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Energy Efficient Distributed Receiver Based Cooperative Medium Access Control Protocol for Wireless Sensor Networks

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Energy Efficient Distributed Receiver Based Cooperative Medium Access Control Protocol for Wireless Sensor Networks

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November 2013

As the candidates Supervisor I agree/do not agree to the submission of this thesis

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Signature Date

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I dedicate this work to my lovely family, Thabile and Sithabiso Gama, you two are God sent.

Abstract

Wireless sensor networks are battery operated computing and sensing devices that collaborate to achieve a common goal for a specific application. They are formed by a cluster of sensor nodes where each sensor node is composed of a single chip with embedded memory (microprocessor), a transceiver for transmission and reception (resulting in the most energy consumption), a sensor device for event detection and a power source to keep the node alive. Due to the environmental nature of their application, it is not feasible to change or charge the power source once a sensor node is deployed. The main design objective in WSNs (Wireless Sensor Networks) is to define effective and efficient strategies to conserve energy for the nodes in the network. With regard to the transceiver, the highest consumer of energy in a sensor node, the factors contributing to energy consumption in wireless sensor networks include idle listening, where nodes keep listening on the channel with no data to receive; ovehearing, where nodes hears or intercept data that is meant for a different node; and collision, which occurs at the sink node when it receives data from different nodes at the same time. These factors all arise during transmission or reception of data in the Transceiver module in wireless sensor networks.

A MAC (Medium Access Control) protocol is one of the techniques that enables successful operation while minimizing the energy consumption in the network. Its task is to avoid collision, reduce overhearing and to reduce idle listening by properly managing the state of each node in the network. The aim, when designing a MAC protocol for WSNs is to achieve a balance amongst minimum energy consumption, minimum latency, maximum fault-tolerance and providing QoS (Quality of Service).

To carefully achieve this balance, this dissertation has proposed, designed, simulated and analyzed a new cooperative MAC scheme with an overhearing avoidance technique with the aim of minimizing energy consumption by attempting to minimize the overhearing in the WSN. The new MAC protocol for WSNs supports the cooperative diversity and overhearing communications in order to reduce the effects of energy consumption thus increase the network lifetime, providing improved communication reliability and further mitigating the effects of multipath fading in WSNs. The MAC scheme in this work focuses on cooperation with overhearing avoidance and reducing transmissions in case of link failures in order to minimize energy consumption. The cooperative MAC scheme presented herein uses the standard IEEE 802.15.4 scheme as its base physical model. It introduces cooperation, overhearing avoidance, receiver based relay node selection and a Markov-based channel state estimation. The performance analysis of the developed Energy Efficient Distributed Receiver based MAC (E^2DRCMAC) protocol for WSNs shows an improvement from the standard IEEE 802.15.4 MAC layer with regard to the energy consumption, throughput, reliability of message delivery, bit error rates, system capacity, packet delay, packet error rates, and packet delivery ratios.

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Definition of Terms

ACK: Acknowledgement

AWGN: Additive White Gaussian Noise

BER: Bit Error Rate

CDMA: Code Division Multiple Access

CRN: Call for Relay Node

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CQI: Channel Quality Indicator

DN: Destination Node

DPx: Data Packet number x

DRMACSN: Distributed and Route Aware MAC Protocol for WSNs

DSP: Data Sending Packet

E^2DRCMAC: Energy Efficient Distributed Receiver based MAC for WSNs

MAC: Medium Access Control

MRC: Maximum Ratio Combining

NoST: Number of Simultaneous Transmissions

NT: Neighboring Table

PN: Pseudo Noise

PRP: Preamble Request Packet

QoS: Quality of Service

RF: Radio Frequency

RFP: Ready to Forward Packet

RN: Relay Node

RRP: Ready to Receive Packet

Rx: Receive

SN: Source Node

SNR: Signal to Noise Ratio

SR ARQ: Selected Repeat ARQ

TDMA: Time Division Multiple Access

Tx: Transmit

Tx/Rx: Transmit/ Receive

WCoopMAC: WSN Cooperative MAC

WSN: Wireless Sensor Network

Definition of Symbols

L_{Pack}: Length or Packet Size

Av_{Pack}: Average number of packets

V : Working Voltage

L_{ACK}: Length of ACK

L_{DATA}: Length of DATA

I_S : Transceiver Current in Sleep

I_B : Transceiver Current in Back-Off

I_{Rx} : Transceiver Current in Active Rx

I_{Tx} : Transceiver Current in Active Tx

λ : Message Arrival Rate

L_{Msg} : Average Message Size

N_P : Total Number of Packets to Tx

M_S : Total Number of Messages to Tx

RI_{Tx} : Relay Nodes Tx Current

D_{Tx} : Data Transfer Rate

C_{AWGN} : The Channel Capacity

B_W : The available channel bandwidth

P_A : Probability of Active State

P_B : Probability of Back-off State

P_S : Probability of Sleep State

Rb : The bit rate.

T_{DEL} : Total Delay

T_{CoopTx} : Total Delay for Cooperative Tx

T_{DTx} : Total Delay for Direct Tx

$T_{CoopReTx}$: Total Delay for Cooperative Packet re-Tx

Chapter 1:

1 Introduction

Generally, wireless sensor networks (WNSs) comprise of a substantial number of wireless sensor nodes formed into clusters and randomly distributed over an area of interest to perform a specific task or application. Each sensor node in the WSN is capable of performing sensing, processing, storing, transmission and reception functions. However, the transmitting and reception function consume the energy provided by the power source more than the sensing and processing actions. This gives rise to the main problem in WSNs, which is to conserve the energy consumed by the nodes when they are transmitting or when they're receiving data over the WSN. Part of the energy conservation solution is to employ cooperative relay node selection and medium access control techniques when dealing with WSNs. The best relay node is selected based on the channel quality information and employing a cooperative relay node limits the retransmissions thus conserving energy for WSNs. The medium access control may combat the energy conservation problem by reducing overhearing, idle listening, collisions and control packets.

This chapter details the background of the wireless sensor networks, the architectural design of wireless sensor nodes down to the core components (hardware) of their assembly, and their applications and challenges. The chapter further defines the MAC protocols and their challenges, research motivation, methodology and objectives. Finally, the chapter discusses the important contributions made and material published as a result of the research. To end the chapter, the dissertation outline and chapter summary are presented.

1.1 WSN Architecture

Generally, a WSN density may range from just a handful to thousands of nodes set up to achieve a common sensing and computing function, as can be seen in Figure 1. The sensor nodes in a WSN all report to a single sink node. The reporting of events to the sink node may either be event driven, query based or periodic [1].

(a) **Event Driven Reporting:** Whenever the event of interest is detected, the sensor node will send the resulting signal to the sink node.

(b) **Query Based Reporting:** The sink node initiates a query to all or selected sensor nodes in the WSN. This query entails that the selected sensor nodes send their information to the sink node.

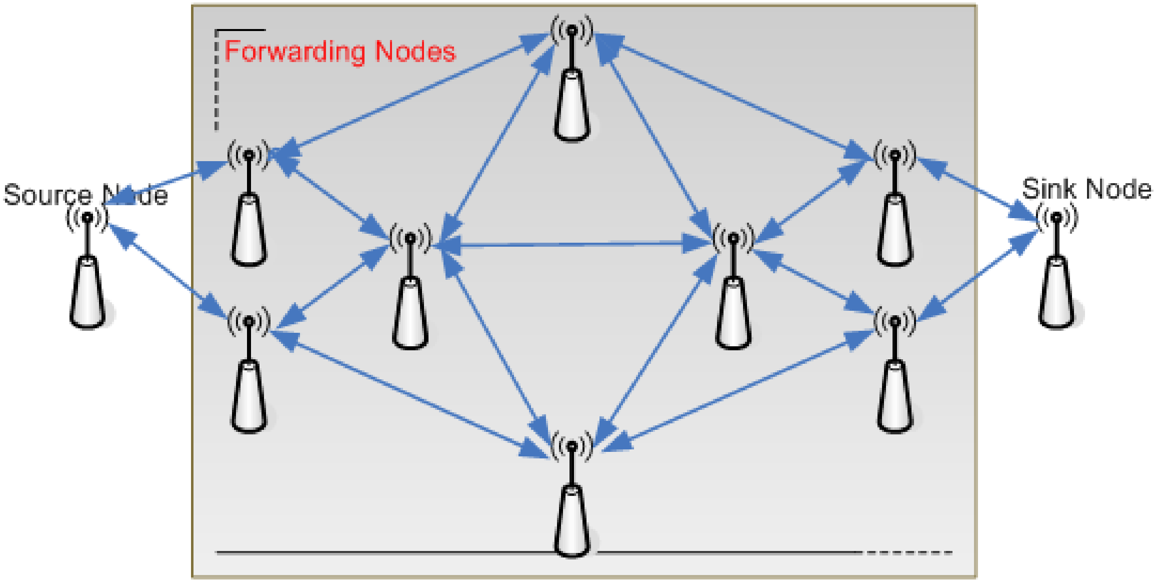

Figure 1: General WSN Architecture

(c) **Periodic Reporting:** At predetermined regular intervals the sensor nodes in the WSN sends its detected signal to the sink node.

1.1.1 Sensor Node Composition

The main components making up a sensor node include the microprocessor chip, the power source, the sensor device and the transceiver, as depicted in Figure 2.

(a) **Microprocessor:** The microprocessor, with memory, is an essential component in a wireless sensor node as it asists in collecting and processing the information. The microprocessor is also responsible for decision making as to where the data is to be sent and where it was received from. The micropocessor is responsible for the sensor nodes' response according to the actual application of the entire WSN [2]. The memory is traditionally used as storage of programmes and the nodes' data.

(b) **Power Source:** The power source for a wireless sensor node can not be an electronic power supply as the sensor node may be deployed in terrestrial environments. For this reason, the power source is usually a battery providing energy. However, the sensor node may be powered by the environment in terms of solar cells [2].

(c) **Sensor Device:** The sensor device provides the interface between the physical environment and the sensor node. The sensor device provides the sensor node with the ability to observe and sometimes control the environment in which the sensor node is deployed [2].

(d) **Transceiver:** The transceiver is required for both the transmitting and receiving action for each wireless sensor node. The operation of the transceiver is to alter a sequence of bits into (sometimes from) radio waves [2]. These bit streams would come from (or be sent to) the microprocessor component.

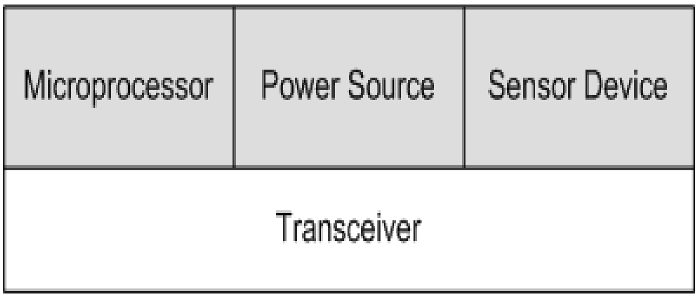

Figure 2: General Wireless Sensor Node Composition

In terms of energy consumption, adopted from the Chipcon CC2240 device, the components in Figure 2 perform as depicted in Table 1. The power source component provides 100% of the sensor nodes energy for all its operations. Consider a situation where a sensor node has exhausted its energy level, then the average depletion per component is provided in Table 1. This shows that on average, the microprocessor uses up to 30% of the nodes' battery life, the sensor device uses up to 21% of the nodes' energy, while the transceiver component uses up most of the energy of the sensor node at an average 49% [3].

Table1: Table of Energy Consumption by Sensor Node Components

Component	**% Energy Consumed**
Microprocessor	30
Power Source	-100
Sensor Device	21
Transceiver	49

Since, as can be seen in Table 1, the transceiver consumes the most energy for the sensor node in the sensor network, the analysis presented in this dissertation focuses its attention mainly on the transceiver component describing the transmission and reception procedures.

1.2 WSN Applications

There are a number of real life applications of WSNs. For most physical applications there exists an appropriate sensor technology which can be deployed to operate disaster relief applications such as wildfire detection and military applications, intrusion detection, medicine and health care, event detection, tracking etc. WSNs can also be used to facilitate management of large building facilities where keyless entries may be required in order to grant access to the building. The following are a few real life applications where WSNs are deployed.

(a) **Facility Management and Intrusion Detection:** When managing access to facilities as large as a companys′ building, a WSN may be applied to provide keyless entries to authorized personnel of different levels. WSN may also be used in site intrusion as well. In this case, WSNs are used to enhance security measures.

(b) **Event Detection:** A simple event detection application of WSNs will be when a single local sensor node detects the event and reports the detected event to the sink of the network. To perform slightly more complex event detections requires neighbour nodes to cooperate when performing the event sensing before the event can be validated and sent back to the sink. An example of this would be fire detection. In this case, wireless sensor nodes act cooperatively to report an event of a fire to a sink node, which would then report this to the base station to either sound an alarm or activate sprinklers.

(c) **Tracking:** A WSN can report back to the sink updates estimating speed and direction of any sources position. Tracking is often done by nodes in cooperation. The cooperating nodes determine the position, speed and direction of a mobile event and send the updates to the sink. An example of this application is in vehicle tracking, used for both commercial and personal vehicles.

(d) **Periodic Measurements:** With or without an event detected, the sensor nodes may be required to send environmental updates to the sink node presenting measurements of some physical parameters such as temperature [2].

1.3 WSN Challenges

For WSNs to provide the proper service in the environments that they may be deployed in, there are a number of challenges they need to overcome. This section explains in detail a few of the challenges, which include fault tolerance, lifetime maximization, scalability, maintainability and programmability [2].

(a) **Fault Tolerance and Scalability:** WSNs must be able to tolerate node failure. This can be achieved by employing redundant node deployment. Architectures and protocols for WSNs must be designed to be able to scale the number of nodes in the WSN.

(b) **Lifetime Maximization:** Since wireless sensor nodes solely obtain their energy supply from a battery source, these devices need to be employed in architectures and protocols designed to minimize the excessive energy loss in the network.

(c) **Programmability and Maintainability:** Once most WSN applications are deployed in their environment, the WSN has to monitor and manage its own status and health. Most importantly, the sensor node devices should be programmable in order to implement their operations.

(d) **Quality of Service:** When designing WSN systems, it is important that the resulting system provides a balanced quality of service for all the performance metrics without compromising any one of them. The performance metrics providing quality of service include message delay, network lifetime, throughput, message delivery ratio, energy consumed per node, etc.

(e) **Varying Node Densities:** The node density is defined as the number of nodes deployed in an area. There are different node densities for different WSN applications and for each application the node density may vary over time and we need a network that can adapt to these variations. The reason for varying node densities range from node movement, nodes losing their battery energy, nodes being introduced to the network, etc.

(f) **Multihop Transmissions:** In most cases in WSNs the probability of successful direct data transmission between a sender and a receiver is very limited and the data transmission itself is energy consuming, especially over long distances. In an attempt to increase the probability of successful data transmission in the network one must consider the use of relay nodes.

(g) **Energy Efficiency:** In order to enhance the network lifetime of the system, the system needs to be energy efficient. This means that the system should be designed such that each node in the network does not consume more energy than it should per transmission and reception.

1.3.1 Factors Affecting Energy Consumption in WSNs

The three main factors affecting the energy consumption in WSNs are packet collisions at the receiver, overhearing and idle listening.

(a) **Overhearing:** When a node, in proximity to either the source or sink node, hears or intercepts the messages that are not directed to it, this is referred to as overhearing in WSNs. When a node receives a message not intended for it, that energy becomes wasted during the reception process. If more than one node intercepts the same message meant for a different sink node, then the energy wasted only escalates and the network lifetime depreciates very quickly [4].

(b) **Collision:** If the medium access control (MAC) is not designed to a high standard, then it can not avoid collision at the receiving node. The energy is wasted due to the needed retransmissions for each and every packet collision that occured during a frame of transmission.

(c) **Idle Listening:** A sensor node does not know when the event will be detected or when it will be required to be the receiving node. However, when a sensor node keeps its radio 'on' even though it is not sensing or detecting any event, it wastes a lot of energy. It is the responsibility of the MAC protocol to decrease the time that the node spends doing nothing. This constitutes idle listening.

(d) **Control Packets:** Each control packet used during the communication requires transmission and reception (Tx/Rx). The dissertation has established that the Tx/Rx action is the one that consumes the most energy, hence minimizing the control messages in the network is essential in providing the overall system quality of service and in providing enhanced network lifetime by saving energy in the network.

1.4 WSN MAC Protocols and Challenges

The main research area, when it comes to WSNs, is how to improve the network lifetime and network reliability. This includes mainly the aspects relating to the energy consumption patterns in the network. In order to solve the energy consumption problem in WSNs one needs to address the main factors that lead to excessive energy consumption in WSNs. The three main factors are packet collision, node idle listening, and overhearing [4]. Cooperative diversity introduces a mechanism whereby an extra cooperative relaying node is used to relay messages from the source to the sink node. The cooperative diversity schemes currently used in WSNs generally lead to improved network lifetime and network reliability. That being clearly noted, it is also noted that the effects of combining cooperative diversity schemes with overhearing communications are yet to be considered in WSN based research. The work done in this project proposes a new MAC protocol for WSNs that attempts to minimize the energy consumption by addressing the effects of packet collision and overhearing in WSNs. The work proposes an energy efficient distributed receiver based cooperative MAC protocol with overhearing avoidance technique for WSNs. Each time there is a new data arrival at the source node the MAC protocol provides an algorithm that involves the selection of a relay node and the assignment of transmission slots to all source nodes that have data to transmit at the time. Relay node selection and source node transmission slot allocation are all performed at the destination node in order to minimize the effects of collision in the network. Letting the destination node decide on the transmission path and transmission slot assignment during each transmission allows it to manage how the data packets will arrive at the receiver side. This is because that is generally where the collision will occur in the network. The inclusion of the relay node for each transmission increases the networks$'$ spatial diversity, hence making the communication a cooperative communication.

The proposed MAC protocol further maintains a three state mechanism that ensures that unused nodes are sent to sleep state at the time of transmission so that they will not listen to currently ongoing communication unnecessarily. This state mechanism also ensures that nodes that attempt to send without being allocated a proper transmission slot or nodes that cause channel congestion are sent to a back-off state. The state mechanism facilitates the operation of the nodes currently taking part in the continuing active data packet transmission and reception.

1.5 Motivation

This dissertation serves to document how the research work deals with the factors affecting energy consumption in WSNs by providing a new distributed cooperative receiver based MAC protocol for WSNs. The proposed MAC protocol is receiver based, and it addresses and significantly reduces the effects of collisions in the network. The proposed MAC protocol also attempts to minimize the effects of overhearing without using an excessive number of control packets. The proposed MAC scheme uses a three state system (SLEEP, ACTIVE and BACK-OFF) to ensure that sensor nodes that are not required for communication during a particular frame of transmission keep their radios off until they are required to assist on the transmission. Cooperative diversity methods used in WSNs have so far succeeded in improving the communication reliability and network lifetime. The proposed MAC protocol introduces a close association between cooperative diversity and overhearing communications, which has so far not been considered in any MAC protocol designs for WSNs in the recent past. Cooperation in WSNs improves the diversity gain by letting multiple sensor nodes with a single antenna in a network environment share their sensor radios [5]. Combining cooperative diversity schemes with overhearing avoidance techniques in WSNs assists wireless networks in mitigating the effects of multipath fading, while improving the communication reliability in the wireless channel. The proposed MAC includes the ovehearing avoidance scheme in order to reduce the effects of overhearing, which is a major contributing factor to excessive energy consumption in WSNs. The proposed MAC protocol also caters for the cases where a direct link between the source and destination node is either broken or represented by a relatively low channel quality value. It does so by selecting the best relay node to forward the messages between the source and destination node.

1.5.1 Objectives and Methodology

The main objectives and design goals for the research work are to:

(a) Design a new cooperative MAC protocol that supports overhearing communications to conserve energy consumption for WSNs.

(b) Evaluate the performance of the proposed MAC protocol in terms of throughput, packet delay, energy conservation patterns and network lifetime, through simulations.

(c) Develop an energy analysis model for the proposed MAC protocol.

These goals and objectives defined the methodology to which the work presented in this document adheres in order to produce the desired outcome.

1.5.2 Project Contributions

The major contributions of the work in this dissertation are: a new distributed cooperative MAC scheme for WSNs with overhearing avoidance using a receiver based model for selecting cooperative nodes; a Markov based analytical framework for energy consumption model. The combining of cooperative communications with overhearing avoidance is shown to provide better energy consumption levels thereby increasing the network lifetime.
This work has resulted in the following papers:

1. Sithembiso Gama, Thippeswamy Muddenahalli, Tom Walingo, Fambirai Takawira, ”Energy Efficient Distributed Receiver Based Cooperative MAC for Wireless Sensor Networks”. *IEEE Africon Conference*, September 2013.

   This article presented a new Energy Efficient Distributed Receiver Based Cooperative Medium Access Control protocol for wireless sensor networks (E^2DRCMAC for WSNs). WSNs employ cooperative diversity techniques in order to improve network lifetime and overall network reliability. The proposed MAC scheme focuses on cooperation with overhearing avoidance and reducing transmissions in case of link failures in order to minimize energy consumption in the network to improve the network lifetime. This article also presented an analytical model for the packet delay to show the improved performance when cooperation is introduced as revealed by the simulation results. The findings presented in this article include percentage energy used in the network, throughput, packet delay, and packet delivery ratio.

2. Sithembiso Gama, Tom Walingo, Fambirai Takawira, "Channel Quality Estimation for Energy Efficient Cooperative MAC Protocol for WSNs". *Southern Africa Telecommunication Networks and application conference (SATNAC 2013)*, September 2013.

   Consider a cooperative relay network consisting of a Source Node (SN), Relay Nodes (RNs) and a Destination Node (DN). For such a network the availability of the Channel Quality Indicator (CQI) is crucial for the nodes in the network to adapt to channel conditions and thus make strategic decision on which path is best to use for any particular transmission. This article proposed a channel quality estimation method based on the energy efficient distributed receiver based cooperative medium access control protocol for Wireless Sensor Networks (E^2DRCMAC for WSNs). The article proposed a method for the SN to obtain instantaneous CQI values of the direct link between itself and the DN (SN-DN). Should this link be poor or not have sufficient required resources, then a method for the DN to obtain instantaneous CQI values of the link between itself and all RNs in the transmission radius of both itself and the SN (RNs-DN) is provided as part of the scheme. Furthermore it is assumed that the link SN-RNs has all the resources sufficient. We developed a simulator for the E^2DRCMAC scheme to show that the proposed channel estimation scheme for a cooperative MAC will result in improved energy savings per node in the network, reliability of message delivery, channel capacity and packet error rates (PER).

