC-Spring, pp.1–5, April 2009.

[24] Chen Feng and Qin Xiaowei, "Cooperative Virtual Cell Clustering for Green Cellular Networks", IEEE75th Conference on vehicular Technology, pp.1 – 5, May 2012.

[25] F. Daquan, J. Chenzi, L. Gubong, L. J. Cimini, Jr., F. Gang, and G. Y. Li, "A survey of energy-efficient wireless communications," IEEE Communications Surveys & Tutorials, vol. 15, pp. 167-178, 2013.

[26] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," IEEECommunications Magazine, vol. 42, pp. 74-80, 2004.

[27] V. Shah, N. B. Mehta, and R. Yim, "The Relay Selection and Transmission Trade-off in Cooperative Communication Systems," IEEE Transactions on Wireless Communications, , vol. 9, pp. 2505-2515, 2010.

[28] D. Dongliang, Q. Fengzhong, Z. Wenshu, and Y. Liuqing, "Optimizing the battery energy efficiency in wireless sensor networks," in 2011 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), pp. 1-6, 2011.

[29] J. Choi, D. J. Love, and T. P. Bidigare, 'Coded Distributed Diversity: A Novel Distributed Reception Technique for Wireless Communication Systems', IEEE Transactions on Signal Processing, vol. 63, no. 5, pp. 1310–1321, Mar. 2015.

[30] H. Viswanathan and M. Weldon, 'The Past, Present, and Future of Mobile Communications', Bell Labs Technical Journal, vol. 19, pp. 8–21, Aug. 2014.

[31] T. Watteyne, S. Lanzisera, A. Mehta, and K. S. J. Pister, 'Mitigating Multipath Fading through Channel Hopping in Wireless Sensor Networks', IEEE International Conference on Communications, May 2010.

[32] F. A. Tobagi, ”Modeling and performance analysis of multihop packet radio networks,” Proc. of the IEEE, pp. 135–155, January 1987.

[33] T. Watteyne, S. Lanzisera, A. Mehta, and K. S. J. Pister, "Mitigating Multipath Fading through Channel Hopping in Wireless Sensor Networks," in IEEE International Conference on Communications (ICC) , pp. 1-5, 2010.

[34] J. Qiao, X. Shen, J. W. Mark, Q. Shen, Y. He, and L. Lei, 'Enabling device-to-device communications in millimeter-wave 5G cellular networks', IEEE Communications Magazine, vol. 53, no. 1, pp. 209–215, Jan. 2015.

[35] A. F. Naguib, V. Tarokh, N. Seshadri, and A. R. Calderbank, ''A space-time coding modem for high data rate wireless communications”, IEEE Journal on Selected Areas in Communications, vol.16, pp.1459-1478, 1998.

[36] Z. Yu, W. Xinhua, and Z. Tianshi, "Hybrid AF and DF with network coding for wireless Two Way Relay Networks," in IEEE Wireless Communications and Networking Conference (WCNC), pp. 2428-2433, 2013.

[37] T. Wang and G. B. Giannakis, "High-Throughput Cooperative Communications with Complex Field Network Coding," in 41st Annual Conference on Information Sciences and Systems 2007, (CISS 07), pp. 253-258, 2007.

[38] M. Torabi, D. Haccoun, and J. F. Frigon, "Relay Selection in AF Cooperative Systems: An Overview," IEEE Vehicular Technology Magazine, vol. 7, pp. 104-113, 2012.

[39] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing Uplink Capacity via User Cooperation Diversity", In Proceedings of IEEE International Symposium on Information Theory, pp.156, August 1998

[40] A. K. Sadek, W. Su, and K. J. R. Liu, "Multi-node Cooperative Communications in Wireless Networks", IEEE Transactions on Signal Processing, vol.55, no.1, pp.341–355, January 2007.

[41] Z. Yi "Distributed Space-Time Block Codes in Wireless Cooperative Networks", PhD Thesis submitted to the Department of Electrical and Computer Engineering, Queen's University, Canada, June 2009.

[42] H. X. Nguyen, N. N. Tran, and H. T. Nguyen, 'Performance analysis of adaptive decodeand-forward relaying in non-coherent cooperative networks', EURASIP Journal on Wireless Communications and Networking, vol. 2013, no. 1, pp. 1–13, 2013.

[43] H. Zhao and Y. W. Marye, 'Adaptive modulation for cooperative wireless communication systems', 2014 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), pp. 102 – 105, Aug. 2014.