3. Sithembiso Gama, Tom Walingo, Fambirai Takawira, "it Energy Analysis for the distributed receiver based cooperative MAC for wireless sensor networks", *under review, IET WSN*.

   This work presented the energy analysis of the new Energy Efficient Distributed Receiver based Cooperative Medium Access Control scheme for wireless sensor networks (E^2DRCMAC for WSNs). The cooperative MAC scheme developed herein incorporates cooperation, overhearing avoidance, receiver based relay node selection and a Markov-based channel state estimation onto the standard IEEE 802.15.4 scheme. The solution is developed based on a receiver oriented approach when selecting cooperative relay nodes and using a store and forward scheme to relay the packets to the destination node. This works' main focus was in combining the cooperative packet relaying with overhearing avoidance in order to reduce node energy consumption hence enhancing the network lifetime. As performance criteria, the energy consumed per node is investigated against packet arrival rate and average Signal-to-Noise ratio. The percentage of energy consumed and packet throughput are also investigated as the proposed MAC scheme is compared against the standard IEEE 802.15.4 MAC over the estimated channel conditions. The results showed that the proposed MAC scheme with cooperation and overhearing avoidance resulted in both improved performance and improved energy saving patterns.

Some parts of the research presented in these papers are included in this dissertation.

1.6 Organization of Thesis

Chapter 2 discusses a number of already existing MAC protocols for WSNs. This is needed in order to obtain a basic understanding of the characteristics of a good MAC protocol and how such a protocol would be of assistance in WSNs. This chapter analyzes the advantages and drawbacks found in the already existing work and how these can be improved.

Chapter 3 provides the detailed aspects of the new MAC protocol that is implemented and analyzed for the purposes of this work. This chapter proposes a new cooperative MAC scheme that employs both cooperation and overhearing avoidance technique. The selection of a cooperative relay node follows a receiver based approach and the overhearing scheme uses a Turn Off Redundant Nodes (TORN) system so as to save energy consumption by the nodes thereby providing improved network lifetime. The chapter further discusses the simulation model that was used to simulate the proposed MAC protocol and the simulation model is validated by comparison with an IEEE 802.15.4 MAC standard. It details the implementation structure that was followed by means of flow diagrams and algorithms. Finally, the chapter provides a validation using simulation results. The simulation results presented in this chapter compare the QoS provided by the proposed MAC, as opposed to that of the IEEE 802.15.4 MAC standard.

Chapter 4 reveals in depth, the analytical framework of the proposed MAC scheme. The analysis performed in this chapter includes, the channel model, the energy consumption model and delay.

The analytical framework follows a three state Markov process for the node state analysis and an N state Markov process for the network state analysis. These both assist in solving the energy efficiency model and the channel model. This chapter also details the results and discussion thereof. It compares the analytical and simulation results and draws the respective conclusions from there.

Chapter 5 investigates the effects that varying the cooperative relaying schemes has on the proposed MAC scheme. The cooperative relaying schemes investigated include Amplify-and-Forward, Decode-and-Forward and Store-and-Forward. The chapter thereby validates why Store-and-Forward is used for the proposed MAC scheme instead of the possible Amplify-and-Forward or Decode-and-Forward. The analytical results of the three respective schemes are compared and therespective conclusions are drawn from there.
Chapter 6 is a conclusion of the work. The chapter gives a detailed conclussion of all the chapters presented in the dissertation. This chapter also details possible future work that could make for better research avenues relating to the work conducted herein.

1.7 Summary

In this chapter the basic theory of WSNs is introduced by discussing their applications and challenges. These challenges raise much of the research attention that the WSNs have been receiving over the past few years. This chapter then looked at the research motivation, which is why this research needed to be carried out. The idea is that after we have looked at the challenges in WSNs regarding medium access and energy efficiency one had to develop a cooperative MAC protocol for WSNs that can provide energy efficiency, reduced packet collision and reduced network overhearing while employing a cooperative diversity approach together with an overhearing avoidance scheme. We then discussed the methodology that was followed in the design of such a protocol and the objectives and outcomes that the research is or was intended to produce.

Chapter 2

2 MAC Protocols for WSNs: Survey

2.1 Introduction

The main reasons for energy consumption in WSNs is due to collision, overhearing and idle listening, hence most or all of the MAC protocols discussed in this document are an attempt at designing a protocol that will minimize one or all the above. To design an optimal MAC protocol for WSNs one must attempt to achieve low latency in that there should be as few hops as possible from sender to destination, high fault tolerance, since the medium access should have no (or few) collisions and jamming and finally, it must coexist with other MAC protocols [6]. MAC protocols for WSNs can be categorized into two types; contention based or schedule based. Schedule based MAC schemes use a predefined scheduling method to schedule the nodes into a queue as to which node will transmit first in the frame of transmission and the nodes in the network follow the specified schedule. Contention based MAC schemes generally allow the sensor nodes to start transmission to the sink node, based on which node won the contention to send first during a particular frame of transmission. Contention based protocols are mostly prone to collision, idle listening and overhearing. The good thing about contention based protocols is their ability to adjust easily to topology changes and the fact that they have no time synchronization requirements. On the other hand, schedule based protocols manage to avoid idle listening, collision and overhearing but are subject to time synchronization requirements. This chapter performs a critical review of cooperative and non cooperative MAC schemes in their CDMA and TDMA forms, overhearing avoidance schemes in WSNs and also critically reviewed cooperative relaying methods for cooperative MACs in WSNs. Finally, the chapter presents an overview of the developed MAC protocol addressing some of the concerns raised in the critical review of the existing MAC protocols.

2.2 Non Cooperative MAC Protocols

Generally, non cooperative MAC protocols involve scenarios where each source node in the network sends its data packets directly to the destination node without any intermediate node relaying its data for it. These protocols can be differentiated in terms of their characteristics into schedule based, non-schedule based and hybrid based. Hybrid MAC schemes are those that are designed based on both both the contention based and the schedule based MAC schemes. A good example of a hybrid based MAC protocol is when it is designed such that it incorporates the good characteristics of schedule based, contention based and non-scheduled based protocols into a single better performing protocol.

2.2.1 CDMA Based MAC Protocols

CDMA based MAC protocols are MAC schemes that base their physical model on the CDMA technology which pertains with code assignment to transmitting and receiving nodes in WSNs. Generally, MAC protocols for WSNs cater more for the power consumption factor and almost neglect other factors such as latency, accuracy, fault tolerance and reliability. Introducing CDMA technology in MAC protocols for WSNs helped address a number of factors that had been neglected. In CDMA based MAC protocols each signal occupies much greater bandwidth, needed for sending information. For the receiver to be able to decode the coded data it must be synchronized with the transmitting nodes Pseudo Noise (PN) [2], which increases system data security.

The main advantages to CDMA based MAC protocols is that it achieves latency, fault-tolerance and scalability, and using the PN code to synchronize both the transmitter and the receiver, helps the protocol achieve system security.

The disadvantages are that latency, fault-tolerance and scalability are achieved at the expense of power consumption. Also for such protocols there exists the problem of how to develop a code assign protocol to assign a code to each node or its messages in larger networks, while this PN code is also needed in order for sensor nodes to avoid collision. It is also generally harder to always ensure that the two CDMA nodes (sender and receiver) are synchronized with the same PN codes.

(a) **Distributed Route Aware MAC for WSNs (DRMACSN)**: For the channel access scheme, DRMACSN employs the spread slotted aloha, approach which the nodes use in order to contend for the unoccupied mini slots in a frame. At each instance DRMACSN places each node in one of three states, which are sleep, wake-up or active. DRMACSN uses a routing protocol to specify the route from source node to destination prior to the MAC transmission [7]. Without any data to be transmitted in the buffer and without any data to receive, a node is then sent to sleep mode for a random time interval and before transmission the protocol checks whether the number of simultaneous ongoing transmissions has not exceeded the blocking threshold, and also that the channel load has not been exceeded. In order to provide a design for an efficient MAC protocol, DRMACSN considers the aspects such as energy conservation, thus prolonging the network lifetime, scalability, should the node density and topology be altered, addition and elimination of sensor nodes in the network over time. This protocol also takes into consideration the network fairness, throughput and data delivery delay [7]. The focus for DR-MACSN is mainly in reducing energy consumption using a distributed route aware protocol, which presents much reduced idle listening time and a good collision avoidance mechanism.

The main drawback in DRMACSN is that messages may be corrupted as a result of the multiple access interference in CDMA [7].

The advantage of DRMACSN is that the scheme possesses a relatively good collision avoidance mechanism. If a message is too long, the sender and receiver will be granted medium access for the transmission of all the data fragments [7]. The algorithm in [7] proposes that the receiver node examines channel overload before an attempt to transmit data is made allowing the protocol to provide much improved success probability.

(b) **A Multi-Channel Energy Efficient MAC (CMAC):** CMAC is a desynchronized transmitter oriented MAC scheme as proposed in [8]. This protocol makes use of multiple channel support prominent in sensor nodes. It requires only a low-power wake-up radio and a single half-duplex transceiver. For CMAC to provide energy-efficiency, sensor nodes are placed in default sleep mode and are woken up only when necessary. CMAC is an attempt to provide collision-free messaging exchange without a separate control channel and without affecting channel fairness and latency. The effects of collision, overhearing, idle listening and control packet overhead are eliminated in CMAC by each sensor nodes ability to obtain default sleep mode and enabling of multi-channel message exchange without extra hardware requirements [8]. Sleep mode helps the protocol conserve much of its energy. Whenever a node wishes to transmit, a series of pulses are sent by the low-power wake-up radio to wake-up the single half-duplex transceiver which then takes care of the transmission. Whenever the single half-duplex transceiver, is idle, CMAC sends its nodes to sleep to preserve energy, thus providing extended network lifetime [8]. During the sleep period of the single half-duplex transceiver, all tasks are delegated to the low-power radio but transmission is handled by the single half-duplex transceiver.

CMAC requires minimal hardware, provides 200% reduction in terms of energy consumption compared to SMAC [8], while showing (50-150%) improvement in both throughput and end-to-end delay. Also, this protocol is most preferable in time-critical scenarios and is collision-free during data transmission.

The main drawback in CMAC is that collision may be possible during control message exchange and that the protocol is prone to deafness and overhearing when a certain node attempts to communicate with a node that is still engaged in communication with a different node [8].

2.2.2 TDMA Based MAC Protocols

TDMA based MAC protocols are the MAC schemes that base its physical model on the TDMA technology which pertains to time slot assignment or time schedules given to each node which requires transmitting resources in the network. TDMA MAC schemes in WSNs are used mainly as processes that allow time slot allocation amongst neighbor nodes in the network in order to provide a collision free access to the channel. Normally, TDMA schemes lead to reduced latency in the network because of the fact that, apart from collision avoidance, such schemes also minimize the number of time slots in each transmission frame.

(a) **Dynamic Energy Efficient MAC Protocol**: The protocol proposed in [9] is a Dynamic Energy Efficient (DEE) MAC protocol that reduces energy consumption by sending idle nodes to sleep so as to prevent idle listen. Protocol is designed for low traffic rate Sensor Networks and to reduce delay noticeably [10]. TDMA schemes make it possible to combine clustering solutions thus allowing the protocol to reduce the cost of idle listening [9]. In DEE MAC node-radios can be switched off during idle times. Data transmission in DEE MAC is divided into two phases, cluster formation phase and transmission phase. Cluster formation phase is the time duration for nodes to form into clusters and for each cluster to decide on a node to be cluster-head, based on which node has the highest power-levels in the cluster. Clusters are formed dynamically after each transmission and a new cluster-head has to be decided each time. Transmission phase is the time duration for nodes to access a channel to transmit on.

The advantages of the TDMA based protocol, as proposed in [9], are that nodes in each cluster can arrange themselves such that the node with more power-level may become the cluster-head; sensing radius is application specific; only nodes with data to transmit or receive are switched on in each session and the system waits until clusters are formed before going into transmission phase. It is also important to note that DEE MAC would maximize performance if inter-cluster communication (communication through nodes) was used instead of intra-cluster communication (communication through cluster-nodes).

The disadvantages in DEE MAC is that it does not yet consider the possibility of packet loss during contention period and it does not yet include the work of maximizing throughput and minimizing latency.

(b) **Traffic Adaptive MAC Protocol**: TRAMA is a schedule based (TDMA) protocol providing a collision free channel for WSNs. Energy consumption in TRAMA is achieved by the fact that the channel is collision free. Also, nodes that are not either transmitting or receiving are sent into a low power idle state [11]. TRAMA is more energy efficient with better throughput results compared to SMAC but this protocol has higher latency compared to both SMAC, and IEEE 802.11.

(c) **Distributed Energy Aware-MAC**: As most MAC protocols for WSNs, DE-MAC focuses on energy-efficiency in the WSN systems. DE-MAC makes good use of the advantage of TDMA to avoid collision and control packet overhead. To avoid overhearing and idle listening, the protocol uses a periodic sleep-listen concept. The main approach in DE-MAC is to treat critically weak (less powerful) sensor nodes in a distributed manner. In order to accomplish load balancing such nodes are used less frequently in the network processes [12]. By a local selection procedure, DE-MAC selects the nodes with least amounts of energy in the network and then subjects them to longer sleeping periods compared to other neighboring nodes. The weaker nodes selection procedure used in this protocol is integrated with TDMA slot assignment protocol [12]. DE-MAC is an energy-efficient MAC protocol based on the positive characteristics of the TDMA protocol. Initially, in DE-MAC, all nodes are allocated the same number of transmission slots in a TDMA frame. But it is noticeable that over a period of time several sensor nodes in the network fall into a critical energy state. These nodes are then treated differently. In its own time slot, if a node has no data to transmit, it is sent into sleep mode.

The main advantages in DE-MAC are firstly, that it does not suffer from extra loss in terms of throughput, secondly, DE-MAC protocol saves energy by assigning half as much the listen time slot to critical sensor nodes and twice as much listen time to the nodes that are currently well off in terms of power, thirdly, that this protocol does not require any contention mechanism since each node has their slots pre-assigned with its low energy nodes are sent to longer sleep periods in order to balance the energy amongst the nodes, thus increasing energy savings and network lifetime. Finally, in this protocol no two nodes can transmit in the same slot; this is adopted from TDMA schemes [12].

The main disadvantage in DE-MAC is that packet loss may occur due to interference and depreciating signal strength.

(d) **SPARE-MAC**: SPARE-MAC implements a dynamic TDMA based MAC protocol with all the nodes synchronized. It is aimed at limiting the impact due to traffic overhearing and idle listening. SPARE-MAC is characterized by low-to-moderate traffic and low sensor mobility. SPARE-MAC operation is such that each sensor node is allocated time slots according to distributed scheduling [13]. Energy wastage is limited by the fact that the source node is turned on only during the receiving period of the intended destination node. This limits the impact of overhearing, idle listening and over-emitting. In SPARE-MAC, all sensor node resources are allocated according to periodical frames sectioned into time slots. Each sensor node follows a Reception Schedule. which is a set of time slots for which a sensor is active for data reception, so each node must be notified of the Reception Schedule of all its potential receivers. SPARE-MAC uses Wake-up Reliable Reservation Aloha protocol to assign a Reception Schedule to each sensor node, broadcast it to the neighbor nodes and also to grant a new sensor node access to the network. SPARE-MAC assumes unsuccessful transmission if there is no ACK received back at the transmitter [13]. Average amount of energy consumed per frame is compiled from the weighted average of the energy consumed in reception, idle state, transmitting and sleeping state.

Although collisions are not entirely prevented, SPARE-MAC reacts to a collision event with proper countermeasures. Another positive is that SPARE-MAC presents improved throughput with less energy consumption and faster delivery compared to SMAC [13]. But one must highlight that SPARE-MAC does not prevent collisions entirely, and the fact that collisions may occur whenever multiple sensor nodes transmit on the same Reception Schedule. It is also important to note that the energy savings in SPARE-MAC is attained at the expense of an increased probability of collision.

2.2.3 Hybrid MAC Protocols

A hybrid MAC protocol is generally a combination of the benefits that are present in both schedule based and non-schedule based protocols. Such a protocol is designed to switch between the two forms, depending on the network load conditions. A hybrid protocol will perform as a non-schedule based protocol for low network congestion conditions and as the network load conditions increase the protocol and uses its schedule based approach. This subsection discusses a few of the already existing hybrid MAC protocols for WSNs, closely looking at their advantages and drawbacks.

(a) **Zebra MAC**: Z-MAC, as proposed in [14], is a hybrid MAC protocol for WSNs that combines the strengths of TDMA and CSMA protocol while it offsets weaknesses of both. CSMA was chosen for its simplicity, flexibility, and robustness [14]. Furthermore, CSMA does not require any clock synchronization. Also, the fact that in CSMA node joining and leaving are handled without extra operations and the data packets can be transmitted at any time without contention, this reduces transmission delay [14]. TDMA was chosen since it schedules transmission times for neighboring nodes to occur at different times; this helps solve the hidden node problem in TDMA schemes. Another positive factor about TDMA is that for low contention, channel utilization is much lower. The scheme proposed in [14] was a successful attempt at capitalizing on the advantages of each protocol and eliminating the draw backs of each protocol. Z-MAC has a great adaptability to contention levels, under low contention Z-MAC takes on the performance and behavior of CSMA, while under high contention Z-MAC takes on the performance and behavior of TDMA. This hybrid scheme is robust to dynamic topology changes and time synchronization failures. In Z-MAC, CSMA is the baseline protocol and a TDMA schedule is used to enhance contention resolution [14].

The advantages in Z-MAC are that it has high channel utilization and low latency under low contention. This is adopted as a CSMA characteristic. Furthermore, it also has high channel utilization under high contention, which is a TDMA characteristic. This protocol, as proposed in [14] can adapt to the level of contention in the network. All this aids in reducing collision amongst two-hop neighbors at low cost. The worst case Z-MAC performance is equivalent to CSMA and in Z-MAC a node can transmit at any time and not necessarily at the beginning of a slot, provided a channel is clear which is determined by carrier-sense.

The drawbacks in Z-MAC are its cost of trial and error in CSMA, trial may cause access collision; two or more nodes transmitting at the same time may cause signal degradation at the destination. This protocol is also prone to Hidden Node Problem, causing throughput degradation. For the TDMA scheme in Z-MAC, finding an efficient time schedule is non-trivial and a central node is required in order to achieve a collision free schedule [14]; these schemes need clock synchronization which requires frequent message exchanges, which uses up energy and handling dynamic topology changes in TDMA schemes is expensive.

(b) **Wise MAC**: In Wise MAC, each sensor node has two communication channels. The TDMA channel is for data access and the CSMA channel is for control signals. Wise MAC monitors and reduces energy consumption during idle listening by using non-persistence CSMA technique with preamble sampling [15]. Wise MAC performs better than SMAC in terms of energy consumption since it is adaptive to both high and low network traffic.

(c) **Self-Organizing MAC for WSNs**: SMACS is a schedule based MAC protocol WSNs that combines TDMA with either CDMA or FDMA. Its main drawback in SMACS is that it wastes time slots when there is no data to be transmitted.

2.2.4 Contention Based MAC Protocols

Contention based MAC schemes in WSNs define the MAC schemes in which the sensor nodes need to contend to access the medium at the beginning of each frame of transmission. The contention may be based on resources such as the channel quality (CQI), Signal-to-Noise ratio, time of arrival, priority of message ect. The node with the best specified resource wins the contention at the beginning of the frame of transmission and gets to use the medium.

(a) **Sensor MAC:** The protocol proposed in [2] is based on sleep-listen schedules driven by some locally managed synchronization. Neighbor nodes form virtual clusters and fall into the same sleep-listen schedule. At listen periods of a certain cluster, neighboring nodes wake-up and listen for data transmission [2]. This means if a node has two other neighboring nodes belonging to different clusters, then it will follow two sleep-listen schedules so it services both clusters. Protocol is intended to solve the idle listening problem, the collision problem and overhearing. All these are problems in WSNs that lead to excessive energy consumption. Protocol employs the method of message passing by dividing up long messages into frames and then sends them in a burst. The positives of message passing in SMAC are that it minimizes communication overhead and saves energy. The negative is that it introduces unfairness in the medium access.

    The advantages of SMAC are mainly that the energy wasted due to idle listening is countered for by sleep schedules and the collision avoidance is provided by carrier sense. SMAC focuses mainly on the energy efficiency aspect of WSNs.

    SMAC is prone to overhearing and suffers in terms of latency since most nodes spend the time in sleep mode. Nodes belonging to a number of different clusters result in energy being wasted due to idle listening. This is just to highlight a few disadvantages of the protocol proposed in [2].

(b) **Contention Reserve MAC:** The protocol CRMAC proposed in [16] combines the advantages of both schedule-based schemes and contention-based schemes. CRMAC is a protocol best suited for intra-cluster WSNs, low load networks and short packet transmissions [16]. CR-MAC was intended to eliminate the effects of collision that are present in most contention-based protocols leading to energy wastage such as overhearing and retransmission by introducing a schedule based approach. The schedule-based approach introduced by CRMAC avoids any collisions and reduces packet overhead needed for data transmission [16], which contributes to the much needed energy saving but most schedule schemes lack in synchronization and network flexibility. Having considered the pros and cons of both the contention-based and schedule-based approaches, CRMAC uses a hybrid super-frame structure. CRMAC uses CSMA to send slot reserve packets to the cluster-head. This is so that a node can obtain permission to transfer data in the next guaranteed time slot. Super-Frames allow the protocol to reserve slots before the actual transmission takes place to avoid collision. Only the node that owns the transmission slot will have access to the channel to transmit its data to the cluster-head with all other nodes sleeping [16].

The advantage with CRMAC is that it provides effective reduction of the probability of collisions and also provides reduced propagation delay which leads to increased energy-efficiency. Combining the advantages of both schedule-based schemes and contention-based schemes allows CRMAC to connect slot allocation and contention mechanisms together [16]. In CRMAC the communication is contention-free and all nodes transmit data according to the schedule table. The main disadvantage is that the nodes still have to spend some time in contention phase.

(c) **Berkeley MAC**: BMAC is a contention based MAC protocol that provides proper balance between latency, throughput and energy consumption.