[44] W. Xiaoyan, L. Jie, and W. Kui, "Transmission Rate Enhancement of Cooperative Communications in Wireless Networks," in 31st International Conference on Distributed Computing Systems Workshops (ICDCSW, pp. 345-349), 2011.

[45] B. Zafar, S. Gherekhloo, and M. Haardt, "Analysis of Multihop Relaying Networks: Communication Between Range-Limited and Cooperative Nodes," IEEE Vehicular Technology Magazine, vol. 7, pp. 40-47, 2012.

[46] I. Krikidis, J.S. Thompson, and P.M. Grant , "Cooperative Relaying With Feedback for Lifetime Maximization ", IEEE International Conference on Communications Workshops, pp.1 - 6 , May 2010.

[47] D. Dongliang, Q. Fengzhong, Z. Wenshu, and Y. Liuqing, "Optimizing the battery energy efficiency in wireless sensor networks," in IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), pp. 1-6, 2011.

[48] G. Brante, R. Demo Souza, and L. Vandendorpe, "Battery-aware energy efficiency of incremental decode-and-forward with relay selection," in IEEE Wireless Communications and Networking Conference (WCNC), pp. 1108-1112, 2012.

[49] Wei Yifei, Wang Chaowei, Song Mei, Ma Yue and Wang Xiaojun, "Energy Saving Relaying Scheme in Wireless Cooperative Networks Using Markov Decision Process", IEEE Conference on Vehicular Technology, pp.1 – 5, May 2012.

[50] L. Bin, W. Wenjie, Y. Qinye, Y. Rong, L. Yubo, and W. Chen, "A New Cooperative Transmission Metric in Wireless Sensor Networks to Minimize Energy Consumption

per Unit Transmit Distance," IEEE Communications Letters, vol. 16, pp. 626-629, 2012.

[51] W. Feng and L. Jiangchuan, "Networked Wireless Sensor Data Collection: Issues, Challenges, and Approaches," IEEE Communications Surveys & Tutorials, vol. 13, pp. 673-687, 2011.

[52] I. F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," IEEE Communications Magazine, vol. 40, pp. 102-114, 2002.

[53] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: a survey," IEEE Wireless Communications, vol. 11, pp. 6-28, 2004.

[54] P. Sungjin, L. Woongsup, and C. Dong-ho, "Fair Clustering for Energy Efficiency in a Cooperative Wireless Sensor Network," in IEEE 75th Vehicular Technology Conference (VTC Spring), pp. 1-5, 2012.

[55] P. Mangayarkarasi, M. Ramya and S. Jayashri, “Analysis of various power allocation algorithms for wireless networks”, International Conference on Communications and Signal Processing, pp.133 – 136, April 2012.

[56] S. Can and Y. Chenyang, "Is Two-Way Relay More Energy Efficient?," in 2011 IEEE Global Telecommunications Conference (GLOBECOM 2011), pp. 1-6, 2011.

[57] R. Devarajan, S. C. Jha, U. Phuyal, and V. K. Bhargava, "Energy-aware user selection and power allocation for cooperative communication system with guaranteed quality-of-service," in 12th Canadian Workshop on Information Theory (CWIT), pp. 216-220, 2011.

[58] L. Hung-Quoc, A. S. Ibrahim, and K. J. R. Liu, "Wireless network cocast: location-aware cooperative communications with linear network coding," , IEEE Transactions on Wireless Communications, vol. 8, pp. 3844-3854, 2009.

[59] J. Yindi and H. Jafarkhani, "Distributed differential space-time coding for wireless relay networks,", IEEE Transactions on Communications, vol. 56, pp. 1092-1100, 2008.

[60] I. Krikidis, J. S. Thompson, and P. M. Grant, "Cooperative Relaying with Feedback for Lifetime Maximization," in IEEE International Conference on Communications Workshops (ICC), pp. 1-6, 2010.

[61] C. Shuguang, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," IEEE Journal on Selected Areas in Communications, vol. 22, pp. 1089-1098, 2004.

[62] C. Rui and Y. Liuqing, "The Affecting Factors in Resource Optimization for Cooperative Communications: A Case Study," IEEE Transactions on Wireless Communications, vol. 11, pp. 4351-4361, 2012.

[63] A. S. Ibrahim, A. K. Sadek, W. Su, and K. J. R. Liu, "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?," IEEE Transactions on Wireless Communications, vol. 7, pp. 2814-2827, 2008.

[64] S. Kawasaki, Y. Kobayashi, and S. Yoshida, "High-power, high-efficiency microwave circuits and modules for wireless power transfer based on green-Eco technology," in IEEE Radio and Wireless Symposium (RWS) pp. 28-30, 2013.

[65] Q. Zhao and H. Li, ‘Performance of differential modulation with wireless relays in Rayleigh fading channels’, IEEE Communications Letters, vol. 9, no. 4, pp. 343–345, Apr. 2005.

[66] A. Keshavarz-Haddad and M. A. Khojastepour, ‘On capacity of deterministic wireless networks under node half-duplexity constraint’, 47th Annual Allerton Conference on Communication, Control, and Computing (Allerton), pp. 887–891, Sep. 2009.

[67] Y. G. Kim and N. C. Beaulieu, ‘Relay Advantage Criterion for Multi-hop Decode-andForward Relaying Systems’, IEEE Transactions on Wireless Communications, vol. 13, no. 4, pp. 1988–1999, Apr. 2014.

[68] M. El-Aaasser, and M.Ashour, "Energy aware classification for wireless sensor networks routing," 15th International Conference on Advanced Communication Technology (ICACT), pp.66, 71, 2013.

[69] A. G. Marques, W. Xin, and G. B. Giannakis, "Minimizing Transmit Power forCoherent Communications in Wireless Sensor Networks With Finite-Rate Feedback," IEEE Transactions on Signal Processing, vol. 56, pp. 4446-4457, 2008.

[70] C. Long, H Chen, and L Li, "Energy-Efficiency Cooperative Communications with Node Selection for Wireless Sensor Networks," Pacific-Asia Workshop on Computational Intelligence and Industrial Application, (PACIIA '08), vol. 2, pp. 761,765, 2008.

[71] L. Viet-Anh, R. A. Pitaval, S. Blostein, T. Riihonen, and R. Wichman, "Green cooperative communication using threshold-based relay selection protocols," in International Conference on Green Circuits and Systems (ICGCS), pp. 521-526, 2010.

[72] C. Dan, J. Hong, and L. Xi, "An Energy-Efficient Distributed Relay Selection and Power Allocation Optimization Scheme over Wireless Cooperative Networks," in IEEE International Conference on Communications (ICC), pp. 1-5, 2011.

[73] H. Kim, S.-R. Lee, C. Song, K.-J. Lee, I. Lee, "Optimal power allocation scheme forenergy efficiency maximization in distributed antenna systems", IEEE Trans. Commun., vol. 63, no. 2, pp. 431-440, Feb. 2015.

[74] M. El-Aaasser, and M.Ashour, "Energy aware classification for wireless sensor networks routing," 15th International Conference on Advanced Communication Technology (ICACT), pp.66,71, 2013.

[75] F. Etezadi, K. Zarifi, A. Ghrayeb and S. Affes, " Decentralized Relay Selection Schemes in Uniformly Distributed Wireless Sensor Networks", IEEE Transactions on Wireless Communications , vol.11, iss.3, pp. 938 – 951, 2012.

[76] D. Dongliang, Q. Fengzhong, Z. Wenshu, and Y. Liuqing, "Optimizing the battery energy efficiency in wireless sensor networks," in IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), pp. 1-6, 2011.

[77] G. Brante, R. Demo Souza, and L. Vandendorpe, "Battery-aware energy efficiency of incremental decode-and-forward with relay selection," in 2012 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1108-1112, 2012.

[78] C. Long, H Chen, and L Li, "Energy-Efficiency Cooperative Communications with Node Selection for Wireless Sensor Networks," Pacific-Asia Workshop on Computational Intelligence and Industrial Application, (PACIIA '08), vol. 2, pp.761,765, 2008.

[79] A. G. Marques, W. Xin, and G. B. Giannakis, "Minimizing Transmit Power for Coherent Communications in Wireless Sensor Networks With Finite-Rate Feedback," IEEE Transactions on Signal Processing, vol. 56, pp. 4446-4457, 2008.

[80] C. Wang, and S. JuSyue, "An Efficient Relay Selection Protocol for Cooperative Wireless Sensor Networks," IEEE Wireless Communications and Networking Conference, (WCNC 2009), pp. 1-5, 2009.