The main advantage with BMAC is that the protocol does not miss any data packets since the sensor node radios are repeatedly switched.

The main drawback in BMAC is that it does not provide any implicit protection for problems such as hidden terminal problem for wireless networks and it also introduces some additional latency to the network.

(d) **Asynchronous MAC**: The authors in [17] proposed a protocol called A-MAC which is a contention based energy efficient MAC protocol for WSNs intended for systems in which it is difficult to ensure high quality network synchronization [17]. This scheme presents increased energy utility, ensures successful transmission rate and decreased data packet average waiting time. [17] Proposed a MAC protocol that is set to improve network performance and network lifetime. A-MAC also introduced a system that would be able to run unattended for a large number of years since changing or replacing batteries in WSNs is quite cumbersome. In A-MAC, nodes maintain their own phase switching schedules which reduces the dependency on network time synchronization. This means each node is either in one of its two states; off-phase or on-phase. Lifetime of a network can be extended by about 0.2 to 0.4 times on A-MAC compared to S-MAC protocol [17] and from that fact one can deduce that A-MAC can implement the energy saving task more successfully than S-MAC. Above that, A-MAC is also 0.3 times more reliable in transmitting data packets compared to S-MAC since failure in transmissions is reduced and the average waiting time in A-MAC is 0.3 times shorter than in S-MAC [17]. There are also less out of date data packets when using A-MAC than when using S-MAC.

The advantages in A-MAC is that it extends the sleeping times (off-phase) while reducing the listen times (on-phase) to just about enough for all the nodes to send the packets that are ready to be sent out. Although this may be good for energy saving it however affects the systems latency negatively. This MAC scheme also ensures that nodes belonging to the same clusters switch to similar phases simultaneously.

If a packet arrived during the transmitting clusters off-phase then the transmission will be delayed considerably, resulting in system high latency. The other disadvantage is that the nodes start to send data through contention with each node given a threshold time by which it should have transmitted its data else the transmission is treated as a failed transmission.

(e) **PQ-MAC**: This protocol proposed in [18] tackles the problems of overhearing and idle listening by providing a periodic sleep-listen and providing quality of service and focusing on reducing the latency of the message [18]. PQMAC adaptively controls the network traffic based on data priority levels. The data to be transmitted from source to destination is divided into 4 levels where level 0 is for high priority and level 3 is for low priority. This data is placed into a transmission queue which will start by servicing the high priority data. The main aim in PQMAC is to improve QoS and reduce latency, all while maintaining energy efficiency [18]. This protocol provides a fast packet transmission. To achieve this, it maintains a priority queue, gives additional listen time in the sleep state which solves the latency problem and allows low-priority data to be sent only when there is no high-priority data in the queue. By assigning priority to the data to be transmitted, PQMAC addresses the fast sending of more important data, based on priority levels. To maintain energy efficiency, PQMAC provides advanced wake-up scheme which uses dynamic priority listening, helping to manage scheduling based on traffic information, providing accurate data transmission meaning data is sent without losses while reducing transmission delay.

The clear disadvantage in the protocol proposed in [18] is that the medium has unfairness for all the data regarded as of low-importance or low-priority.

2.3 An Introduction to Cooperative Diversity

In cooperative system networks, there exists a node representing a potential cooperative relay. The cooperative relay node assists in the communication between the data source node and the data destination node. The cooperative relay node receives a noisy version of the signals transmitted by the source node; it then uses cooperative relaying techniques such as the Amplify-and-Forward, Decode-and-Forward or Store-and-Forward technique to transmit an amplified, decoded or resulting version of the transmitted signal to the destination node [5] respectively. The destination node thus receives two copies of the transmitted signal which are independently faded. The cooperative relaying schemes are generally dependent on the channel quality between source node and the cooperative relay node and the channel quality between the relay node and the destination node. Thus using cooperative diversity together with the cooperative relaying schemes is advantageous in wireless networks since the quality of the channel decreases with distance. However, how the Amplify-and-Forward, Decode-and-Forward and Store-and-Forward schemes perform will depend on the position of the relay node with respect to both the source and destination node. Preferably, the relay should be closer to both the source and destination node. Knowing where a certain relay node is positioned may be influential in determining how many cooperative packets can be forwarded as a function of the relative distances [5].

When compared with traditional Single Input Single Output (SISO) non-cooperative communication schemes, cooperative communication schemes such as Multiple Input Multiple Output (MIMO) systems bring more energy saving to WSNs with improved performance in fading wireless channels [19]. These aid the cooperative diversity systems to achieve reliable communication at a lower transmission energy cost. Cooperative diversity attempts to achieve spatial diversity by allowing a number of sensor node devices to emulate antenna arrays by relaying data signals to each other. Furthermore spatial diversity and other diversity techniques provide improved performance in wireless networks by mitigating and exploiting multipath fading [20]. In cooperative diversity systems, total energy consumption consists of the energy of transmissions, local communication energy cost and transceiver circuit energy [19]. It has been investigated and established that cooperative communication leads to a more energy efficient network beyond a threshold transmission distance. A drawback of such systems is the extra delay due to the schemes non-simultaneous long-haul transmissions. Next is a brief look at three major cooperative diversity techniques in short range WSNs.

Consider cooperative networks with a source, destination and two relay nodes RN_1 and RN_2 as depicted in Figure 3. The two relay nodes depicted above receive data signals transmitted from

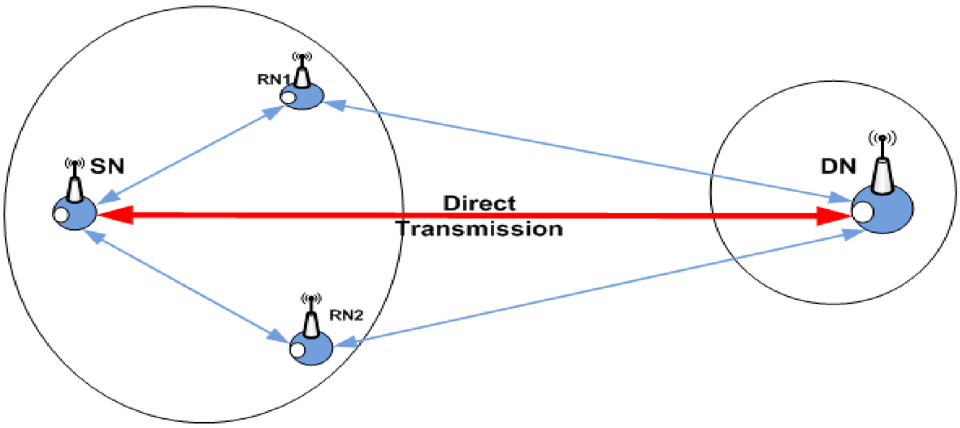

Figure 3: Cooperative Communication Network with two Relays

the source node and forward them to the destination node as their own. Using more relay nodes improves end-to-end transmission reliability between the source and destination nodes. The two relay nodes may also share the data signal received from the source node. This way they exploit the spatial diversity of the cooperative communication [20]. Cooperative communication improves the data packet delivery probability since it allows the source node to experience fading at the destination without the transmission failing because the relay nodes are there to provide an alternative data packet delivery system thus contributing to the reliable communication in cooperative diversity schemes. Diversity is necessary to mitigate effects resulting from multipath propagation such as fading. The extra node/s is how cooperative diversity schemes realize the diversity. The main drawback of employing relay nodes in wireless networks is that sensor nodes cannot implement simultaneous communications by transmitting and receiving at the same time in the same frequency band [20].

2.3.1 Cooperative MAC Protocols

Cooperation in MACs for WSNs imply having a relay node through which a source node will send its data to the sink node. This applies in circumstances when the source and sink node may be too far apart or simply linked through a very poor channel such that the communication may be compromised and deemed low quality. In cooperative WSNs′ MAC protocols, the destination node receives multiple copies of the same signal since the neighbors of the transmitting node cooperate with it by repeating the overhead signal [21]. This means that a node close to the source node can assist it to relay its data packets to the destination node. The advantage of this is that the neighboring node can be much closer to the destination node compared to the source node.

(a) **Cooperative-MAC**: The protocol COMAC as proposed in [21] is a MAC protocol that enables cooperative communication by employing 802.11 based radios. It enhances cooperative communication since it uses overhead packets from a certain nodes neighbor nodes. COMAC protocol provides throughput enhancement and high energy savings for high circuit energy consumption cases. Cooperative communication is proven to be more energy efficient compared with non-cooperative MAC schemes. This protocol improves the systems′ throughput and energy efficiency more so for long transmission distances and conservative circuit energy consumption values [21]. The improved throughput is due to the gain in diversity obtained by cooperative diversity making the channel more robust to errors and advantageous in terms of long haul transmissions. COMAC protocol has been proven to provide enhancement in throughput for both point-to-point and multi point-to-point medium to long-haul transmissions [21].

The advantages In COMAC are that the same range that can be served in non-cooperative schemes can be realized with decreased transmission power, the packet success rate is improved with decreased receive threshold through longer transmission ranges and transmission power kept constant and the throughput in COMAC is not affected by how many nodes are in contention for the medium.

The main disadvantages in COMAC are that the source uses RTS/CTS packet exchange at the start in order to determine mode of transmission. If a relay node fails to cooperate then the source node will not attempt to cooperate with for future transmissions [21], and this protocol consumes more energy due to the additional consumption of energy at the relay node but it is still below that of direct communication non-cooperative protocols.

(b) **WSC-MAC**: WSC-MAC is a protocol proposed in [22] in order to improve network reliability by using cooperative communication. The protocol attempts to define a relay node efficiently with a use of only a few control messages. WSC-MAC as a cooperative communication scheme uses a single antenna for multiple nodes [22]. WSC-MAC focuses on the importance of identifying the most efficient and effective relay node from a set of neighboring nodes. The selection of the relay node to forward the data packets is done either by using Link State Evaluation or Automatic Forwarder Selection both discussed in [22]. For the selection of the best relay node, WSC-MAC uses a cross layer design in order to gain information from the physical layer. In WSC-MAC, the probability of successful transmission increases with decreasing distances between nodes.

The protocol saves bandwidth because the total number of transmitted packets is lower when using cooperative communication [22]. Furthermore, the protocol reduces the ACK traffic and provides enhanced packet delivery and network reliability for low density networks.

The only main disadvantage in WSC-MAC is that it shows no improvement for high density networks.

(c) **A Cooperative MAC Protocol for WSNs with Minimal Control Messages (COSMIC)**: COSMIC [23] is a MAC protocol for WSNs based on CSMA/CA and supports cooperative communication with minimum overhead [23]. It exploits cooperative relaying in order to reduce energy consumption and enhance channel capacity. The main idea is that, while the direct channel between source node and destination node may be affected by fading, the channel between the cooperative relay node and the destination node may have better transmitting conditions. If a neighbor node cannot enhance the direct transmission, it retires off the transmission silently and neighbor nodes not common to both the sender and the receiver, will silently drop the packet [23]. If the desired relay node can overhear all packets transmitted by the source node then it makes more sense that the packet is retransmitted via a better channel by the relay node instead of the source node. If the destination node is able to decode a data packet from the sender, it sends an ACK signal so that the relay node does not have to retransmit the packet unnecessarily. The neighbor with the best channel conditions will be selected as the cooperative relay node for a particular source node.

The number of control packets in a scheme contributes to the energy wastage. Hence in COSMIC, the advantage is that, only one control packet is used for relay selection. Another advantage is that COSMIC provides no excess and non-required retransmissions and compared to CSMA, delivery ratio is enhanced 0.95 times for a network with up to 100 nodes density. This cooperative MAC protocol also produces less packet loss while increasing the network lifetime by 25% compared to non-cooperative schemes. It also avoids the transmission of the packet several times on a poor channel by selecting a better node to relay the signal.

The main disadvantage is that all neighbor nodes fit for relaying the packets have to go through a contention period before the neighbor node with shortest back-off period can relay the data packets.

(d) **Cooperative-TDMA**: The time division protocol proposed in [24] focuses on improving the probability of correct packet transmission and throughput by using cooperative transmission in Rayleigh fading channels. C-TDMA improves the throughput of the conventional TDMA by over 40% by employing the designs of cooperative MAC. Cooperative diversity techniques are essential and effective in designing energy-efficient protocols with improved quality of service in WSNs. In C-TDMA, firstly a node uses its allocated time slot in each frame to transmit its own data packet. Secondly, due to channel impairments, packets that failed during previous frames may need to be retransmitted. Each node monitors time slots in each frame while cooperating with other frames to manage the retransmissions. Each node serves already existing packets in its buffer in a First in First Serve approach [24]. Each packet is served accordingly during its allocated time slot with all packets allocated equal time slots. Should the transmission fail, it will then be transmitted in the following frame until transmission is successful.

In C-TDMA the neighbor nodes assist the source node to retransmit its lost packet. C-TDMA also eliminates channel impairments that exist because of fading while increasing the probability of correct packet reception thus vastly improving throughput. Compared to conventional TDMA, C-TDMAs diversity gain was found to improve the probability of correct packet reception. This brought about an increase in throughput by 44% [24].

The main drawback in C-TDMA is that it can improve packet retransmission while idle time slots are available; it is less effective when traffic load is high with only a few idle slots available [24].

(e) **Cooperative Low Power Listening MAC for WSNs (CLPLMAC)**: The authors in [25] proposed CLPLMAC which is a Multi Input Multi Output (MIMO) transmission scheme focusing on reducing latency, transmission energy, retransmission probability and the effects of fading. [25] Investigated CLPLMAC both the Beam Forming (BF) MIMO and Spatial Multiplexing (SM) MIMO schemes and found the BF MIMO scheme to be the more efficient in terms of performance. SM MIMO scheme introduces the possibility of having a number of cooperative receivers [25]. Combining a cooperative communication scheme with an efficient MIMO scheme yields a more energy efficient cooperative MIMO protocol with low latency. In order to select an effective relay node and coordinate the sharing of the Channel State Information while avoiding collision this protocol implements an ACK reply and uses redundant control packet transmissions [25] and the process of selecting the cooperative node is carried out during the control packet exchange. The implementation of this protocol considers the impact due to the imperfect synchronization caused by clock jitter and it exploits the advantages of distributed cooperative MAC while it keeps the transceiver turned on using low power listening scheme.

In CLPLMAC, all transmissions including data packet transmission occur at low power. This provides network scalability; a node may join or leave the network at any given point and this protocol requires no prior knowledge concerning neighboring nodes in order to perform data transmission or reception.

This protocol is subject to possible packet loss and idle listening, leading to retransmissions and loss of energy efficiency [25], and it also has some low energy expended because sensor nodes are always on.

2.4 IEEE 802.15.4 Standard

The IEEE 802.15.4 is a new network standard which specifies the MAC and physical layer of wireless personal area networks. The IEEE 802.15.4 standard was introduced in the year 2003 and proved to be a low-cost communications standard with moderate network complexity [26]. The IEEE 802.15.4 standard allowed the mesh networks and the wireless sensor networks′ systems to collect data with high accuracy, and to have longer node battery life spans and low latency

[26]. In this section we investigate a couple of MAC protocols using the IEEE 802.15.4 standard. Furthermore, we look at their pros and cons to determine if the standard could be utilized to yield better results in terms of throughput and energy saving patterns for wireless sensor networks.

2.4.1 IEEE 802.15.4 MAC Protocols

[15] modified the MAC layer of the IEEE 802.15.4 standard and added to it a *State Transition Scheme*. This work also achieved a low back-off delay time for nodes that are deemed to have higher occuring transmissions. This was done by altering the minimum Back-off Exponent value for those particular nodes and making it smaller. The main advantage of the work presented in [15] is that their approach achieved a higher network efficiency thereby providing increased throughput performance. However, [15] only presented the simulated and the proposed approach was not analyzed.

The work in [27] proposed a joint model for the IEEE 802.15.4 physical and MAC layers. [27] based the physical layer on the channel models and the radio models in an aid to evaluate the reliability of the link. The MAC model of [27] was based on the Markov chain model for the IEEE 802.15.4 MAC Standard. This method provided improved delay performance and node reliability.

[28] proposes an energy efficient MAC protocol for wireless sensor networks that reduces energy consumption by letting nodes enter the sleep state inside the active duration period when they have no data to send. The protocol in [28] further uses non-persistent CSMA which incorporates the adoptive back-off exponent (ABE) in order to reduce the network collision. This MAC scheme focuses on reducing the energy consumption by examining both idle listening and frame collision. This MAC scheme rather sends non-transmitting and non-receiving nodes to sleep state because the idle state consumes far more energy than it should. The energy model state diagram of the scheme is presented in [28].

2.5 Overhearing

One of the most important factors affecting the energy consumption in WSNs is the overhearing problem. Overhearing by a sensor node is a process where and when a particular sensor node receives a data or control packet that is not specifically meant for it. The reason why overhearing is a major issue is because firstly, the node in the neighbourhood of the receiving node does not have a specified mechanism with which it can ignore a packet that is meant for it without receiving and decoding it first. Secondly, the overhearing process consumes as much energy as the receiving process [4].

2.5.1 Overhearing Avoidance Techniques

(a) **Reducing Overhearing**: [4] proposes a technique to take care of the overhearing and idling problems together. The main idea proposed by [4] is to send non receiving or non transmitting nodes to a low-power listening state while keeping them in non sleep mode. Although this prevents both idle listening and overhearing to a certain degree, the drawback for such a scheme is that the time required for a node to transition from active to idle mode is long enough to still allow overhearing of a certain percentage of the information not meant for it.

(b) **Overhearing Avoidance in SMAC**: As described by [2], SMAC is based on sleep-listen schedules driven by some synchronization. Neighbor nodes form virtual clusters and fall into the same sleep-listen schedule. [29] proposes techniques to lessen the energy wastage in the SMAC protocol. This includes an overhearing avoidance technique applied to save energy in the WSN running a SMAC protocol. The work proposed by [29] suggests dividing a message into tiny fragments which are then transmitted in a single burst. This work also suggests passing a message over the nodes in the line to the sink node to avoid sending data over long distances which may result in packet retransmissions and energy wastage. Although this scheme saves the energy which could have been caused by the overhearing it however does not solve the idle listening problem and the transmission over a number of helper nodes may result in higher latency.

2.6 Cooperative Relaying Schemes

2.6.1 Amplify-and-Forward

The work proposed in [30] investigates the effects that the Amplify-and-Forward scheme has in providing spatial diversity in order to combat fading. Amplify-and-Forward schemes, in cooperative wireless networks, deal with amplifying and relaying a signal, originally from the source node, to the destination. Generally, the resulting relayed signal is considered to be an amplified version of the orignal signal with a signal gain factor G. The signal gain factor for the Amplify-and-Forward scheme depends on the channel coefficient, noise and transmitted energy [31]. However, Amplify-and-Forward schemes, from time to time, tend to also forward an amplified noise together with the amplified signal. Usually, the signal gain factor, G, is aimed at inverting the effects of fading in the cooperative transmission link.

(a) **Cluster-Based MAC Protocol in Multi-user MIMO WLANs**: the standard IEEE 802.11n, [32] proposed a MIMO system for wireless LANs that enhances data rates and allows the occurrence simultaneous transmissions by multiple users. [32] proposed using a CSMA/CA and grouping sensor nodes into clusters so as to allow sensor nodes belonging to one cluster to be able to simultaneously transmit or receive their data at any time. This approach was then tested in a cooperative network where the cooperative relay nodes employed the Amplify-and-Forward technique to forward the data amongst the multiple sensor nodes.

    The advantage of the work proposed by [32] is that it uses a CSMA/CA technique assisted by both clustering and the Amplify-and-Forward techniques to achieve distributed spatial multiplexing gain and broaden the network scope respectively.

    However, to be able to successfully implement the MIMO system with cluster-based CSMA/CA and cooperative diversity with simultaneous Tx/Rx cluster action with absolutely no interference would prove a hard task or rather unrealistic or non ideal.

(b) **Distributed Switch and Stay in WSNs**: By means of a single Amplify-and-Forward cooperative relay node, [33] proposed an energy efficient three node WSN system that employed the distributed switch and stay technique with an aim to provided simplify analysis in WSNs [33]. Distributed switch and stay in WSNs allows the sink node to not use any combining scheme after receiving a signal that was transmitted cooperatively by the source node through a cooperative relay node. Distributed switch and stay systems simply keep a threshold Signal-to-Noise ratio with which it compares the Signal-to-Noise ratio of the received signal from the source node. If the Signal-to-Noise ratio of the direct link between the source and sink node is lower than the threshold then the sink node switches and uses the cooperative channel to transmit receive data from the source node.

    The advantage of the work proposed by [33] is that it increases the system throughput since there will be a higher percentage of successfully transmitted packets in the WSN.

    The main drawback of such a system is the use of control packets between the sink node and the two other nodes (source and relay node). This arises since for the sink node to know the Signal-to-Noise ratio of the direct link it must have received some control packet from the source node. If the Signal-to-Noise ratio is below the threshold then before the relay node assists with the cooperative transmission the sink node has to inform both the source and relay nodes that cooperative communication is to be used. The uses of extra control packets in a system may lead to more energy being utilized by the sensor nodes in the system.

(c) **Optimum Power Allocation for Amplify-and-Forward Cooperation Strategy** : The work proposed in [34] suggests an Amplify-and-Forward cooperative scheme to achieve the optimal transmission power thereby reducing the network lifetime of the WSN. [34] analysed the Amplify-and-Forward technique using a single relay and concluded on the energy saving patterns. The work further analysed the Amplify-and-Forward technique under a multiple relay environment and concluded on the energy saving patterns then compared with the single relay node approach. The proposed scheme used the Maximum Ration Combining technique (MRC) to make a decision on the final received signal. The Amplify-and-Forward technique was used since it preserves the original signal without losing any information since no decision has to be made at or by the cooperative relay node before it forwards the data [34].

2.6.2 Decode-and-Forward

The work presented in [31] derived an analytical framework analyzing the probability of error for both the Decode-and-Forward and the Amplify-and-Forward relaying schemes. The analysis revealed that more diversity was achieved by the Amplify-and-Forward relaying scheme. In the Decode-and-Forward scheme, generally, the relay node decodes and re-encodes the signal from the source node before forwarding it to the destination. The Decode-and-Forward technique ensures that only the correctly decoded signals are forwarded.