[81] G.Reise, andG. Matz, "Optimal transmit power allocation in wireless sensor networks performing field reconstruction," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 3105-3108, 2012.

[82] G.Reise, andG. Matz, "Optimal transmit power allocation in wireless sensor networks performing field reconstruction," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 3105-3108, 2012.

[83] H. Wan, J.-F. Diouris, G. Andrieux, "Power allocation for virtual MISO cooperative communication in wireless sensor networks," Wireless Technology European Conference (EuWIT), pp. 69-72, 2010.

[84] L. Juan, H. Jinyu, W. Di, and L. Renfa, "Opportunistic Routing Algorithm for Relay Node Selection in Wireless Sensor Networks," IEEE Transactions on Industrial Informatics, vol. 11, pp. 112-121, 2015.

[85] L. Lingya, H. Cunqing, C. Cailian, and G. Xinping, "Relay Selection for Three-Stage Relaying Scheme in Clustered Wireless Networks," IEEE Transactions on Vehicular Technology, vol. 64, pp. 2398-2408, 2015.

[86] S. Liu, S. Jin, H. Zhu, and K. K. Wong, "On Impact of Relay Placement for Energy-Efficient Cooperative Networks," Communications, IET, vol. 8, pp. 140-151, 2014.

[87] S. Zhengguo, F. Jun, C. H. Liu, V. C. M. Leung, L. Xue, and K. K. Leung, "Energy-Efficient Relay Selection for Cooperative Relaying in Wireless Multimedia Networks," IEEE Transactions on Vehicular Technology, vol. 64, pp. 1156-1170, 2015.

[88] G.Reise, andG. Matz, "Optimal transmit power allocation in wireless sensor networks performing field reconstruction," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 3105-3108, 2012.

[89] B. Li, H. Li, W. Wang, Z. Hu, and Q. Yin, "Energy-Effective Relay Selection by Utilizing Spacial Diversity for Random Wireless Sensor Networks," IEEE Communications Letters, vol. 17, pp. 1972-1975, 2013.

[90] J. Haghighat, M. Eslami, and W. Hamouda, "Relay Pre-Selection for Reducing CSI Transmission in Wireless Sensor Networks," IEEE Communications Letters, vol. 20, pp. 1828-1831, 2016.

[91] Z. Zhou, S. Zhou, J. H. Cui, and S. Cui, "Energy-Efficient Cooperative Communication Based on Power Control and Selective Single-Relay in Wireless Sensor Networks," IEEE Transactions on Wireless Communications, vol. 7, pp. 3066-3078, 2008.

[92] F. A. Onat, A. Adinoyi, Y. Fan, H. Yanikomeroglu, J. S. Thompson, and I. D. Marsland, "Threshold Selection for SNR-based Selective Digital Relaying in Cooperative Wireless Networks," IEEE Transactions on Wireless Communications, vol. 7, pp. 4226-4237, 2008.

[93] Z. Sheng, J. Fan, C. H. Liu, V. C. M. Leung, X. Liu, and K. K. Leung, "Energy-fficient Relay Selection for Cooperative Relaying in Wireless Multimedia Networks," IEEE Transactions on Vehicular Technology, vol. 64, pp. 1156-1170, 2015.

[94] B. Li, H. Li, W. Wang, Z. Hu, and Q. Yin, "Energy-Effective Relay Selection by Utilizing Spacial Diversity for Random Wireless Sensor Networks," IEEE Communications Letters, vol. 17, pp. 1972-1975, 2013.

[95] L. Chen and G. Wei, "A Distributed Energy Efficiency Optimization Scheme for Cooperative Virtual MIMO System," in IEEE 78th Conference on Vehicular Technology (VTC Fall), pp. 1-5, 2013.

[96] J. Jiang, M. Dianati, M. A. Imran, R. Tafazolli, and S. Zhang, "Energy-Efficiency Analysis and Optimization for Virtual-MIMO Systems," IEEE Transactions on Vehicular Technology, vol. 63, pp. 2272-2283, 2014.

[97] L. Dong, W. Xiaoling, Y. Liang, C. Hainan, W. Yanwen, and Z. Xiaobo, "Energy Efficient dynamic cooperative virtual MIMO based routing protocol in wireless sensor networks," in 8th International Conference on Communications and Networking (CHINACOM), pp. 523-527,2013.