(a) **TDMA in MIMO Decode-and-Forward Systems**: The cooperative relaying system in [35] considers a two-way MIMO system where a source and sink node communicate using a half-duplex cooperative relay node employing a Decode-and-Forward technique. In achieving a precise resultant of the signal at the sink node, the two-way cooperative relay node used in this system decodes the signal and XORs the decoded signal on the bit level before retransmitting them between the source and sink nodes. The sink node, upon receiving the forwarded signal, then demodulates this decoded signal by XOR-ing it with the the actual signal that was transmitted on the bit level [35]. The result of such a system showed an improved diversity gain when using the optimum time division strategies [35].

(b) **VoIP Decode-and-Forward Cooperative MAC**: The MAC scheme proposed in [36] is a Decode-and-Forward cooperative MAC for Voice over Internet Protocol (VoIP) wireless mesh networks. The proposed MAC shows a great deal of novelty as it uses a limited number of control packets, packet aggregation, differential detection and an ability to adjust the packet retransmission limit for every packet sent over the network so as to each minimum delay in cooperative wireless systems [36]. With the help of these, the protocol achieves an improved energy reduction performance on a per transmitted bit basis.

(c) **Relay Selection MAC with Overhead and Collision**: The work proposed by [37] introduces a cooperative MAC in which a relay selection method is strictly based on the throughput. This work employs a maximum throughput selection algorithm to find the relay node best suited to forward the data between the source and sink node. The selected cooperative relay node would then be used with Amplify-and-Forward or Decode-and-Forward to relay the data from the source node to the sink node. The underlying MAC scheme of the work proposed in [37] is the IEEE 802.15.4 DCF MAC. The system throughput is derived for all three possible transmissions (direct, Amplify-and-Forward and Decode-and-Forward) and factors into consideration the possibility of collision, frame error and overhead. However this system focuses and analyses only the throughput as the performance metric, there is no proof that other performance metrics (Energy, BER, delay etc) such as were not compromised.

2.6.3 Store-and-Forward

The work in [38] presented the traditional Store-and-Forward technique. Generally, a relay node employing a Store-and-Forward relaying scheme forwards the data packets to the destination and keeps copies of the information in its buffer. These data packets are kept for purposes of data retransmission.

(a) **WSNs in Health Monitoring**: The WSN based health monitoring system proposed in [39] provides an example of how WSN can be applied to real life applications. [39] proposed a WSN Store-and-Forward network architecture for health care monitoring that is based on the standard IEEE 802.14.5 MAC layer. This network interfaces WSN with the internet and the data is forwarded between the WSN to the internet via a router using the Store-and-Forward technique. The main drawback for such a network is that the WSN side of the network may run through their battery supply faster than the Mesh routed network hence it needs to be monitored timously to ensure that dead nodes are replaced or have their power source replaced quickly because any health care system is a critical system.

2.7 Proposed MAC Protocol Improvements

As some advantages and drawbacks of the already existing work have been pointed out, the MAC scheme proposed by this dissertation deals directly (or indirectly) with the drawbacks that still exist in MAC protocol design. The proposed MAC scheme is a cooperative distributed receiver based MAC protocol for WSNs with Overhearing avoidance. The proposed MAC protocol is based on the IEEE 802.15.4 CDMA standard and uses a Store-and-Forward relaying technique.

It has been proven that cooperative MAC schemes perform better than the non cooperative MAC schemes in terms of throughput and energy consumption. This is due to the fact that when a cooperative relay node is employed for the transmission there exists a higher rate of successful transmissions and less packet retransmissions because when cooperation is used the channel employed tends to be of higher quality and the distances for the transmissions lessen. The resulting lower number (or percentage) of retransmissions means that a node can quickly go back to sleep instead of performing more retransmissions. This ensures that more energy is conserved by each node in the network. The MAC proposed in this dissertaion is a receiver based approach when selecting a cooperative relay node. This reduces the number of collisions at the receiver as the receiving node selects the relaying nodes and so has no unexpected nodes sending data hence causing collisions at the reciever node. When nodes (or their packets) collide at the receiving node then retransmission of the collided nodes (or packets) needs to occur, thereby consuming more of the nodes energy. By employing a receiver based approach, this problem is taken care of and nodes consume less energy. The CDMA physical model of the IEEE 802.15.4 standard was chosen because of it is a low-cost communication standard with moderate network complexity [26].

To further conserve energy per node, the proposed MAC scheme employs an overhearing technique which runs turn off redundant nodes on every frame of transmission to ensure that no (or very little) overhearing occurs. The decision to employ the Store-and-Forward cooperative relaying technique over the Amplify(or)Decode-and-Forward is justified by an analysis performed on the proposed MAC using the three cooperative relaying schemes to determine which one performs best in terms of energy conservation.

2.8 Conclusion

In order to understand the WSNs architectures and protocols a survey of MAC protocols for WSNs was carried out on a number of previous papers that proposed different types of MAC protocols for WSNs. This ranges from non-cooperative to cooperative schemes. We have provided a critical review of the existing cooperative and non-cooperative MACs, the CDMA and TDMA MACs, the contention based and schedule based MACs and also a critical review of cooperative relying (Amplify-and-Forward, Decode-and-Forward and Store-and-Forward) schemes used in cooperative MAC protocols for WSNs. Furthermore the chapter discussed in depth the operation of the IEEE 802.15.4 standard as it forms an integral part of the work proposed in the next chapter. From the review the main research gap that was identified was that the effects of combining cooperative diversity systems with overhearing avoidance systems, which have not been studied and analysed effeciently for WSN MACs. Hence this dissertation proposed, simulated and analyzed a cooperative MAC scheme with overhearing avoidance to combat the existing deficiencies in MACs for WSNs.

Chapter 3:

3 Distributed Receiver Based Cooperative MAC

3.1 Introduction

WSNs employ cooperative diversity techniques in order to improve network lifetime and overall network reliability. The proposed MAC scheme focuses on cooperation with overhearing avoidance and reducing transmissions in case of link failures in order to minimize energy consumption in the network to improve the network lifetime. According to the survey undertaken on MACs for WSNs, combining the effects of cooperative diversity and overhearing avoidance leads to improved network reliability, QoS and lifetime. The cooperative MAC scheme developed herein incorporates cooperation, overhearing avoidance and a receiver based relay node selection onto the CDMA based IEEE 802.15.4 standard. The solution is developed based on a receiver oriented approach when selecting cooperative relay nodes and using a store and forward scheme to relay the packets to the destination node. This chapter details the proposed receiver based cooperative MAC protocol for WSNs. The chapter begins by providing a high level description of the proposed MAC protocol. The chapter then describes how the CDMA communication codes are assigned to the nodes in the the network before detailing the frame of transmission. The chapter then explains the two phases of transmission namely the direct and the cooperative transmission phases and describes how the decision of whether to transmit directly or cooperatively is made. The two transmission phases are explained in terms of algorithms. The next section in the chapter is the packet retransmission mechanism required for failed cooperative transmission phase. The simulation model is then explained with an aid of a MAC protocol comparison with existing work. The final two sections describe the performance metrics that were investigated and the simulation results are descussed before the chapter is concluded.

3.2 Protocol Description

For the purposes of reliable and effective communication, the scheme assumes that each node is assigned three unique codes for communication. The source node uses a transmitter based code to perform all the data transmissions from itself to any other node in the network. The destination node uses a receiver based code to process the packet reception and thus reply back to any required transmission. Any other nodes in the network will use a common code to perform network updates during each frame. Each source node may have two main transmission phases; namely, the direct transmission phase and the cooperative retransmission phase. In the direct transmission phase the source node transmits directly to the destination node. In the cooperative retransmission phase the source node transmits its data through a cooperative relay node. However, the direct transmission phase is always attempted and only when it is unsuccessful will the cooperative retransmission phase be implemented. The transmission frame used for each transmission depends on which transmission phase/s is/are to be used. Should the cooperative retransmission phase be required, then a receiver based approach will be used to select the cooperative relay to be used for the transmission in that particular frame. The relay node selected will be as the result of it having the best channel quality indicator (CQI) during that frame. Each sensor node in the network maintains information about each node in its transmission radius. This information is updated once in every frame using a Neighboring Table (NT). It is assumed that each sensor node can only establish proper and reliable communication with those nodes within its one-hop transmission radius.

3.3 Assigning Communication Codes

The source node uses a transmitter based code to perform all the preamble and data packet transmissions from itself to any other node in the network. The destination node uses a receiver based code to process the packet reception and thus reply back to any required transmission. Any other nodes in the network will use a common code to perform network updates during each frame. This means that each node is assigned, according to [40], three sets of codes for communicating purposes. The proposed protocol does not deal directly with code assignment to any node. It simply assumes that each node has been assigned all of the three required codes in order for it to perform its communication effectively and reliably. More details about assigning codes to each sensor node in the network are presented in [40].

3.4 Time Slots Assignment

Each SN may have two main transmission phases: the direct transmission phase and the cooperative transmission phase. In the direct transmission phase the SN transmits directly to the DN (Algorithm 1). In the cooperative transmission phase the SN transmits the data through a cooperative RN. However, the direct transmission phase is always attempted and only when it is unsuccessful will the cooperative transmission phase be implemented. Should the cooperative transmission phase be required, then a receiver based approach (Algorithm 2) will be used to select the cooperative RN (with the highest CQI) to be used for the transmission in that particular frame. In the proposed E^2DRCMAC scheme, time slots are divided into similar frames of length 20ms for direct transmissions and 25ms for cooperative transmissions as shown in Figure 4. Each frame consists of mini time slots that accommodate the preamble handshake slot, Network Update slot and data sending slot (inclusive of the ACK). For the direct transmission frame, each handshake slot is fixed to 4ms. The first 2ms is reserved for the preamble sending from the SN and the second 2ms is reserved for Ready to Receive Packet(RRP) reception by the SN. The Network Update slot is fixed to 3ms. In this slot, all the nodes in the interference range are updated with the relevant information such that the redundant nodes are sent back to sleep to save energy. The last slot is the Data sending slot fixed to 13ms. The first 12ms is reserved for data transmission while the final 1ms is reserved for the ACK signal. For the cooperative transmission frame, the 2ms preamble slot is followed by the 5ms relay node selection slot which takes care of the rest of the preamble handshake. While the Network Update Slot is fixed at 3ms, the cooperative data transmission is fixed to 13ms with a further 2ms slot reserved for the cooperative sending of the ACK signal. It is assumed that all trans-

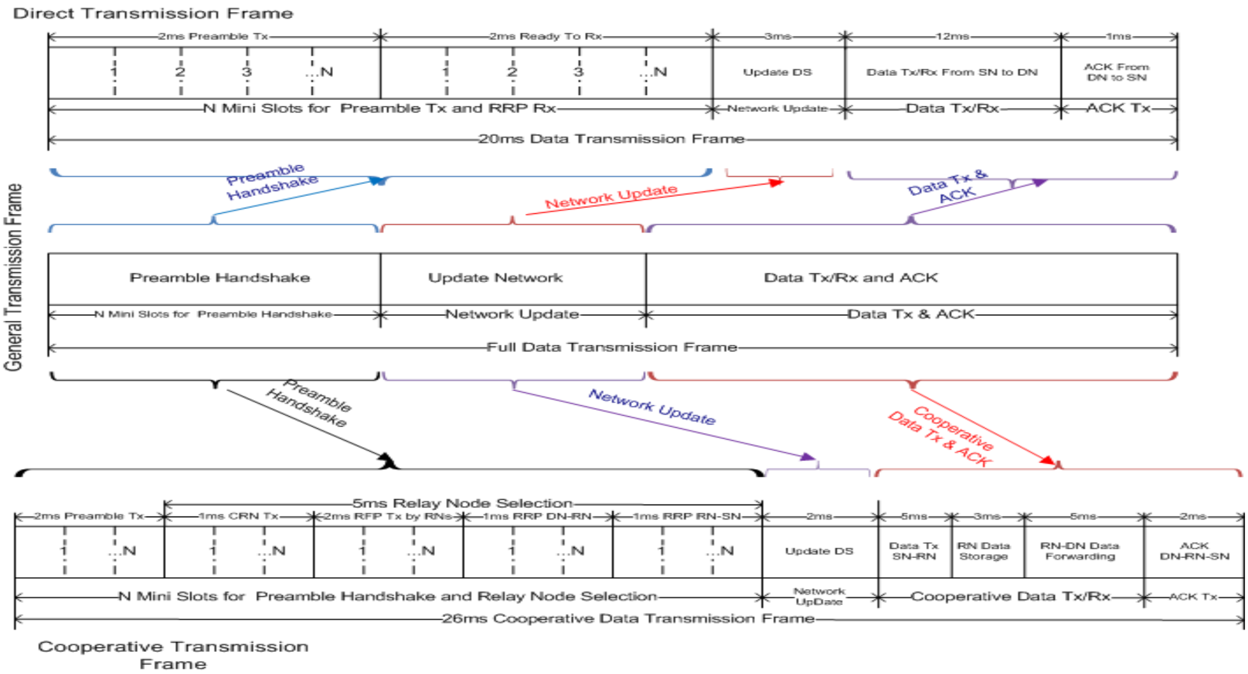

Figure 4: Transmission Frame Structure

missions begin with the beginning of each frame. Each node exists in any one of the three states, sleep, active and back-off shown in Figure 5. The network is composed of a source node, possible relay nodes R1 to RN distributed randomly in the interference range of both the source node and the destination node and the intended destination node as shown in Figure 6. In E^{2}DRCMAC protocol the retransmission phase is only carried out if the direct transmission failed or the communication path for the direct transmission does not have sufficient resources. If the direct communication path

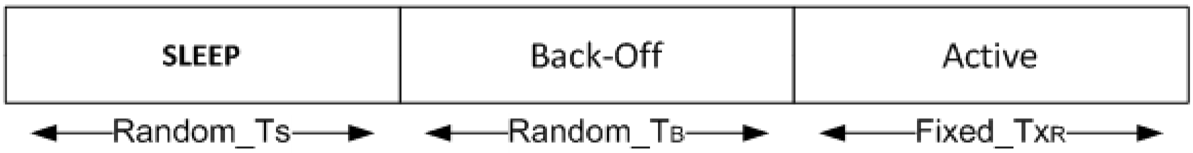

Figure 5: Sensor Node States

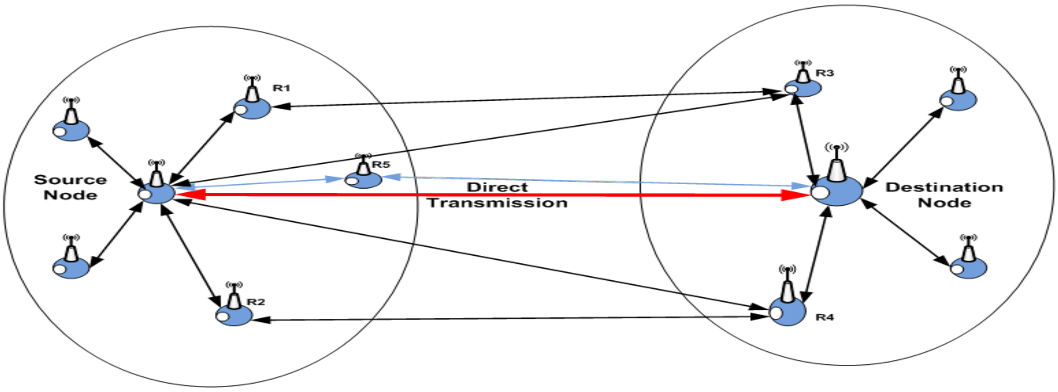

Figure 6: Cooperative WSN Architecture

between the source and destination node is near perfect then there is no need to select a cooperative relay node for the transmission. This means that the proposed protocol addresses both the cooperative and the non-cooperative schemes simultaneously all depending on the channel status between the communicating nodes within the network. The algorithms for the direct transmission, the cooperative transmission and the overhearing avoidance are now described.

3.5 Phase 1: Successful Direct Transmission

Direct transmission is employed when the SN-DN link has a CQI value that is above or equal to the chosen CQIT thus making the direct link sufficient for the data transmission to occur.

SN wakes from sleep mode after time Ts

if *Data in SN buffer* **then**

while *Channel Load NoST* $<$ *Threshold NoST* **do**

SN enters Tx/Rx Active state

SN selects a Mini slot from the preamble packet (PRP) slot

SN sends PRP to DN and broadcasts it to all RNs in the interference range

DN uses the received PRP to estimate the instantaneous SNR and CQI for the direct link

DN enters Tx/Rx Active state

DN sends RRP To SN and All RNs in the interference range

Do Algorithm 3

end

SN goes to Back-Off state for time TB

else

SN remains in Sleep State for a further time Ts

end

Algorithm 1: Successful Direct Transmission

3.6 Direct or Cooperative Transmission: The Decision

The decision as to whether to employ direct transmission or cooperative transmission is based on the Signal-to-Noise ratio of both the direct link and the cooperative relay link of the selected best relay node. When there is data to be sent between the source and sink node, the Signal-to-Noise ratio of the direct link is calculated from the preamble. If this Signal-to-Noise ratio of the direct link is greater than the threshold Signal-to-Noise ratio then the direct transmission is employed. However, if the Signal-to-Noise ratio of the direct link is less than or equal to the threshold Signal-to-Noise ratio then the cooperative relay node is selected for the cooperative transmission; and if the Signal-to-Noise ratio of the selected cooperative link is greater than the threshold then the cooperative transmission is employed. This is presented in Figure 7.

3.7 Phase 2: Cooperative Retransmission

In a case where the direct transmission fails, the process of selecting a relay node for the cooperative communication then becomes necessary. Generally the source node will send its PRP (Preamble Packet) as per normal transmission described above. If this PRP is received erroneously by the destination node, or if the CQI value calculated for that particular PRP signal is below threshold,

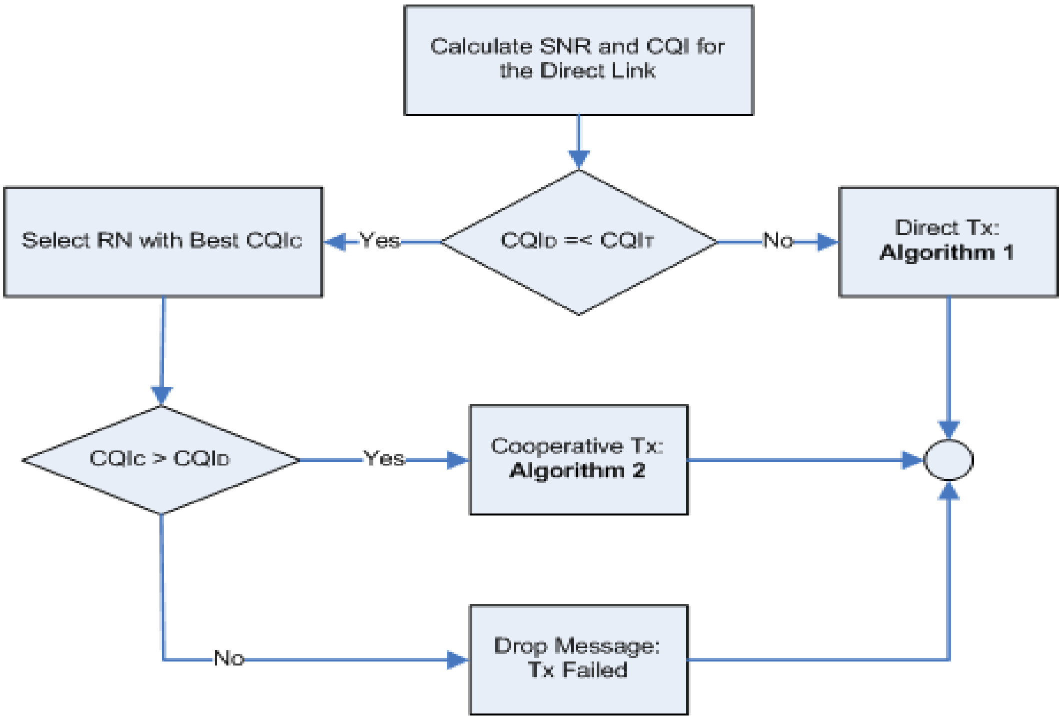

Figure 7: The Direct or Cooperation Decision Flowchart

then the need for cooperative communication arises. This MAC scheme is receiver based, so the receiving destination node will be the one that will invite possible cooperative relay nodes for its cooperative transmission methods. In a case where the direct transmission fails, the process of selecting a relay node for the cooperative communication then becomes necessary. Algorithm 2 highlights the necessary steps for data transmission during cooperative communication and the data sending process in the cooperative retransmission phase is as depicted in Figure 8 .

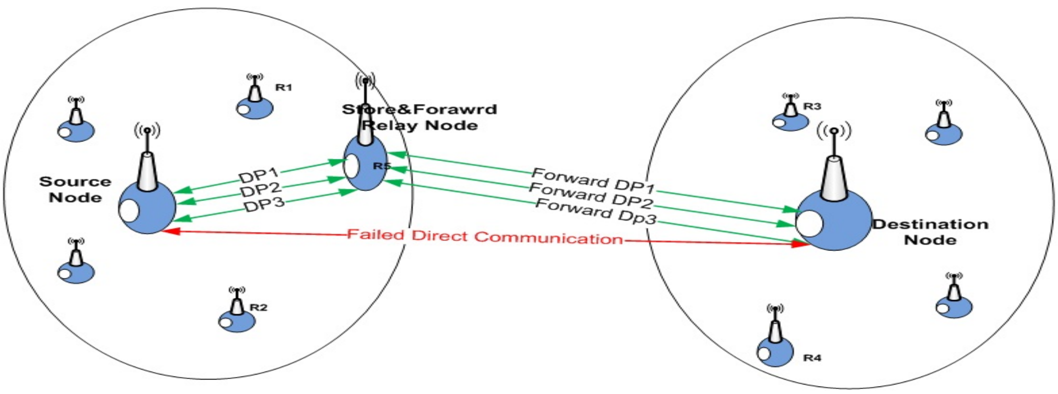

Figure 8: Cooperative Data Transmission

SN wakes from sleep mode after time Ts

if *Data in SN buffer* **then**

while *Channel Load NoST* $<$ *Threshold NoST* **do**

SN enters Tx/Rx Active state

SN selects a Mini slot from the PRP slot

SN sends preamble packet (PRP) to DN and broadcasts it to all RNs in the interference range

DN uses the received PRP to estimate the instantaneous SNR and CQI for the direct link

if $CQI_D \leq CQI_T$ **then**

DN enters Tx/Rx Active state

DN rejects PRP from SN

DN uses (Call to RN) CRN to invite Possible RNs

Possible RNs compute SNR_C and CQI_C from the CRN

RNs send RFP to DN

Based on the RFPs DN estimates instantaneous SNR_C and CQI_C

DN selects RN with Highest CQI

if $CQI_C \leq CQI_D$ **then**

Selected RN sends RRP to SN

Do Algorithm 3

else

Drop Current Message

Send Node Back to Sleep State

end

else

Do Algorithm 1

end

end

SN goes to Back-Off state for time T_B

else

SN remains in Sleep State for a further time Ts

end

Algorithm 2: Successful Cooperative Transmission

3.8 Overhearing Avoidance Technique

For both the direct and the cooperative transmissions, the overhearing avoidance follows as soon as the SN receives the RRP from either the DN or the RN respectively.

SN creates a Network Update Packet

if *Direct Transmission is used* **then**

  SN sends a Data Sending Packet (DSP) and a Turn Off Redundant Node (TORN) Packet to all the RNs in the interference range

  All RNs are sent into a Redundant Nodes List (RNL)

  Radios of nodes in the RNL are turned off to save battery life

  SN sends Data Packets to the DN

  DN sends ACK to the SN

else

  SN sends a DSP and a TORN Packet to all the RNs in the interference range except selected RN

  The RNs that were not selected to be the cooperative RN for that frame of Tx are sent into a Redundant Nodes List (RNL)

  Radios of nodes in the RNL are turned off to save battery life

  SN sends Data Packets to the RN

  RN uses Store and Forward Technique [13] to forward the data packets to the intended DN

  DN sends ACK to the SN via the RN

end

Algorithm 3: Overhearing Avoidance Technique

3.9 Packet Retransmission Mechanism

Should there be any data packet that is not transmitted correctly during the cooperative communication, the protocol employs the retransmission of that particular data packet using Selective Repeat ARQ protocol [41]. If for instance the relay node attempted to forward four data packets to the destination node and the destination node replies with a NACK indicating that the third packet was received erroneously, the relay node sends a signal to the source node to inform it that it will be retransmitting the data packet to the destination node because it was not received correctly [42]. Note that the advantage of using store and forward is that the relay node will keep all the forwarded data packets in its buffer until a positive ACK is received from the destination node confirming that all the data packets were received correctly. The relay node will then select the third data packet (DP3) in its buffer and retransmit it to the destination node again using the Selective ARQ retransmission scheme. After the selected data packet has been forwarded correctly to the destination node then a positive ACK is sent to the relay node to end the communication.

3.10 The Simulation Model

To build the event-driven simulation model for the energy model of this particular MAC scheme one assumes the behavior of the cc2240 WSN transceiver [43]. The results presented in this work were obtained from a visual c++ event driven simulator that simulated the proposed cooperative E^2DRCMAC and compared those against the direct transmission and the IEEE 802.15.4. The simulation parameters are depicted in the Table 2.

Table 2: Simulation Parameters

Parameter	*Value*
Number Of Nodes	3-100
Eon-off	0.0001J
Eoff-on	0.002J
V	5V
DATA	128bytes
ACK	12bytes
Average Packets Per Message	6
Average Neighbor Per Node	5
Packet Size	16bytes
Message Length	128bytes
Area	1000mx1000m

To be able to build the simulation model for the system, we developed the following flow of events and put them in a flow chart to explain clearly what the proposed model entails, Figure 9.
The topology and positioning of the 100 nodes WSN simulated in this work are scattered over a $1km^2$ area and are presented in Figure 10 below.

3.11 Network Packet Formats

This defines all the packet format structures used in the proposed protocol. The packet formats provided in Figure 11 are respectively the ready to forward, ready to receive, ACK, preamble request and data packet structures. For each node the Network Table packet structure maintains the information about the following network entities: Node ID: a unique identifier for each node in the

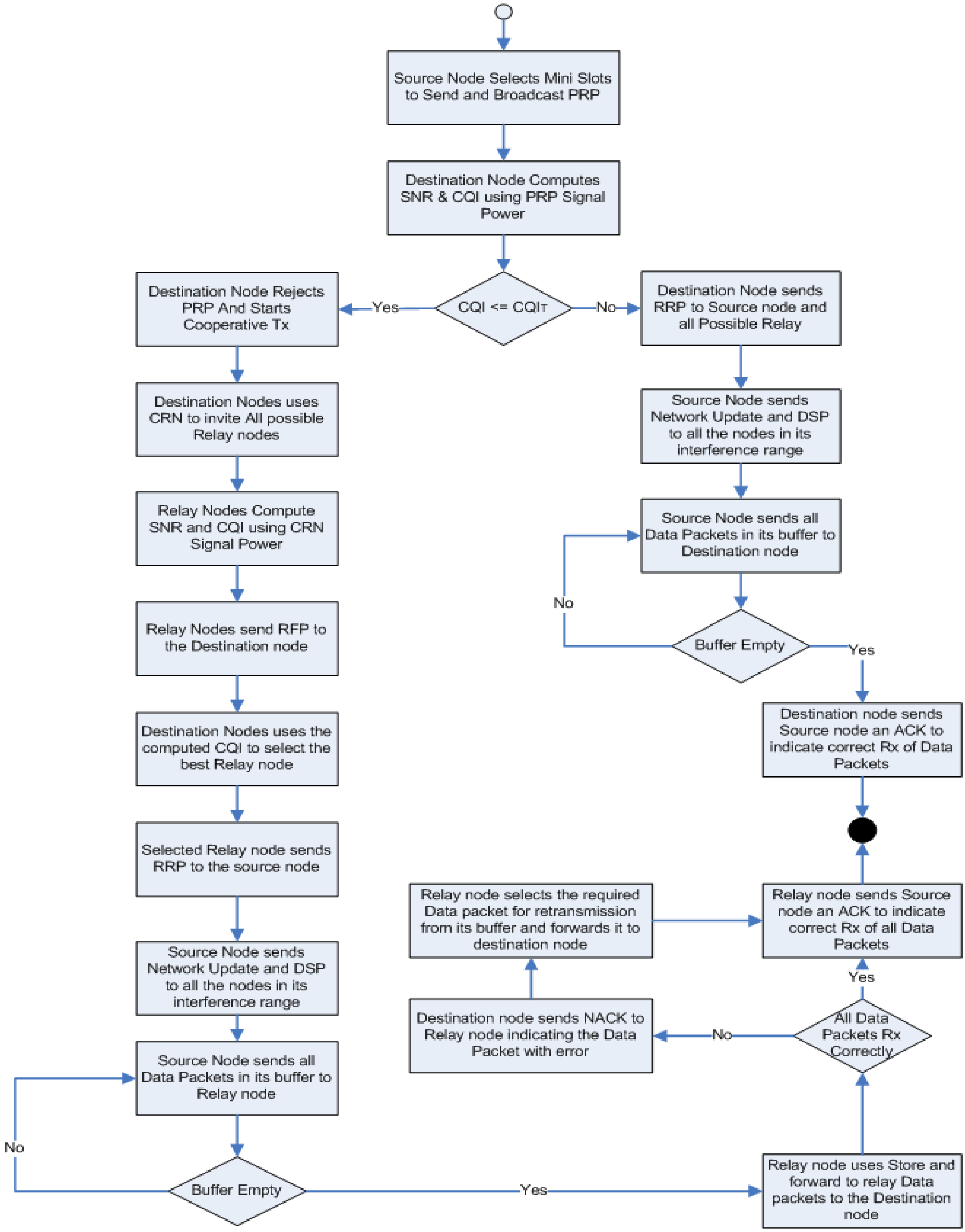

Figure 9: Simulation Flow Model

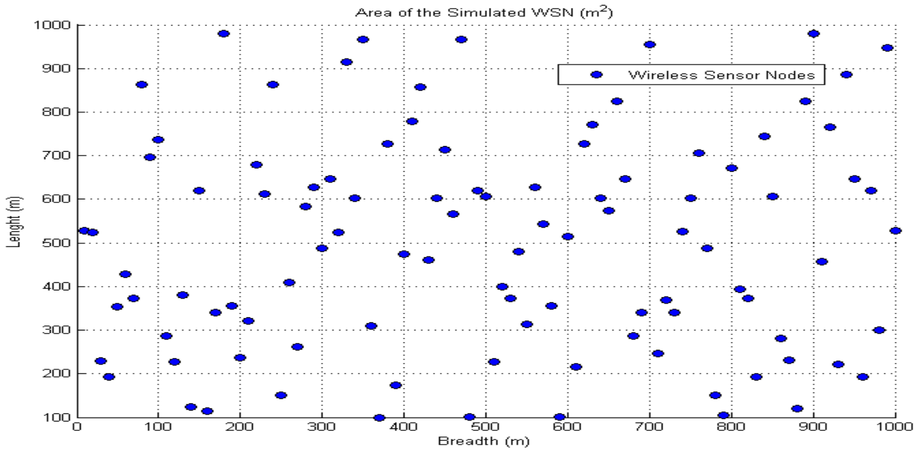

Figure 10: The Simulated Node Positioning for the E^2DRCMAC

network; Neighbors: defines all the nodes within a certain transmission radius; NoST: Number of Simultaneous Transmissions; CQI: Channel Quality Indicator and battery: Nodes remaining battery level.

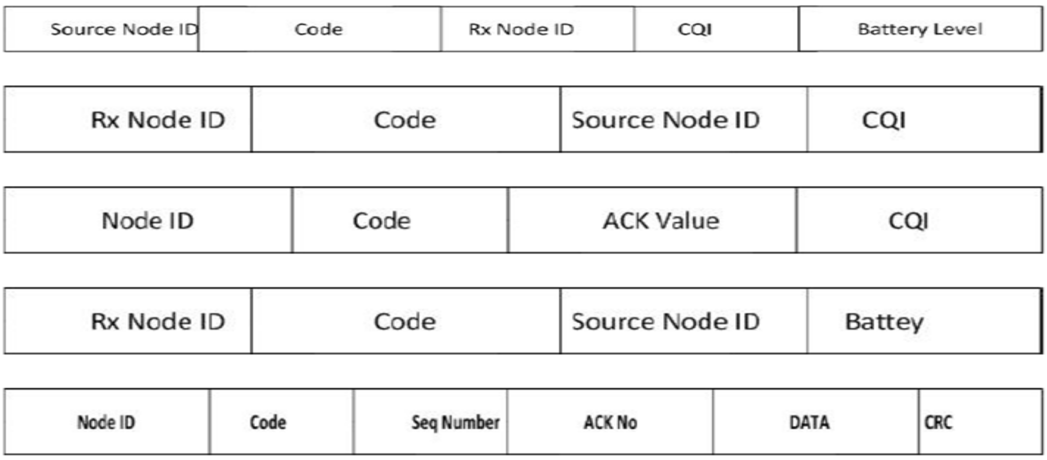

Figure 11: Network Packet Formats

Each node can exist in either Sleep, Back-Off or Active state. The node will maintain its Sleep state for a geometrically random time Ts and then check its buffer for data after each period of Ts seconds. The nodes Back-Off state is also maintained for a random time TB and then the node will check if the channel load has cleared before moving into the Active state. The Active state itself is maintained for a fixed time interval TA. A node will only move to the Active state if the channel load has been cleared or is less than a certain threshold value as discussed in Table 3. It is assumed that the node receives a message to transmit in its buffer while it is in sleep mode. The transition from one state to the next is triggered by a well-controlled event. Table 3 lists the events and state transitions corresponding to each event starting from the sleep state together with the corresponding state diagram. Let k = Channel load = NoST.

Table 3: Events and State Transitions

Event Description	*State Transition*
No data arrival & Time has not expired	Sleep To Sleep
Data Arrival & $k < $ Threshold	Sleep To Tx/Rx
Data in buffer	Tx/Rx To Tx/Rx
No data in buffer	Tx/Rx To Sleep
Data arrives & $k \geq$ Threshold	Sleep To Back-off
Timer not expired & $k \geq$ Threshold	Back-off To Back-Off
Timer expired & $k < 0$ Threshold	Back-off To Tx/Rx

The algorithm describing the steps that take place in Back-off state is as follows:

```
Set TB as Back-Off Timer
Set Channel Threshold
while Back-Off TB Not Expired do
    Obtain Current NoST
    if NoST is Less Than Allowed Threshold then
        Go To Active Tx/Rx State
    else
        Remain in Back-Off State
    end
end
```

Algorithm 4: The Back-off State

The algorithm describing the steps that take place in Sleep state is as follows:

```
Set Ts as Sleep Timer
Set Channel Threshold
while Sleep Ts Not Expired do
    Obtain Current NoST
    if There is Data In Buffer then
        if NoST is Less Than Allowed Threshold then
            Go To Active Tx/Rx State
        else
            Go To Back-Off State
        end
    else
        Remain in Sleep State
    end
end
```

Algorithm 5: The Sleep State

The algorithm describing the steps that take place in Active state is as follows:

SN selects Mini Slots For PRP transmission

DN computes SNR and CQI

if *CQI is less than CQIT* **then**

  DN rejects PRP

  DN uses CRN to invite Possible RNs and the Possible RNs compute SNR and CQI

  RNs send RFP to DN and the DN selects RN with Highest CQI

  RN sends RRP to SN and the SN sends DSP Network Update to all neighboring nodes

  SN sends Data Packets to RN

  while *Buffer is !Empty* **do**

    RN Forwards Packets To DN

    if *!All Packets Received Correctly* **then**

      DN sends NACK To RN

      RN selects Required Packet To Retransmit

      RN sends ACK To SN

    else

      RN sends ACK To SN

    end

  end

  Go To Sleep State

else

  DN sends RRP To SN and All Possible RNs

  SN sends DSP Network Update to all neighboring nodes

  SN sends Data Packets to DN

  while *Buffer is !Empty* **do**

    RN Forwards Packets To DN

    if *!All Packets Received Correctly* **then**

      DN sends NACK To SN

      SN selects Required Packet To Retransmit

      DN sends ACK To SN

    else

      DN sends ACK To SN

    end

  end

  Go To Sleep State

end

Algorithm 6: The Active Tx/Rx State

3.12 MAC Protocol Comparison

We compare the E^2DRCMAC scheme with the IEEE 802.15.4 MAC scheme (ABE) in terms of energy consumption percentages. To re-simulate the results presented in [28] we followed the algorithm and approach provided for a IEEE 802.15.4 Energy efficient MAC in [28]. The E^2DRCMAC is based on the IEEE 802.15.4 network standard. Without the relay node selection, channel estimation and the overhearing avoidance procedures, E^2DRCMAC reduces to the IEEE 802.15.4 MAC scheme as shown in Figure 12. In simulation results of Figure 13, it is shown how the percentage in energy consumption is reduced by introducing cooperative node selection, channel estimation and overhearing avoidance in IEEE 802.15.4 based MAC scheme.

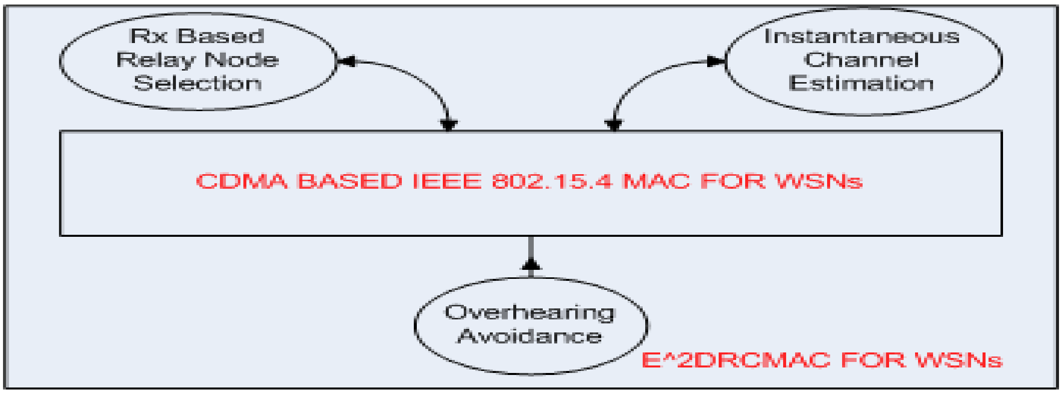

Figure 12: E^2DRCMAC in Relation to the 802.15.4 MAC

3.13 Performance Evaluation Metrics

To evaluate the performance of the proposed MAC protocol,authors have selected and investigated the following performance metrics:

(a) **Percentage Energy Consumed:** The percentage energy consumed per node represents the amount of energy each node consumes per frame of transmission over its total available energy when the simulation began.

(b) **Throughput:** Throughput represents the successfully received packets per node per frame. This metric measures the effectiveness that the MAC scheme has in terms of successful packet delivery.

(c) **Packet Delivery Ratio:** Packet delivery ratio measures the ratio of the total number of packets successfully delivered at the destination to the total number of packets sent by the source nodes in the WSN.

(d) **Packet Loss:** Packet loss measures the rate at which the packets are lost in the WSN.

3.14 Simulation Results and Discussion

We simulated a Poisson packet arrival model where each node in the network is a source node at the beginning of each frame where only a predetermined number, less or equal to a given threshold value, of source nodes can begin sending their data in every frame where each frame lasts up to a simulated 20 milliseconds. In these cases mentioned, the E^2DRCMAC outperforms the scheme in [28] in terms of percentage in the energy savings and throughput as confirmed by the simulation results shown in Figure 13 and Figure 14 respectively.

The results of Figure 13 show the percentage energy consumption vs. the packet per second load. The schemes that were investigated are the ABE scheme, the ABE scheme with periodical sleep both of [28] and the proposed E^2DRCMAC. The results have been compared with the published work of [28]. Using the ABE scheme together with periodical sleep within active periods the energy consumed reduces dramatically when compared to using just the ABE scheme without periodic sleep. The percentage in energy consumption further reduces as the cooperation and overhearing avoidance were introduced as evident below. Figure14 shows the comparison in throughput sim-

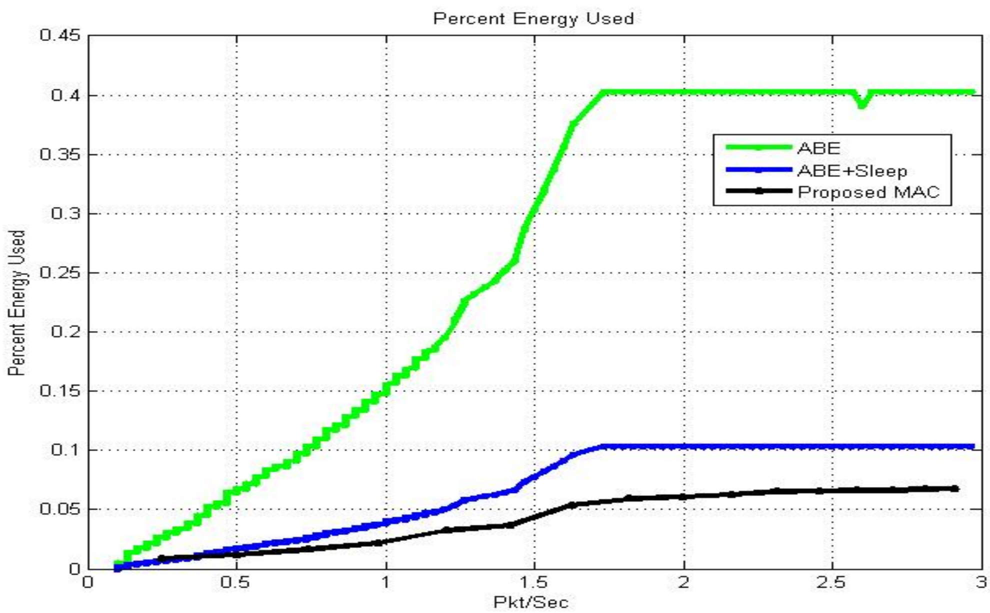

Figure 13: Energy Consumption vs. Packet per Second Load

ulated for both the IEEE 802.15.4 MAC scheme and our E^2DRCMAC. The throughput represents the successfully received packets per node per frame. It shows that for the offered load, at values between 0 and 2.1 packets per second, the E^{2}DRCMAC protocol provides better throughput than the IEEE 802.15.4MAC scheme.

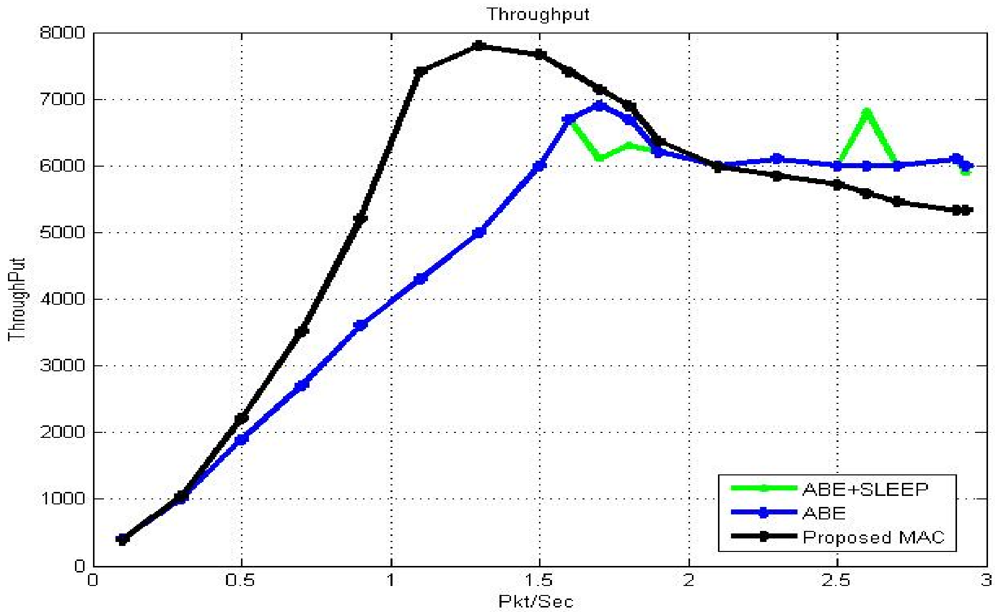

Figure 14: Throughput vs. Packet per Second Load

The positive difference gets larger, reaching its peak value (about 56% increase) at around 1.3 packets per second. This is due to the fact that on top of the IEEE 802.15.4, E^{2}DRCMAC adds cooperation, providing better packet delivery rates for up to a certain load. Also, due to the diversity gain brought by cooperation, the decrease in the BER results in more packets being transmitted successfully hence enhancing the system throughput.