[98] A. J. Goldsmith, and S. G. Chua, “Adaptive Coded Modulation for Fading Channels,” IEEE Transactions on Communications, Vol. 46, No. 5, pp. 595-602, 1998.

[99] X. Liu, X. Gong, Y. Zheng, "Reliable Cooperative Communications Based on Random Network Coding in Multi-Hop Relay WSNs", IEEE Sensors Journal, vol. 14, no. 8, pp. 2514-2523, Mar. 2014.

[100] N. Islam, S. Kandeepan, and J. Scott, "Optimal rate adaptation for energy efficiency with MQAM and MFSK," in 2014 International Symposium on Wireless Personal Multimedia Communications (WPMC), 2014, pp. 328-334.]

[101] J. G. Proakis, Digital Communications, 4th ed. New York: McGraw- Hill, 2000.

[102] T. H. Lee, “The Design of CMOS Radio-Frequency Integrated Circuits.” Cambridge, U.K.: Cambridge Univ. Press, 1998.

[103] J. Cioffi, Digital Communications. Stanford, CA: Stanford Univ. Press, Fall 2001.

[104] A. Paulraj, R. Nabar, and D. Gore, Introduction to Space-Time Wireless Communications, Cambridge, U.K.: Cambridge Univ. Press, 2003.

[105] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge, U.K.: Cambridge Univ. Press, 2003.

[106] I. Demirkol et al., “Mac Protocols for Wireless Sensor Networks: A Survey,” IEEE Communications Magazine, Vol. 44, No. 4, pp. 115-121, 2006.

[107] S. Beygi, M. Kafashan, H. R. Bahrami, T. Le-Ngoc, and M. Maleki, ‘Space–Time Trellis Codes for Two-Way Relay MIMO Channels With Single-Antenna Relay Nodes’, IEEE Transactions on Vehicular Technology, vol. 62, no. 8, pp. 4040–4045, Oct. 2013.

[108] S. Sohaib and S. Zaheer, ‘Space Time Coded Signal Space Diversity for Multi-Hop Cooperative Wireless Communication’, 79th IEEE Vehicular Technology Conference (VTC Spring), pp. 1–5, May 2014.

[109] M. Di Renzo et al., ‘Spatial Modulation for Generalized MIMO: Challenges, Opportunities, and Implementation’, Proceedings of the IEEE, vol. 102, no. 1, pp. 56–103, Jan. 2014.

[110] H. Phan, T. Q. Duong, T. A. Tsiftsis, and H. Zepernick, ‘Distributed orthogonal space–time block coding in wireless relay networks’, IET Communications, vol. 7, no. 16, pp. 1825–1835, Nov. 2013.

[111] V. Tarokh, N. Seshadri, and A. R. Calderbank, ‘Space-time codes for high data rate wireless communication: performance criterion and code construction’, IEEE Transactions on Information Theory, vol. 44, no. 2, pp. 744–765, Mar. 1998.

[112] H. X. Nguyen and H. H. Nguyen, ‘Adaptive Relaying in Noncoherent Cooperative Networks’, IEEE Transactions on Signal Processing, vol. 58, no. 7, pp. 3938–3945, Jul. 2010.

[113] Z. Al-qudah, ‘Orthogonal space–time block coding over dirty paper channel: Outage capacity analysis’, Journal of Physical Communication, vol. 15, pp. 16–24, Jun. 2015. J. Choi, D. J. Love, and T.

[114] R. C. H. Chang et al., “Implementation of a High-Throughput Modified Merge Sort in MIMO Detection Systems,” IEEE Transactions on Circuits and Systems I: Regular Papers, Vol. 61, No. 9, pp. 2730-2737, 2014.

[115] M. Rahmati and T. M. Duman, ‘Spectrally Efficient Alamouti Code Structure in Asynchronous Cooperative Systems’, IEEE Signal Processing Letters, vol. 21, no. 5, pp. 545–549, May 2014.

[116] T. Miyano, H. Murata, and K. Araki, "Cooperative relaying scheme with space time code for multi-hop communications among single antenna terminals," in IEEE Conference on Global Telecommunications, (2004. GLOBECOM '04), pp. 3763-3767 Vol.6, 2004.

[117] M. Vajapeyam and U. Mitra, "Performance analysis of distributed space-time coded protocols for wireless multi-hop communications," IEEE Transactions on Wireless Communications, vol. 9, pp. 122-133, 2010.

[118] J. Yindi and H. Jafarkhani, "Distributed differential space-time coding for wireless relay networks," IEEE Transactions on Communications, vol. 56, pp. 1092-1100, 2008.

[119] M. Vajapeyam and U. Mitra, "Performance analysis of distributed space-time coded protocols for wireless multi-hop communications," IEEE Transactions on Wireless Communications,vol. 9, pp. 122-133, 2010.

[120] T. Unger and A. Klein, "On the Performance of Distributed Space-Time Block Codes in Cooperative Relay Networks," Communications Letters, IEEE, vol. 11, pp. 411-413, 2007.

[121] R. J. Whang, L. Huaping, and H. Een Kee, "Transmission pattern selection for relay communication with distributed space-time codes," in2008. 11th IEEE Singapore International Conference onCommunication Systems, pp. 666-670, 2008.

[122] S. Das and M. Ghosh, "Implementation of Full-Diversity Distributed STBC in Cluster-Based Cooperative Communication," in VTC Spring 2008. IEEEConference onVehicular Technology, pp. 1216-1220, 2008.

[123] X. Yao and L. J. Cimini, "Energy efficiency of distributed cooperative relaying," in MILCOM MILITARY COMMUNICATIONS CONFERENCE, pp. 73-78, 2011.

[124] S. K. Jayaweera, "Virtual MIMO-based Cooperative Communication for Energy-constrained wireless sensor networks," IEEE Transactions on Wireless Communications, vol. 5, pp. 984-989, 2006.

[125] A. J. Goldsmith and S. B. Wicker, “Design challenges for energy constrained Ad Hoc Wireless networks,” To appear: IEEE Wireless Communications Magazine, Aug. 2002.

[126] C. Shuguang, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and Cooperative MIMO techniques in sensor networks," IEEE Journal on Selected Areas in Communications, vol. 22, pp. 1089-1098, 2004.

[127] N. I. Zaman, K. M. A. A. Mamun, A. M. M. S. Uddin, and T. Kanakis, "Performance Analysis of MIMO Relaying Channels' Cooperative Diversity for Mobile Networks," in 2010 Second International Symposium on Data, Privacy, and E-Commerce, pp. 95-99, 2010.

[128] S. K. Jayaweera and M. L. Chebolu, "Virtual MIMO and distributed signal processing for sensor networks - an integrated approach," in IEEE International Conference on Communications, 2005. ICC 2005. 2005, 2005, pp. 1214-1218 Vol. 2.

[129] V. K. Sachan, S. A. Imam, and M. T. Beg, "Energy-efficiency of Virtual cooperative MIMO techniques in wireless sensor networks," in 2012 International Conference on Computer Communication and Informatics, pp. 1-5, 2012.

[130] M. L. Chebolu and S. K. Jayaweera, "Integrated design of STBC-based virtual-MIMO and distributed compression in energy-limited wireless sensor networks," in Proceeedings of the Second European Workshop on Wireless Sensor Networks, pp. 267-277,2005.

[131] S. K. Jayaweera, "An energy-efficient virtual MIMO architecture based on V-BLAST processing for distributed wireless sensor networks," in 2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004., pp. 299-308,2004.

[132] D. Jie, L. Danpu, W. Xin, and W. Huari, "An energy-efficient virtual MIMO transmission scheme for cluster-based wireless sensor networks," in 2010 IEEE 12th International Conference on Communication Technology, pp. 809-813,2010.

[133] Q. Gao, Y. Zuo, J. Zhang, and X. H. Peng, "Improving Energy Efficiency in a Wireless Sensor Network by Combining Cooperative MIMO With Data Aggregation," IEEE Transactions on Vehicular Technology, vol. 59, pp. 3956-3965, 2010.

[134] N. I. Zaman, T. Kanakis, and P. Rapajic, "Relaying MIMO for cooperative mobile networks," in 2010 16th Asia-Pacific Conference on Communications (APCC), pp. 368-372,2010.

[135] L. Chen and G. Wei, "A Distributed Energy Efficiency Optimization Scheme for Cooperative Virtual MIMO System," in 2013 IEEE 78th Vehicular Technology Conference (VTC Fall), pp. 1-5,2013.

[136] N. I. Zaman, T. Kanakis, and P. Rapajic, "Relaying MIMO for cooperative mobile networks," in 2010 16th Asia-Pacific Conference on Communications (APCC), pp.368-372,2010.