Figure15 depicts the compared packet delivery ratio for the cooperative phase of E^{2}DRCMAC, IEEE 802.15.4 and direct transmission phase of the E^{2}DRCMAC. The E^{2}DRCMAC shows an improvement over the IEEE 802.15.4 Standard MAC protocol especially at the lower node densities. The improvement in packet delivery, ratio, however reduces as the node density increases but still gives about 4% improvement at node density around 0.14 nodes/m^2.

Figure16 depicts the packet loss rates over the packet per second loads. It can be seen that the rates of the packets lost in the WSN increases with increasing packet arrival loads in the network.

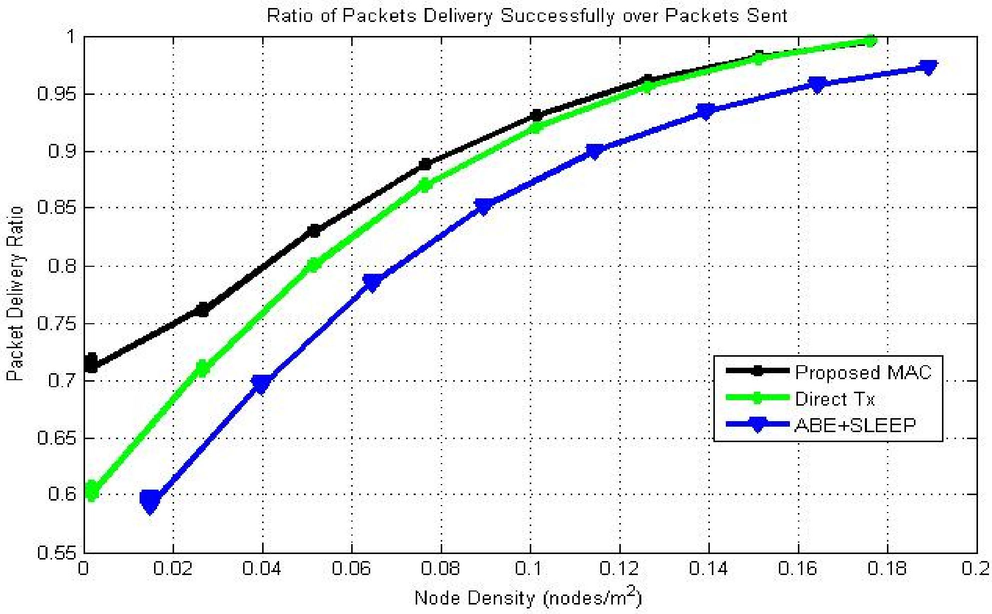

Figure 15: Packet Delivery Ratio

Figure16 further shows that the E^{2}DRCMAC outperforms the traditional IEEE 802.15.4 MAC with ABE and its enhanced ABE + Sleep versions, thereby providing higher delivery rates.

Figure 17 depicts the total number of packets generated as a result of the Poisson arrival pro-

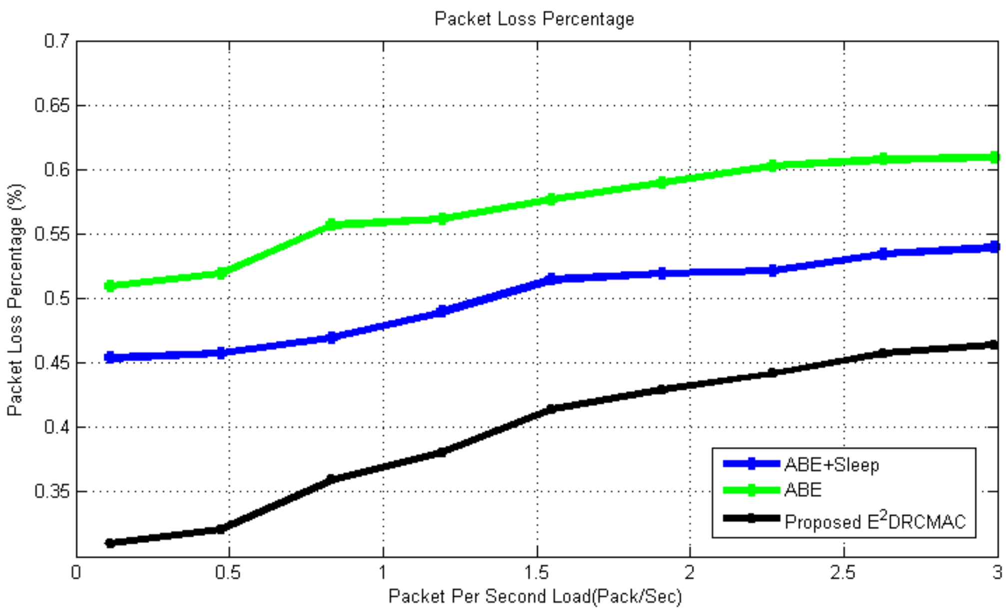

Figure 16: Packet Loss Percentage for the E^{2}DRCMAC

cess. This result is taken over the increasing packet per second loads. Figure 17 also shows the total number of packets received at the destination node for the proposed E^2DRCMAC, the ABE and the ABE + Sleep schemes both of the IEEE 802.15.4 MAC [28]. The results presented validate that the E^2DRCMAC scheme has a better performance since it ensures that more packets are delivered to the destination node for the same range of packet per second loads.

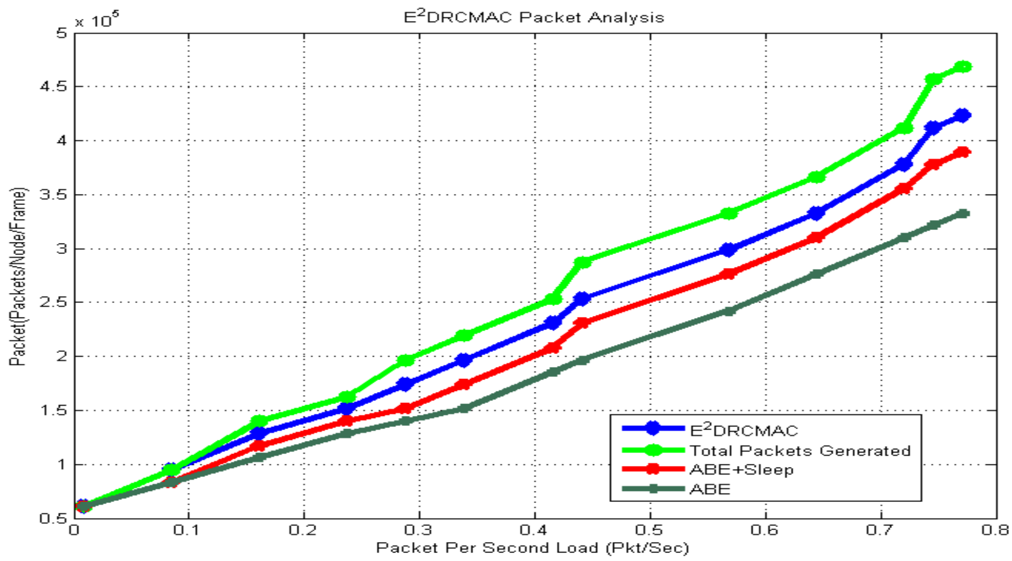

Figure 17: Total Packets Generated and Total Packets Delivered for the E^2DRCMAC,ABE and ABE + Sleep MAC Schemes

3.15 Conclusion

This chapter proposed a cooperative receiver based MAC protocol for WSNs that addressed the deficiencies relating to overhearing communications in cooperative WSNs. The protocol combines cooperative diversity with overhearing avoidance to exploit the spatial diversity and reduce energy consumption by minimizing collisions and overhearing amongst neighboring nodes. A receiver based cooperative relay node selection approach was used to select the cooperative relay node with the best channel quality to the destination. An overhearing avoidance scheme to turn off redundant nodes was added to enhance the QoS and network lifetime of the IEEE 802.15.4 WSNs MAC schemes. The proposed MAC protocol minimized the effects of overhearing by sending all neighboring nodes that are not required for the transmission to sleep each time before beginning the data sending process. Furthermore, this chapter validated the simulation model and the results by performing a protocol comparison with an existing IEEE 802.15.4 MAC for wireless sensor networks. The proposed MAC was shown to perform better than the standard IEEE 802.15.4 MAC in terms of energy conservation, throughput and packet delivery.

Chapter 4:

4 Analysing the Proposed MAC Scheme

This dissertation presents an analytical approach to analyze the proposed MAC protocol for WSNs. Other MAC schemes only consider experimental or pragmatic approaches. The analytical framework of the E^2DRCMAC is based on Poisson message arrivals and a Markov based channel estimation for cooperative relay node selecton under Rayleigh fading conditions. To validate the analytical framework of the proposed MAC scheme, the analytical results are compared with the simulation results and the close relation proves that the analytical framework agrees with the simulated results. This chapter presents the analytical approach used to find the message delay and channel quality for the E^2DRCMAC proposed in chapter 3. The chapter further provides the analytical approach to finding the energy consumed per node in the network and thus evaluate the entire network performance in terms of energy consumed. Firstly, the energy analysis for the direct transmission phase is presented followed by the energy analysis of the cooperative relaying phase. The chapter compares and discusses the analytical and simulation results then makes concluding remarks on the simulated and mathematical behaviour of the system.

4.1 Packet Delay Analysis

With cooperative MAC schemes come reduced retransmission probabilities due to reduced packet error rates. This will in turn reduce the time delay with which the packets reach their respective destination nodes. For each packet to be sent successfully for both the direct transmission phase and the cooperative retransmission phase, the time durations are respectively given by (1) and (2).

$$T_{DTx} = T_{PRP} + T_{CQI_{SN}} + T_{RRP} + T_{NDS} + T_{DATA} + T_{ACK} \tag{1}$$

$$T_{CoopTx} = T_{PRP} + T_{CQI_{SN}} + T_{CRN} + R_N * T_{RFP} + T_{NDS} + T_{CQI_{RN}} + T_{DATA} + T_{DATA_{RN}} + T_{ACK} \tag{2}$$

Where T_{DTx} is the total time duration for the direct transmission phase, while T_{CoopTx} is the total time duration for the cooperative transmission phase, T_{PRP} is the duration for which source node sends the preamble request, $T_{CQI_{SN}}$ is the duration needed for the calculation of the CQI by the destination node, T_{RRP} is the transmission time of a ready to receive reply message sent by the destination node, T_{NDS} is the transmission time required for the source node to perform network updates, T_{DATA} is time required to send the data packet to either the cooperating nodes or the destination node, R_N*T_{RFP} is the time for relay nodes to send their ready to forward packets to the destination node, $T_{CQI_{RN}}$ is the time required for the calculation of the CQI values of all the possible relay nodes, T_{ACK} is the time required to send and receive an acknowledgment signal from the destination back to the source node. $T_{DATA_{RN}}$ is the time required by the cooperating relay nodes to forward the data to the destination node. Now the time duration for an unsuccessful packet transmission that required a cooperative retransmission mechanism is given by (3).

$$T_{CoopReTx} = T_{PRP} + T_{CQI_{SN}} + T_{CRN} + R_N * T_{RFP} + T_{NDS} + T_{CQI_{RN}} T_{DATA} + T_{DATA_{RN}} + T_{ACKWait} + T_{NDS_{RN}} + T_{ARQTx} + T_{ACK} \quad (3)$$

Where $T_{CoopReTx}$ is the total time duration for the cooperative retransmission mechanism for lost packets, $T_{ACKWait}$ is the time used up when the source node waits for an ACK signal that does not arrive due to packet loss, T_{ARQTx} is the time to retransmit the lost packet using selective ARQ repeat. Let there be X number of total direct transmissions and C number of total cooperative transmissions where P_F is the probability of failed cooperative transmissions. The total packet delay is then given by (4).

$$T_{DEL} = X * T_{DTx} + C * T_{CoopTx} + \left(\frac{P_F}{1 - P_F}\right) * T_{CoopReTx} \quad (4)$$

Where T_{DEL} is the total packet delay for the network. These times may be assumed to be the same for all the transmissions since in the simulation the same distances are kept for the interference ranges.

4.2 Channel Model

This work modeled a one hop cooperative relay network as shown in Figure 18. The received signal

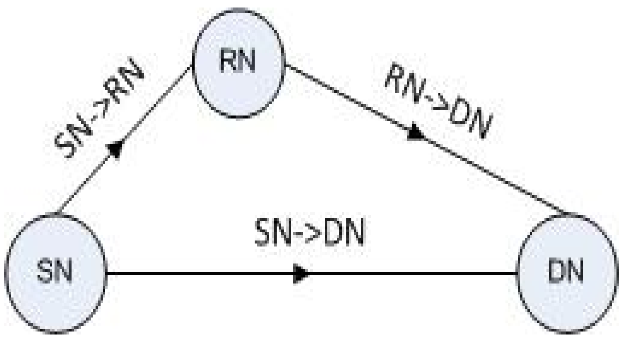

Figure 18: Cooperative Relay Network

from the SN at the DN, $R_{SD}(t)$ and at the RN, $R_{SR}(t)$ are respectively given as

$$R_{SD}(t) = \sqrt{P} * T_X(t) * H_{SD} + n1(t) \quad (5)$$

$$R_{SR}(t) = \sqrt{P} * T_X(t) * H_{SR} + n2(t) \quad (6)$$

where P is the predetermined transmitting power, Tx(t) is the transmitted signal, n1(t) and n2(t) are the AWGN components for the respective links. H_{SD} is the channel coefficient for the SN-DN link while H_{SR} is the channel coefficient for the SN-RN link. If cooperative communication is used, the received signal from the relay at the destination is given as

$$R_{RD}(t) = \sqrt{P} * T_{XR}(t) * H_{RD} + n3(t) \quad (7)$$

where $T_{XR}(t)$ is the signal generated by the relay when cooperation is necessary and n3(t) is the AWGN component for the RN-DN link. H_{RD} is the channel coefficient for the RN-DN link.

At any point, the transmission channel may be categorized as either 'good' or 'bad' depending on the estimated CQI. For the SN to know whether to use direct transmission or to employ a cooperative transmission via a RN it needs to determine or estimate whether the channel between the SN and the DN is 'good' or 'bad' using the CQI. The CQI is dependent on the Signal-to-Noise ratio as follows [7]

$$CQI = \begin{cases} 0 & \text{if SNR} \leq -16 \\ |\frac{SNR}{1.02} + 16.16| & \text{if -16} \leq \text{SNR } \leq 14 \\ 30 & \text{if SNR} \geq 14 \end{cases} \quad (8)$$

A 'bad' channel implies that cooperative communications is to be used. Such a channel is characterized by an estimated CQI value CQI_{SD} that is less than a certain CQI threshold value CQI_T which can easily be

$$P(CQI_{SD} < CQI_T) = P(SNR_{SD} < SNR_T) \quad (9)$$

For the Rayleigh faded channel characterized by H_{SD}, the probability of a 'bad' channel is given by [25]

$$P(SNR_{SD} < SNR_T) = 1 - e^{(\frac{SNR_T}{SNR_{SD}})} \quad (10)$$

where SNR_{SD} is the instantaneous Signal-to-Noise ratio for the SN-DN link and SNR_T is the Signal-to-Noise ratio threshold defining the minimum required CQI value for which the destination can receive the signal from the source node without error or need of relaying. It follows that the probability of a 'good' channel is given by

$$P(SNR_{SD} \geq SNR_T) = e^{(\frac{SNR_T}{SNR_{SD}})} \quad (11)$$

According to Algorithm 2, the probability that a node is admitted onto the network for cooperative transmission can be written as

$$P(SNR_{SD} < SNR_T)P(SNR_{RD} \geq SNR_{T_{RD}}) = \left[1 - e^{\left(\frac{SNR_T}{SNR_{SD}}\right)}\right] e^{\left(\frac{SNR_{T_{RD}}}{SNR_{RD}}\right)} \quad (12)$$

where SNR_{TRD} is the threshold Signal-to-Noise ratio used for the RN-DN link.

4.3 Energy Analysis

Energy consumption in wireless sensor networks is analyzed by looking at each node in the network based on the theoretical node energy consumption analysis data [44]. Each wireless sensor node is comprised of a number of modules which enable it to perform its functions. These modules include the sensor module, the power supply, the microprocessor and the transceiver module. However in this dissertation the energy consumed by the sensor and the transceiver module only is looked at. To obtain the total energy consumed in each node, the effects that each module will have on the total energy consumption is studied. Then the energy consumption model of a wireless sensor network E^2DRCMAC scheme is presented, which combines the energy consumed by each module in each state or state transition that the node may be going through and this is compared with the analytical result yielded by the same model. However, when developing the energy model for wireless sensor networks in a MAC scheme one must take into consideration the possible frame collisions, contention and control message exchanges. The MAC scheme for which this energy model is proposed is a cooperative MAC protocol in which a node may exist in three different states and seven different state transitions as depicted in Figure 19.

4.4 Network and Node Model

For the purposes of the E^2DRCMAC scheme, the message arrivals follow a Poisson distribution with an average number of packets per message (Av_{Pack}) and average packet length fixed at L_{Pack} bytes. Besides each node generating its own messages, it may also be prompted to cooperatively relay messages from other nodes. Assuming an average message arrival rate λ, the probability that the number of messages generated per node in the WSN is X at time T is given by the distribution [45]

$$P(X = k) = \frac{(\lambda T)^k}{k!} * e^{-\lambda T} \qquad \forall\, k > 0 \quad (13)$$

Consider a WSN scenario with a total of N nodes. In this network, nodes are fixed and immobile for their entire battery life. Now let N_S be the total number of nodes in the Sleep State; N_B be the total number of nodes in the Back-Off State and N_A be the total number of nodes in the Active (Tx/Rx) State. Furthermore, the total number of Active nodes is divided into nodes transmitting directly to the destination, X_D, and nodes transmiting to the destination via a cooperative relay node, X_R, such that

$$N_A = X_D + X_R \qquad X_D \geq X_R \tag{14}$$

This gives rise to

$$N = N_S + N_B + N_A \tag{15}$$

Assumptions:

The maximum number of active nodes is assumed to be Ω. It is assumed that any communication that requires a cooperative relay may only use a relay node that is already in its Active state. This means that no node wakes up from Sleep state with a cooperative message to transmit unless there is already a node transmitting in the network, or if so, this message is dropped. It then follows that any number of messages can arrive during the frame of transmission and in any of the three states while cooperative messages can only be relayed by a node in the active state. It is further assumed that when the blocking threshold (Ω) is reached, no new nodes can be admitted onto the Active state in the network.

Each node in the network may exist in any one of the three states presented in Figure 19. A node is in Sleep state when it has no data to transmit. A node is in the Back-off state when it has data to transmit but the channel is already occupied by a high number of transmissions (Ω). A node is in Active state when it is either sending, receiving or relaying data. The state space for the node based Markovian process is

$$S = [SLEEP; BackOff; Active(Tx/Rx)] \tag{16}$$

The transition probability matrix for the node states (P_{Node}) may then be constructed as follows

$$P_{Node} = \begin{vmatrix} P_{SS} & P_{SA} & P_{SB} \\ P_{AS} & P_{AA} & 0 \\ 0 & P_{BA} & P_{BB} \end{vmatrix} \tag{17}$$

The state probabilities are such that P_A is the probability of SN in Active, P_B is the probability of SN in Back-Off and P_S probability of SN in Sleep. For a node currently in state Si, the steady state probabilities can be obtained by solving

$$\Pi_{Si} = \Pi_{S_{i-1}} P_{Node} \tag{18}$$

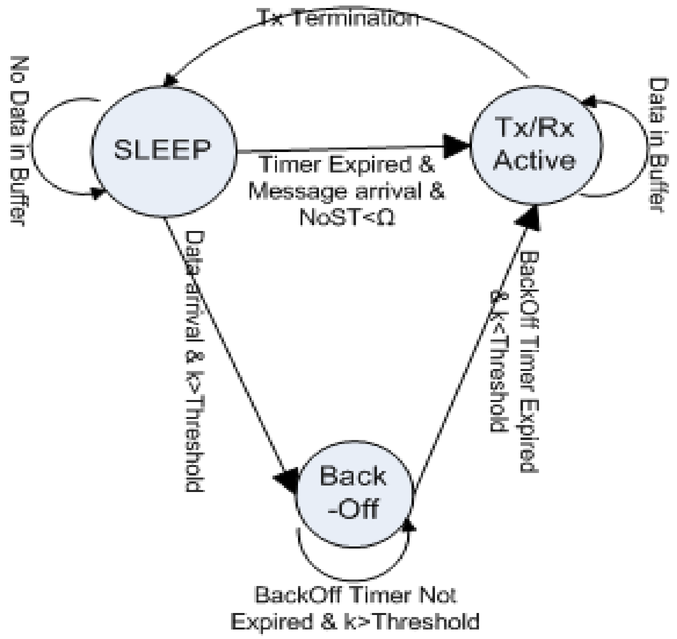

Figure 19: Node State Diagram

and for all S states

$$\sum_{i=0}^{S} \Pi_i = 1 \tag{19}$$

This solves the steady state probability vector

$$\Pi = [\Pi_S, \Pi_B, \Pi_A] = [P_S, P_B, P_A] \tag{20}$$

For the 3 State Markov process of Figure 19, we define the possible scenarios for the node Markov process to evolve. Given that the network has X nodes in the Active (Tx/Rx) state then

(a) For the node in Sleep state we investigate the following 3 scenarios

(i) If the nodes′ sleep timer Ts expires, the node has x message arrivals in its buffer and X $< \Omega$; then the node moves to Active state with probability, P_{SA}, given by

$$P_{SA} = f_{T_S} * P(X < \Omega) * f_A(x) \tag{21}$$

where f_{T_S} is the probability that the sleep time Ts has expired and is given by the binomial process which can be written as

$$f_{T_S} = b(N_S, 1, \mu_S) \tag{22}$$

(ii) If the nodes′ sleep timer Ts expires, the node has x message arrivals in its buffer and X $> \Omega$; then the node moves to Back-off state with probability P_{SB}, given by

$$P_{SB} = f_{T_S} * P(X \geq \Omega) * f_A(x) \tag{23}$$

(iii) If no new messages arrive (x=0) for the node the node remains in Sleep state with probability Pss, given by

$$P_{SS} = f_A(x) \qquad for\ x = 0 \tag{24}$$

(b) For the node in Back-off state we investigate the 2 following scenarios

(i) If the nodes back-off timer T_B expires and X < Ω; then the node moves to Active state with probability, P_{BA}, given by

$$P_{BA} = f_{T_B} * P(X < \Omega) \tag{25}$$

where f_{T_B} is the probability that the back-off timer T_B has expired and is given by the binomial process which can be written as

$$f_{T_B} = b(N_B, 1, \mu_B) \tag{26}$$

(ii) If X ≥ Ω; then the node will remain in back-off state. The probability of this occurance, P_{BB}, is given by

$$P_{BB} = P(X \geq \Omega) \tag{27}$$

(c) For the node in Active state we investigate the 2 following scenarios

(i) While the node has data to be transmitted in its buffer, the node will remain in transmit mode with probability P_{AA}, which can be written as

$$P_{AA} = 1 - f_{T_z} \qquad for\ z = 1 \tag{28}$$

given that f_{T_z} is the probability that the node terminated its transmission.

(ii) If the node terminates its transmission process then the node transitions from Active to Sleep state with probability P_{AS}, which can be written as

$$P_{AS} = f_{T_z} \qquad for\ z = 1 \tag{29}$$

The times T_S and T_B are the sleep and back-off times and they both follow a geometric distribution. The time T_A defines how long a node spends in active state given K packets to transmit and is given by

$$T_A = \frac{N_P * M_S * K}{D_{Tx}} \tag{30}$$

where NP is the total number of packets to transmit, Ms total number of messages to transmit and DTx is the Data Transfer Rate. Therefore the message transmission rate, μ_A, can be written as

$$\mu_A = \frac{1}{T_A} = \frac{D_{Tx}}{N_P * Ms * K} \tag{31}$$

The time duration, Ts, each node spends in sleep state is given by a geometric distribution with mean μ_s. The expected value of Ts, E(Ts), is given as

$$E(T_S) = \frac{1}{\mu_S} \tag{32}$$

with a variance, var(Ts), given as

$$var(T_S) = \frac{(1-\mu_S)}{\mu_S} \tag{33}$$

The time duration, TB, each node spends in Back-Off state is given by a geometric distribution with mean μ_B. The expected value of TB, E(TB), is given as

$$E(T_B) = \frac{1}{\mu_B} \tag{34}$$

with a variance var(TB), given as

$$var(T_B) = \frac{(1-\mu_B)}{\mu_B} \tag{35}$$

Consider the Markov process presented in Figure 20. The Markov process evolves with the renewal of each frame. The state space of the network based Markovian process is

$$S_N = [X] \tag{36}$$

where X is the number of active nodes in the current frame F.

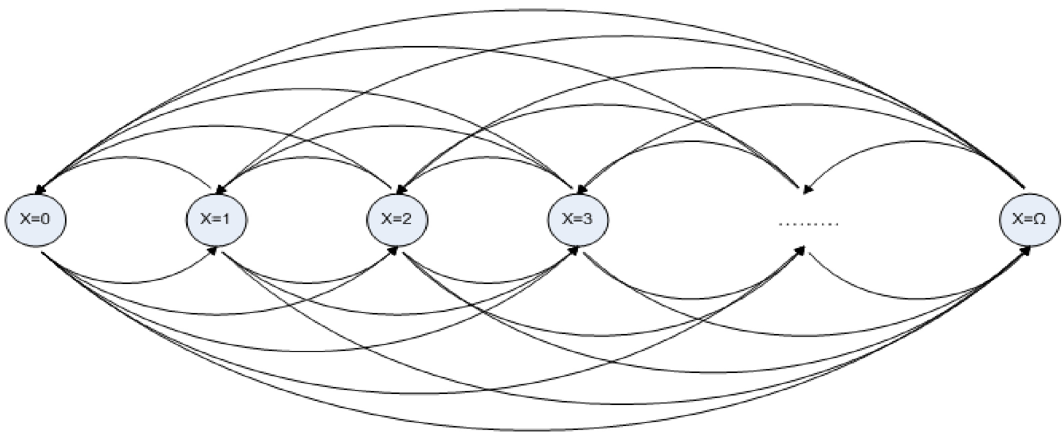

Figure 20: Networkwise Markov Chains

The transition probability matrix, P = P_{ij}, may then be constructed as follows

$$P = \begin{pmatrix} P_{00} & P_{10} & \cdots & P_{\Omega 0} \\ P_{01} & P_{11} & \cdots & P_{\Omega 1} \\ \vdots & \vdots & \ddots & \vdots \\ P_{0\Omega} & P_{1\Omega} & \cdots & P_{\Omega\Omega} \end{pmatrix} \quad (37)$$

where P_{ij} is the probability of moving from having X=i active nodes during frame F to having X=j active nodes in frame F+1. For the Markov process of Figure 20, we can define three possible scenarios. If we consider that during frame F, X=i nodes are active then

(i) If X=i $< \Omega$, then a node with a new message can enter Active state during the next frame, F+1. This is if a message arrival occured for that particular node during frame F. Any one of the i Active nodes can terminate its transmission with a probability, μ_A. Let the number of terminations during any frame F be z $\leq$ i. We can then conclude that the number of new message arrivals during frame F in the network can be given by j-i+z. This is given by the probability

$$\sum_{z=0}^{i} f_A(j-i+z) * f_T(z) \quad i \leq \Omega \ \& \ j \geq i \quad (38)$$

where $f_A(x)$ is the probability that the network had 'x' arrivals at the beginning of frame F+1 which can be defined as

$$f_A(x) = b(N-i, x, \mu_S) \quad (39)$$

$f_T(z)$ is the probability that 'z' nodes terminated their transmissions during the frame F which can be written as a Binomial process

$$f_T(z) = b(i, z, \mu_A) \quad (40)$$

(ii) If the current number of active nodes, X = i $\leq \Omega$ and the terminations are i-j then no more nodes may be admitted into the network as they have message arrivals for frame F+1. This probability can be written as

$$\sum_{z=i-1}^{i} f_A(j-i+z) * f_T(z) \quad i \leq \Omega \ \& \ j \leq i \quad (41)$$

(iii) Finally, if it happens that the current number of active nodes X = i = Ω, then some nodes with message arrivals will not be allowed to enter the active state due to the fact that i-j node terminated during frame F. This probability can be written as

$$f_T(i-j) \qquad i = \Omega \quad \& \quad j \leq i \quad (42)$$

This solves the Markov process with the state transition probabilities, P_{ij}, given as

$$P_{ij} = \begin{cases} \sum_{z=0}^{i} f_A(j-i+z) * f_T(z) & i \leq \Omega \ \& \ j \geq i \\ \sum_{z=i-1}^{i} f_A(j-i+z) * f_T(z) & i \leq \Omega \ \& \ j \leq i \\ f_T(i-j) & i = \Omega \ \& \ j \leq i \\ 0 & Otherwise \end{cases} \quad (43)$$

The steady state probabilities are obtained by solving

$$\Pi_j = \sum_{i=0}^{\Omega} \Pi_i P_{ij} \quad (44)$$

and

$$\sum_{j=0}^{\Omega} \Pi_j = 1 \quad (45)$$

4.5 Energy Consumption Model

Generally the energy consumed per node per frame of transmission is given as

$$E_S + \Pi_B * E_B + \Pi_A * E_A \quad (46)$$

where E_S, E_B and E_A are the energy a node consumes in the sleep, back-off and active state respectively. The energy consumed by a node in Sleep state, E_S, is given by

$$E_S = V \sum^{Ts} I_S + f_T(z) E_{AS} \quad (47)$$

where V is the sensor nodes′ working voltage, Is is the transceiver current in sleep, all adopted from the Chipcon data [46], $f_T(z)$ is the probability of termination for any node 'z', E_{AS} is the energy required to switch from Active to Sleep once the node terminates its transmission. The energy consumed by a node in Back-off state, E_B, is given by

$$E_B = V \sum^{T_B} I_B + P(X \geq \Omega) E_{SB} \quad (48)$$

where I_B is the transceiver current in Back-off adopted from [46] and E_{SB} is the energy required to switch from Sleep to Back-off. The energy consumed by a node in Active transmit state when transmitting directly to a single receiving node, E_{A_D}, is given by

$$E_{A_D} = \frac{V * L_{Pack}}{2D_{Tx}} \sum^{T_A} (I_{Tx} + I_{Rx}) + P(X < \Omega)(E_{BA} + E_{SA} * f_A(x)) \quad (49)$$

where I_{Tx} and I_{Rx} are the transceiver currents for transmiting and receiving respectively, $f_A(x)$ is the probability that x messages arrived, E_{SA} is the energy required to switch from Sleep to Active and E_{BA} is the energy required to switch from Back-off to Active. L_{Pack} is the length or packet size and D_{Tx} is the data transmission rate. Note that the energy consumed by the receiving node is also captured in the active state (48). The energy consumed by a node in Active transmit state when transmitting via a cooperative relay node to a single receiving node, E_{A_C}, is given by

$$E_{A_C} = \frac{2V * L_{Pack}}{3D_{Tx}} \sum^{T_A} (I_{Tx} + I_{Rx}) + P(X < \Omega)(E_{BA} + E_{SA} * f_A(x)) \tag{50}$$

Note that the energy consumed by the receiving process of both the relay and the destination node is also captured in the active state. The transmitting (forwarding) process of the cooperative relay node is also captured in the active state (49), Given X=i active nodes in the network, the total energy consumed per frame of direct transmission, E_D, is then given by

$$E_D = \frac{V}{2} \left(\sum_{i=0}^{\Omega} i\Pi_i \left[\Pi_A \sum^{T_A} \frac{L_{Pack}}{D_{Tx}} (I_{Tx} + I_{Rx}) + P(X < \Omega)(E_{BA} + E_{SA} * f_A(x) \right] + \sum_{i=0}^{\Omega} i\left(1 - \Pi_i\right) \left[\Pi_B \sum^{T_B} I_B + \Pi_S \sum^{T_S} I_S \right] \right) \tag{51}$$

and the energy consumed per node per frame of cooperative transmission, E_C, is given as

$$E_C = \frac{2V}{3} \left(\sum_{i=0}^{\Omega} \sum_{m=0}^{i} \left(i - \frac{m}{2}\right) R_i^m \left[\Pi_A \sum^{T_A} \frac{L_{Pack}}{D_{Tx}} (I_{Tx} + I_{Rx}) + P(X < \Omega)(E_{BA} + E_{SA} * f_A(x) \right] + \sum_{i=0}^{\Omega} i\left(1 - \Pi_i\right) \left[\Pi_B \sum^{T_B} I_B + \Pi_S \sum^{T_S} I_S \right] \right) \tag{52}$$

where Ri^m = m/i is the ratio that out of i active nodes, m are employing a relay (and m are being used as cooperative relays). The combinations of this occurance are such that

(a) if i = 0; then: No active direct transmission and No active cooperative transmission.

(b) if i = 1; then: k=1 active direct transmission and No active cooperative transmission.

(c) if i = 2; then:

- (i) k=2 active direct transmissions and No active cooperative transmission OR
- (ii) k=1 active direct transmission and m=1 active cooperative transmission OR
- (iii) No active direct transmissions and k=2 active cooperative transmission.

This means that, given the number of active node X=i, one can compute the number of the nodes that are cooperative relays, m, as

$$m = \begin{cases} 0 & \forall\ i \leq 1 \\ i - k & \forall\ 2 \leq i \leq \Omega\ \ and\ \forall\ 0 \leq k \leq i \end{cases} \tag{53}$$

The lifetime expectancy for each node is then given by

$$T_{Node} = \frac{InitialBatteryEnergy}{E_D + E_C} \quad (54)$$

The initial Battery Energy is assumed to be distributed randomly between 0-10 (J) for each node in the network. Initially, each node in the network resumes its operation with the battery level presented in Figure 21.

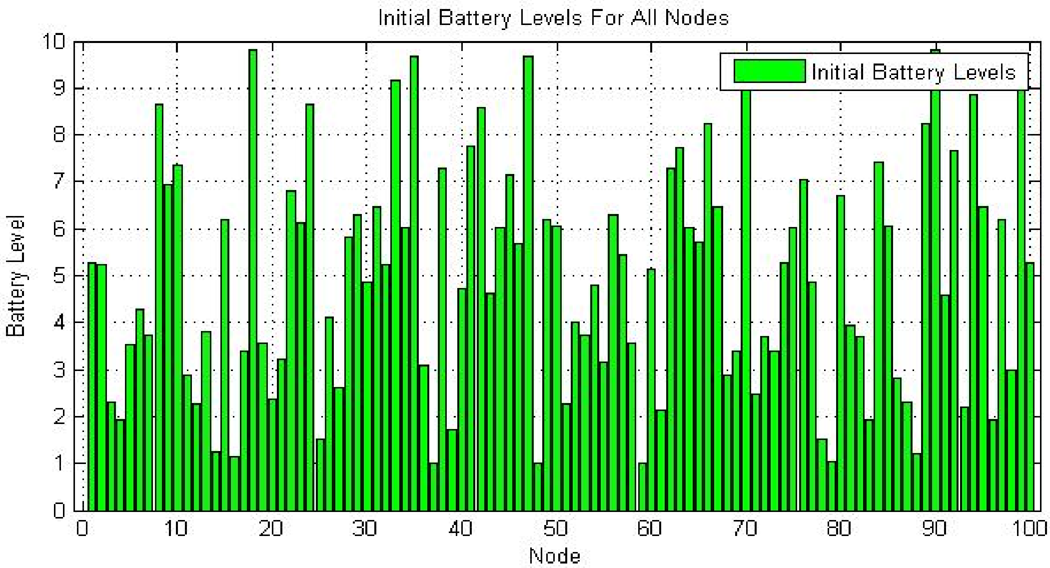

Figure 21: Initial battery levels for the wireless sensor nodes.

4.6 Channel Capacity and Packet Error Rates

This section evaluates the channel capacity and the packet error rates based on the estimated Signal-to-Noise ratio conditions presented by the model. The channel capacity is evaluated based on the estimated Signal-to-Noise ratio conditions presented by the channel model. This represents the highest amount of data, in bits per seconds per Hertz, which can be transmitted reliably and successfully over the channel without losing any accuracy or with as little error as possible. The channel capacity over AWGN channel, C_{AWGN}, is calculated as

$$C_{AWGN} = Bw * log2(1 + SNR) \quad (55)$$

where Bw is the available bandwidth. The Packet Error Rate is defined as the percentage of packets incorrectly received or packets received with error in at least one bit, and is given by

$$P_P = 1 - (1 + BER)^{L_{Pack}} \quad (56)$$

where the Bit Error Rate (BER) is given as

$$BER = 0.5 * erfc(\sqrt{\frac{Eb}{No}}) \tag{57}$$

where the energy per bit to noise power ratio is given by

$$\sqrt{\frac{Eb}{No}} = SNR * \frac{Bw}{Rb} \tag{58}$$

where Rb is the bit rate

4.7 Performance Evaluation Metrics

To evaluate the performance of the proposed MAC protocol, the author has selected, analyzed and investigated the following performance metrics:

(a) **Total Energy Consumed:** A measure of the total energy consumed by the WSN over a given time period. This is obtained by the mathematical expressions in equation (51) for the direct communication and equation (52) for the cooperative communication.

(b) **Network Lifetime:** The Network lifetime refers to the amount of time it takes for a WSN to use up all of its energy such that the entire network is considered non-functional. This is obtained by the mathematical expression in equation (54).

(c) **Average Message Delay:** This is the average amount of time a data packet spends through a wireless network after it has arrived at the source node before it is received at the destination node. This is obtained by the mathematical expression in equation (4).

(d) **Channel Capacity:** The channel capacity represents the highest amount of data, in bits per seconds per Hertz, which can be transmitted reliably and successfully over the channel without losing any accuracy or with as little error as possible. This is obtained by the mathematical expression in equation (55).

(e) **Packet Error Rate:** The Packet Error Rate is defined as the percentage of packets incorrectly received or packets received with error in at least one bit. This is obtained by the mathematical expression in equation (56).

4.8 Numerical and Simulation Results and Discussion

Now we present the energy consumption results for the E^2DRCMAC scheme obtained through simulation and analysis. The simulated results are obtained from an event driven Visual C++ programme simulating the proposed MAC scheme. The analytical results for the set of equations herein were numerically solved using a MATLAB script. The network simulates 100 nodes which are fixed and immobile for their entire battery life. The required simulation parameters are presented in Table 4.

Table 4: Simulation and Analytical Parameters

Parameter	**Value**
L_{DATA}	128bytes
L_{ACK}	12bytes
L_{Pack}	16bytes
Av_{Pack}	6
V	5V
I_S	20 μA
I_B	426 μA
I_{Rx}	19.7mA
I_{Tx}	17.4mA
L_{Msg}	128bytes

The arrival time for the packets is exponentially distributed with the Poisson distribution for the packet arrivals in the network. The analytical model was used to verify the simulation and the behavior of the E^2DRCMAC with different Signal-to-Noise ratio (or CQI) threshold values. The results, as evident in Figure 22 and Figure 23, show that for lower Signal-to-Noise ratio threshold values the model behavior follows the direct transmission where almost all the SN-DN link communications is guaranteed success. As the Signal-to-Noise ratio threshold values are increased in the analysis, more and more SN-DN links fail, thus cooperative relaying is required.

The energy consumed per node increases with increasing packet per second load and increasing average Signal-to-Noise ratio. Both Figure 22 and Figure 23 show that the direct transmission method will impact more on the energy consumption patterns of a WSN when compared to cooperative transmission. The energy consumption levels for each node in the WSN have a major influence on the network lifetime. The energy consumption model has been investigated and the proposed scheme has been shown to have much reduced energy consumption levels per node in each frame of transmission. The results in Figure 24 agree with the energy model. This implies that the proposed cooperative MAC scheme has a higher network lifetime than when just direct transmission is employed. The effect of the overhearing avoidance technique, presented in algorithm 3, is investigated in simulation. The results of Figure 25 show the packet per second load

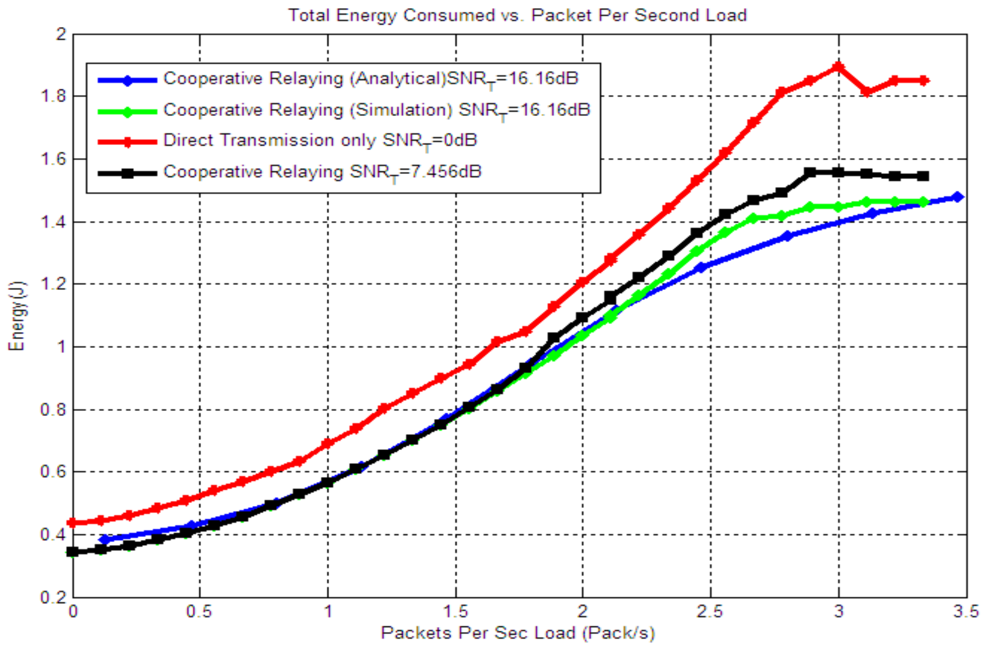

Figure 22: Energy Consumed vs. Packets per Second load

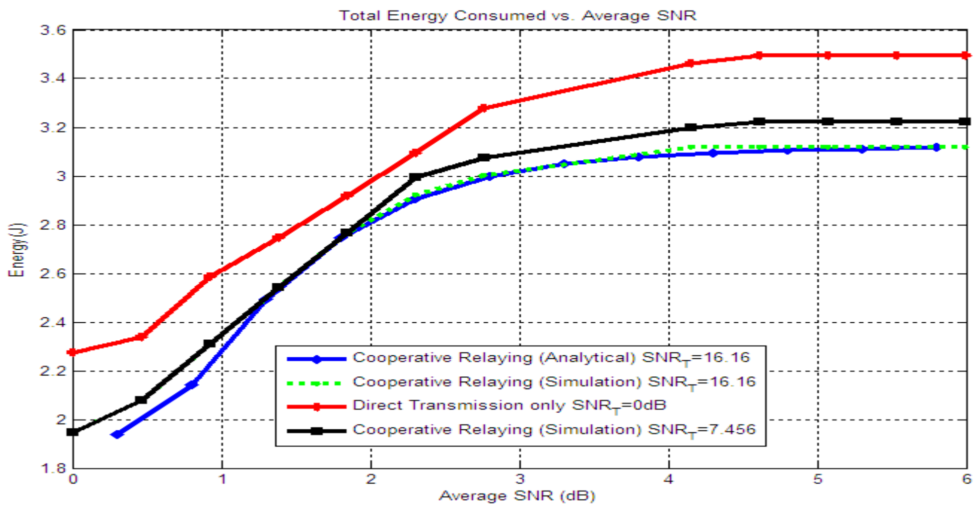

Figure 23: Energy Consumed vs. Signal-to-Noise ratio

versus the total energy (J) consumed per node per frame if the system (both direct and cooperative relay transmission) is simulated without the overhearing avoidance technique for SNR_T of 0dB and 16.16 dB respectively. The results show that the omission of the overhearing avoidance technique results in higher energy consumption levels for the same packet per second loads. This is because during each frame of transmission the radios of the redundant nodes will not be switched off.