[137] L. Chen and G. Wei, "A Distributed Energy Efficiency Optimization Scheme for Cooperative Virtual MIMO System," in 2013 IEEE 78th Vehicular Technology Conference (VTC Fall), pp. 1-5,2013.

[138] K. G. Panda, D. Agrawal, and A. Hossain, "Virtual MIMO in wireless sensor network - a survey," in 2016 Online International Conference on Green Engineering and Technologies (IC-GET), pp. 1-4,2016.

[139] N. Krishnan and B. Natarajan, "Energy Efficiency of Cooperative SIMO Schemes - Amplify Forward and Decode Forward," in 2009 Proceedings of 18th International Conference on Computer Communications and Networks, pp. 1-5,2009.

[140] P. Zhou, W. Liu, W. Yuan, W. Cheng, and S. Wang, "An Energy-Efficient Cooperative MISO-Based Routing Protocol for Wireless Sensor Networks," in 2009 IEEE Wireless Communications and Networking Conference, pp. 1-6,2009.

[141] B. Yang, J. Guo, H. Yu, and D. Zhang, "Cooperative MISO-Based Energy Efficient Routing Strategies for Wireless Sensor Networks," in Second International Conference on Communications and Networking in China, pp. 824-828,2007.

[142] G. Zheng, T. Wei, and J. Li, "A MISO cooperative transmission algorithm for clustering wireless sensor network," in 2011 International Conference on Electronics, Communications and Control (ICECC), pp. 2433-2436,2011.

[143] M. R. Islam and J. Kim, "On the use of selection function in cooperative MISO at wireless sensor network," in 2008 International Conference on Intelligent Sensors, Sensor Networks and Information Processing, pp. 139-144, 2008.

[144] Z. Huang, T. Yamazato, and M. Katayama, "Energy efficiency of cooperative MISO technique in multi-hop wireless sensor networks," in 2008 International Conference on Intelligent Sensors, Sensor Networks and Information Processing, pp. 511-516, 2008.

[145] H. Wan, J. F. Diouris, and G. Andrieux, "Power allocation for virtual MISO cooperative communication in wireless sensor networks," in The 3rd European Wireless Technology Conference, pp. 69-72, 2010.

[146] G. N. Bravos and A. G. Kanatas, "Energy efficiency of MIMO-based Sensor Networks with a Cooperative Node Selection Algorithm," in 2007 IEEE International Conference on Communications, pp. 3218-3223, 2007.

[147] D. S. Papailiopoulos and G. N. Karystinos, ‘Efficient maximum-likelihood noncoherent orthogonal STBC detection’, 46th Annual Allerton Conference on Communication, Control, and Computing, pp. 294–300, Sep. 2008.

[148] J. Hoydis *et al.*, “Green Small-Cell Networks,” *IEEE Vehicular Technology Magazine*, Vol. 6, No. 1, pp. 37-43, 2011.

[149] P. Nayak, and A. Devulapalli, “A Fuzzy Logic-Based Clustering Algorithm for Wsn to Extend the Network Lifetime,” *IEEE Sensors Journal*, Vol. 16, No. 1, pp. 137-144, 2016.

[150] S. M. Hosseini, and M. H. Kahaei, “Target Detection in Cluster Based Wsn with Massive Mimo Systems,” *Electronics Letters*, Vol. 53, No. 1, pp. 50-52, 2017.

[151] F. Wang, and J. Liu, “Networked Wireless Sensor Data Collection: Issues, Challenges, and Approaches,” IEEE Communications Surveys & Tutorials, vol.13, no.4, pp.673-687, 2011.

[152] S. Chakraborty and A. K. Khan, "Evaluation of Wireless Sensor Network Routing Protocols with Respect to Power Efficiency," in 5th International Conference on Computational Intelligence and Communication Networks (CICN), pp. 123-128,2013.

[153] R. C. Shah and J. M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE, pp. 350-355, vol.1,2002.

[154] G. Owojaiye and Y. Sun, 'Focal design issues affecting the deployment of wireless sensor networks for intelligent transport systems', IET Intelligent Transport Systems, vol. 6, no. 4, pp. 421–432, Dec. 2012.

[155] T. Irkhede and P. Jaini, "Cluster and traffic distribution protocol for energy consumption in wireless sensor network," in Students Conference on Engineering and Systems (SCES), pp. 1-5, 2013.

[156] S. Chakraborty and A. K. Khan, "Evaluation of Wireless Sensor Network Routing Protocols with Respect to Power Efficiency," in5th International Conference on Computational Intelligence and Communication Networks (CICN), , pp. 123-128, 2013.

[157] A.A.Aziz, Y.A. Sekercioglu, P. Fitzpatrick, and M. Ivanovich, "A Survey on Distributed Topology Control Techniques for Extending the Lifetime of Battery Powered Wireless Sensor Networks," IEEE Communications Surveys & Tutorials, vol.15, no.1, pp.121-144, 2013.

[158] M. Patil, R.C. Biradar, "A survey on routing protocols in Wireless Sensor Networks," 18th IEEE International Conference on Networks (ICON), pp.86-91, 2012.

[159] G. H. Raghunandan, and B. N. Lakshmi , "A comparative analysis of routing techniques for Wireless Sensor Networks," National Conference on Innovations in Emerging Technology (NCOIET), pp.17-22, 2011.

[160] N.A. Pantazis, S.A. Nikolidakis, and D.D. Vergados, "Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey," IEEE Communications Surveys & Tutorials , vol.15, no.2, pp.551-591, 2013.

[161] M. El-Aaasser, and M. Ashour, "Energy aware classification for wireless sensor networks routing," 15th International Conference on Advanced Communication T echnology (ICACT), pp.66-71, 2013.

[162] A. Preethi, E. Pravin, and D. Sangeetha, "Modified balanced energy efficient network integrated super heterogeneous protocol," in International Conference on Recent Trends in Information Technology (ICRTIT), pp.1-6, 2016.

[163] T. Irkhede and P. Jaini, "Cluster and traffic distribution protocol for energy consumption in wireless sensor network," in Students Conference on Engineering and Systems (SCES), pp.1-5, 2013.

[164] S. Chakraborty and A. K. Khan, "Evaluation of Wireless Sensor Network Routing Protocols with Respect to Power Efficiency," in5th International Conference on Computational Intelligence and Communication Networks (CICN), pp.123-128, 2013.

[165] K. Biswas, V. Muthukkumarasamy, E. Sithirasenan, and M. Usman, "An energy efficient clique based clustering and routing mechanism in wireless sensor networks," 9th International Wireless Communications and Mobile Computing Conference (IWCMC), pp.171-176, 2013.

[166] G.S. Tewolde, and Weihua Sheng, "Energy aware adaptive clustering in wireless sensor networks," IEEE International Conference on Electro/Information Technology (EIT), pp.1-6, 2011.

[167] F. Gomez-Cuba, R. Asorey-Cacheda, and F.J. Gonzalez-Castano,, "A Survey on Cooperative Diversity for Wireless Networks," IEEE Communications Surveys & Tutorials, vol.14, no.3, pp.822-835, 2012.

[168] L. Bin, L. Hongxiang, W. Wenjie, H. Zixia, and Y. Qinye, "Energy-Effective Relay Selection by Utilizing Spacial Diversity for Random Wireless Sensor Networks," IEEE Communications Letters , vol.17, pp. 1972-1975, 2013.

[169] G. Reise, and G.Matz, "Optimal transmit power allocation in wireless sensor networks performing field reconstruction," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp.3105-3108, 2012.

[170] Haitao Wan, J.-F. Diouris, and G. Andrieux, "Power allocation for virtual MISO cooperative communication in wireless sensor networks," Wireless Technology European Conference (EuWIT), pp.69-72, 2010.

[171] S. K. Jayaweera, "Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks," IEEE Transactions on Wireless Communications, vol.5, pp.984-989, 2006.

[172]C. Shuguang, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," IEEE Journal on Selected Areas in Communications, vol.22, pp.1089-1098, 2004.

[173] S. T. Bakhsh, "Energy-efficient distributed relay selection in wireless sensor network for Internet of Things," in 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), 2017, pp. 1802-1807.

[174] Z. Yu, W. Xinhua, and Z. Tianshi, "Hybrid AF and DF with network coding for wireless Two Way Relay Networks," in 2013 IEEE Wireless Communications and Networking Conference (WCNC), pp. 2428-2433, 2013.

[175]S. Kawasaki, Y. Kobayashi, and S. Yoshida, "High-power, high-efficiency microwave circuits and modules for wireless power transfer based on green-Eco technology," in IEEE Radio and Wireless Symposium (RWS) pp. 28-30, 2013.