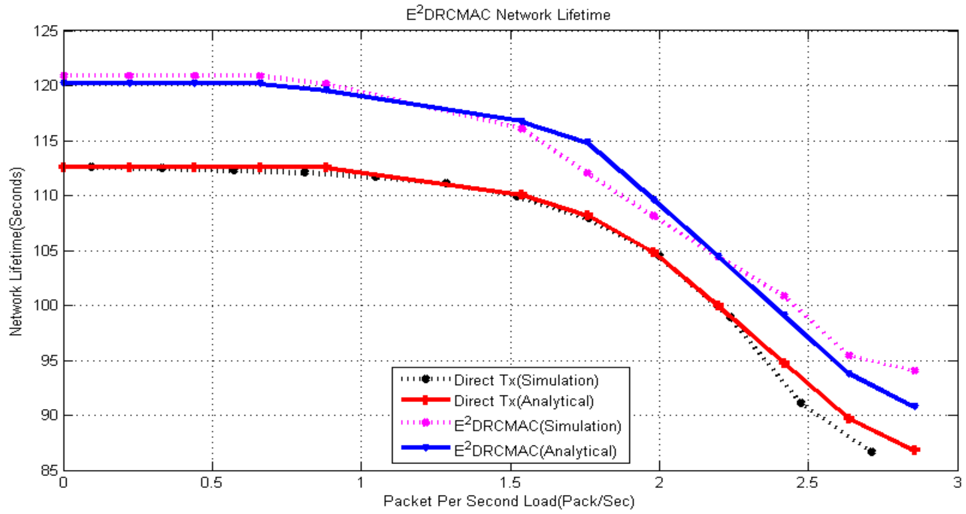

Figure 24: Network Lifetime vs Packet per Second Load

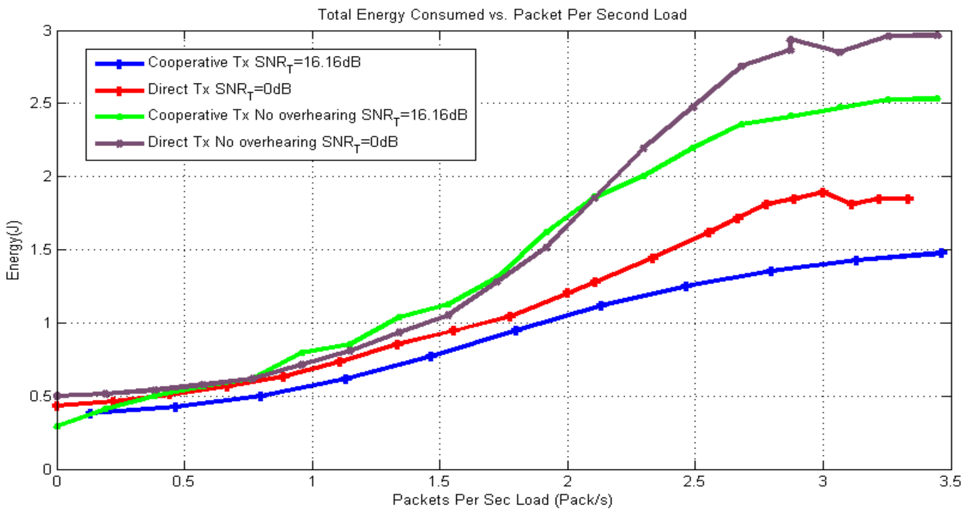

Figure 25: Total Energy Consumed per node with the omission of the overhearing avoidance technique

The arrival time for the packets is exponentially distributed with the Poisson distribution for the packet arrivals in the network. Figure 26 shows the comparison in message delay for direct communication and cooperative communication with overhearing avoidance simulated and analytical. Initially the delay is low, because there are no packets dropped and there are no packet retransmissions for the lower values of offered load. As the offered load increases the message delay also increases, because of packet drops and retransmissions.

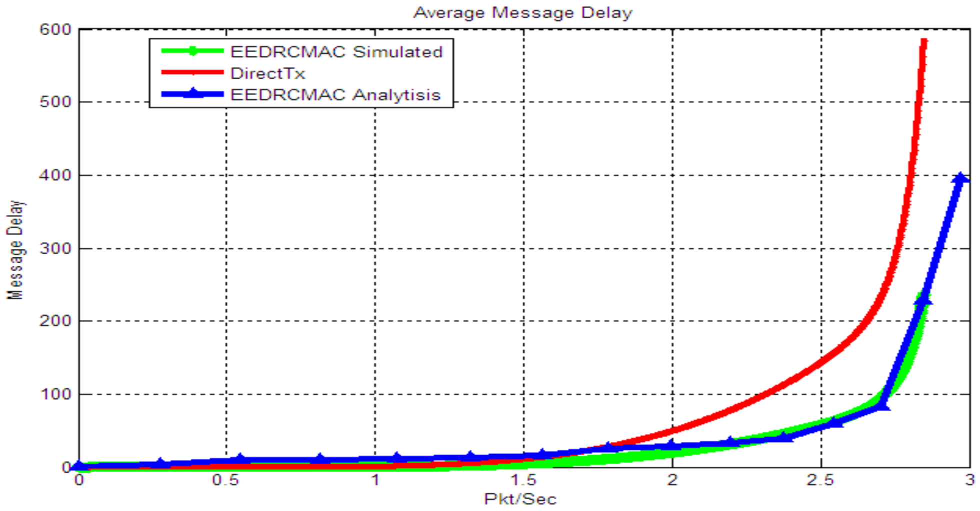

Figure 26: Message Delay vs. Packets per Second Load

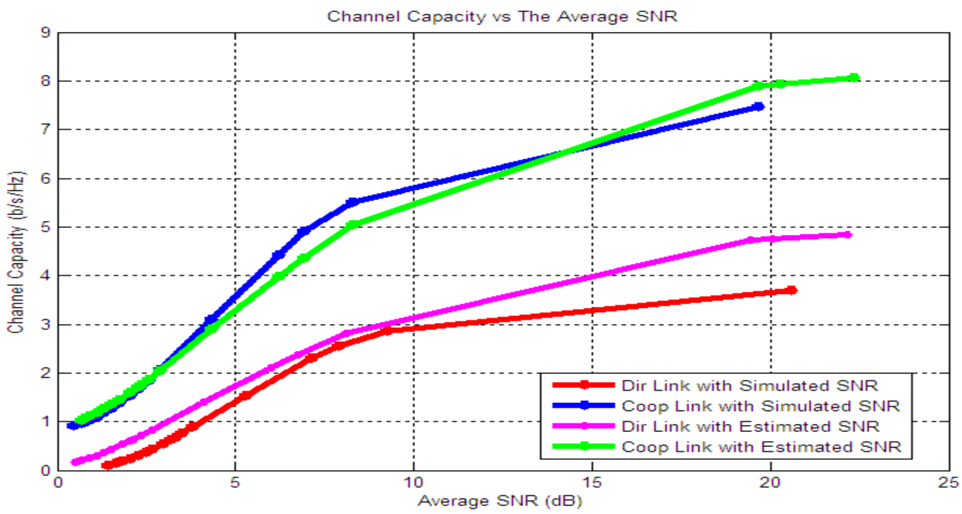

Figure 27: Channel Capacity vs. Average Signal-to-Noise Ratio over a Rayleigh faded E^2DRCMAC Channel

In Figure 27 the average channel capacity is investigated for both the direct transmission and the cooperative transmission phase. Figure 27 shows the findings for both the simulated and the estimated Signal-to-Noise ratio cases. It can be clearly seen that the cooperative phase shows a higher channel capacity for both the simulated and the estimated Signal-to-Noise ratio cases. Figure 28 shows the findings of the PER for both the simulated and the estimated Signal-to-Noise ratio cases. At low average Signal-to-Noise ratio values the difference between the PER for the direct and cooperative is almost negligible. This occurs until the average Signal-to-Noise ratio reaches about 4dB. After that, a clear distinction can be seen in the two schemes and the cooperative

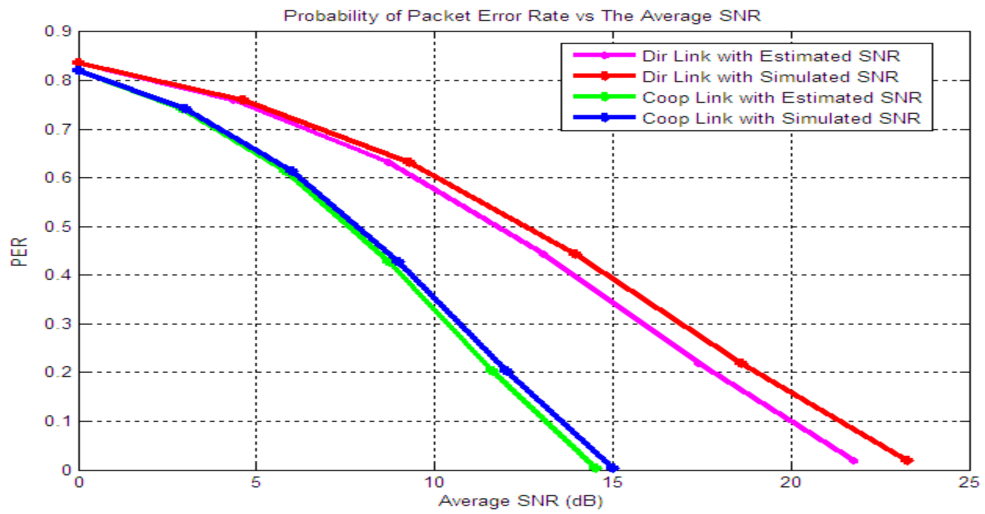

Figure 28: Channel PER vs. Average Signal-to-Noise Ratio over a Rayleigh faded E^{2}DRCMAC

scheme shows better PER performance shown in Figure 28. Both Figure 29 and Figure 30

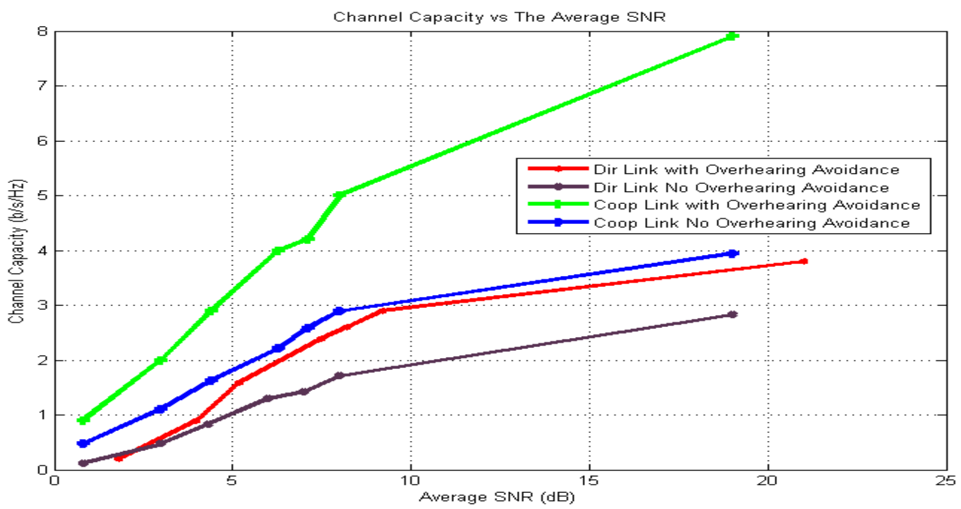

Figure 29: Channel Capacity for the E^{2}DRCMAC with omission of the Overhearing Avoidance

illustrate how the ommission of the Ovehearing Avoidance Technique affects the channel capacity and the packet error rates, respectively. These were simulated against average Signal-to-Noise ratio (dB). Although the cooperation is shown to achieve the best PERs and channel capacity levels, this is only for cases where the overhearing avoidance technique is employed. This is because without the overhearing avoidance in the network, the nodes quickly run out of their energy, giving them limited transmitting capabilities which directly affects the channel capacity and PER of the network.

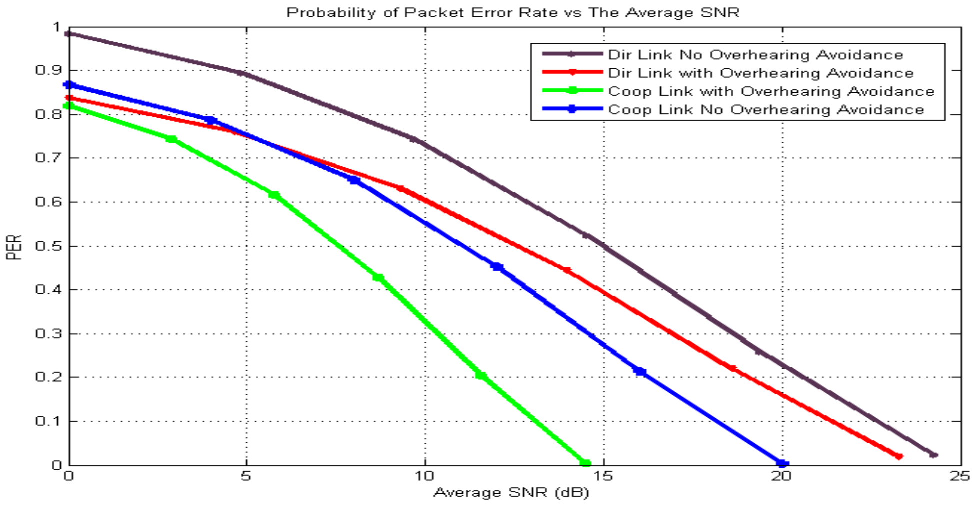

Figure 30: Channel PER for the E^{2}DRCMAC with omission of the Overhearing Avoidance

4.9 Conclusion

This chapter presented the analytical framework for the E^{2}DRCMAC. The MAC scheme is analyzed in terms of energy by employing the Markov process in order to estimate the channel quality of the required links for both the transmission phases. The chapter further investigates how the omission of the overhearing avoidance affects the performance of the protocol in terms of energy consumed, PER and channel capacity. It can be concluded through the simulated and analytical results that the omission of the overhearing avoidance procedure in the proposed MAC scheme results in larger energy consumption percentages per node and hence a shorter network lifetime. This shows the importance of employing the overhearing avoidance technique to conserve energy in WSNs. After the analysis, the investigated performance metrics include the energy consumed per node, PER, channel capacity, message delay and network lifetime. These performance metrics are investigated through both simulations and analytical approaches and the results were closely matched to show the accuracy of the analytical framework.

Chapter 5:

5 Cooperating Relaying Techniques on E^{2}DRCMAC

This chapter analyzes the effects of two modern day cooperative relaying techniques on the MAC scheme proposed herein (E^{2}DRCMAC). The investigated relaying techniques are namely: the Amplify-and-Forward relaying technique and the Decode-and-Forward relaying technique. In the channel model of Chapter 4, the Signal-to-Noise ratio and CQI, for the cooperative relay link RN-DN, were estimated using the signal resulting from the traditional Store-and-Forward Scheme applied at the relay node. Here, the relay node simply stored the original signal from the source node and then forwarded it to the destination. The signal would then remain in the relay nodes buffer for the remainder of the frame time and be discarded before the relay node goes back to sleep. In this chapter the Signal-to-Noise ratio (and subsequently the CQI) are estimated using the signal resulting from the Amplify-and-Forward and the Decode-and-Forward applied by the cooperative relay node to relay the signal to the destination. The estimated Signal-to-Noise ratio values are then used to determine the best relay to be used in cooperative communication for a particular frame of transmission. The aim of the chapter is to investigate which was the best cooperative relaying technique for forwarding data packets in the proposed E^{2}DRCMAC scheme. This chapter derived the cooperatively relayed signals from the relay node to the destination node by obtaining the Amplify-and-Forward and the Decode-and-Forward versions of the signal generated by the relay node during cooperation as a result of Amplify-and-Forward and the Decode-and-Forward applied at the relay node respectively. This, as expected, may enhance only the cooperative link and not the direct transmission.

Consider a two hop cooperative link, shown in Figure 31, where the source node sends data packets to the destination node via a cooperative relay node. The selection of the relay node to be employed is based on the estimated channel Signal-to-Noise ratio (or CQI). The cooperative transmission for the proposed MAC scheme is presented in Algorithm 2 in Chapter 3.

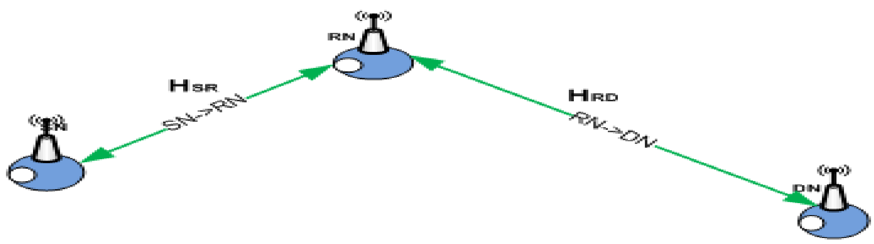

Figure 31: Two hop cooperative link

Generally, the signal sent over a communication channel at any time (t) can be written as

$$y(t) = \sqrt{P} * T_X(t) * H(t) + n(t) \quad (59)$$

where P is the power of the transmitted signal, Tx(t), H(t) is the channel gain (coefficient) and n(t) is the AWGN noise component. The analysis in this work is based on a Rayleigh distributed channel gain.

5.1 Analyising Amplify-and-Forward for E^{2}DRCMAC

As mentioned in Chapter 2, the relay node employing the Amplify-and-Forward technique will generally amplify the received signal from the source node and forward it to the destination. The signals received from the source node at the destination node and the relay node are given in equations (6) and (7) respectively.

The signal, $R^{AF}{}_{RD}(t)$, received at the destination after the relay node is an amplified version of equation (8) which can be written as

$$R^{AF}_{RS}(t) = \sqrt{P} * T^{AF}_X(t) * H_{RD}(t) + n_3(t) \quad (60)$$

where $T^{AF}{}_X(t)$ is the signal generated as a result of Amplify-and-Forward at time t by the relay node and is given as

$$T^{AF}_X(t) = \sqrt{\frac{P * |H_{SR}|^2}{P * |H_{SR}|^2 + N(t)}} * T_X(t) + \sqrt{\frac{1}{P * |H_{SR}|^2 + N(t)}} * n_1(t) \quad (61)$$

Modifying equation (60) using equation (61) it is straight forward to show that

$$R^{AF}_{RS}(t) = P * H_{RD} * |H_{SR}| * \sqrt{\frac{1}{P * |H_{SR}|^2 + N(t)}} * T_X(t) + N(t) \quad (62)$$

The equation (62) is used in place of equation (8) and the normal procedure presented in the Channel model is followed to solve equation (9) and select the best relay node for the cooperative transmission path.

5.2 Analyising Decode-and-Forward for E^{2}DRCMAC

In Decode-and-Forward the cooperative relay node firstly decodes the data signals from a certain source before it forwards them to the destination node.

The signal, $R^{DF}{}_{RD}(t)$, received at the destination after the relay node is a decoded version of equation (8) which can be written as

$$R^{DF}_{RS}(t) = \sqrt{P} * T^{DF}_{X}(t) * H_{RD}(t) + n_3(t) \tag{63}$$

where $T^{DF}{}_{X}(t)$ is the signal generated as a result of Decode-and-Forward at time t by the relay node and is given as

$$T^{DF}_{X}(t) = Y_{DF} * T_X(t) \tag{64}$$

where $T_X(t)$ is the original signal sent from the source node to the relay node and Y_{DF} is the precoding vector for the Decode-and-Forward. The precoding vector is given by

$$Y_{DF} = Y^*_{DF} \cdot \frac{H_{RD}(t) * Y^*_{DF}}{|H_{RD}(t) * Y^*_{DF}|} \tag{65}$$

The precoding vectors are independent of the choice of Y_{DF}^*.

With the Bit Error Rates (BER) given in (57) we can evaluate the numerical results and compare the performance of the cooperative relaying schemes discussed in this chapter.

5.3 Performance Evaluation Metrics

To evaluate the performance of the proposed MAC protocol when subjected to different relaying techniques other than Store-and-Forward, the author selected, analyzed and investigated the following performance metrics:

(a) **Bit Error Rate:** The Bit Error Rate represents the percentage of bits incorrectly received at the detination node over the channel with the estimated channel conditions or packets received with error in at least one bit. This is obtained by the mathematical expression in equation (57) modified with the new Signal-to-Noise ratio obtained from the Amplify-and-Forward and Decode-and-Forward received signals from the mathematical expressions given by equation (62) and equation (63) respectively.

(b) **Transmission Rates:** The same as the channel capacity, the transmission rates here investigate the rate at which the data packets (in BitsPerSecond) that can be transmitted reliably and successfully over the channel with the estimated channel conditions. This is obtained by the mathematical expression in equation (55) modified with the new Signal-to-Noise ratio obtained from the Amplify-and-Forward and Decode-and-Forward received signals from the mathematical expressions given by equation (62) and equation (63) respectively.

(c) **Average SNR:** Represents the average Signal-to-Noise-ratios over which the cooperative relaying schemes were investigated in order to observe which one served the proposed MAC scheme the best. The Signal-to-Noise ratio is obtained from the Amplify-and-Forward and Decode-and-Forward received signals from the mathematical expressions given by equation (62) and equation (63) respectively.

5.4 Numerical and Results and Discussion

To gain complete comprehension as to which cooperative relaying scheme is the most suitable for the E^2DRCMAC how scheme, we investigated the MAC scheme performed in terms of the BER, the transmission rates and the energy consumption per node per frame subject to increasing average SNR. This section presents the numerical results for the E^2DRCMAC scheme. These results for the set of equations of this chapter were numerically solved using a MATLAB script. This section investigates only the results of the cooperative link between the cooperative relay node and the destination node. Thus the SNR threshold is set at SNR_T = 16.16dB for all the plots in this section.

Figure 32 depicts the BER resulting from the analysis of the SNR estimation subject to Amplify-and-Forward, Decode-and-Forward and Store-and-Forward (For Store-and-Forward, see the original analyisis in section 4.3). Figure 32 implies that the average BER performance for all the three cooperative relaying schemes investigated is similar, with a slight improvement in the Amplify-and-Forward and Store-and-Forward as opposed to the Decode-and-Forward scheme. Hence, if the BER was the determining factor then any of the cooperative relaying schemes could be employed with a slightly higher recommendation for the Amplify-and-Forward scheme.

Figure 33 shows the average transmission rates performance for the E^2DRCMAC scheme when subjected to the three different cooperative relaying schemes. Since all schemes investigated use cooperation, they all perform in proximity of one another in terms of transmission rates due to the fact they have roughly the same channel gains over the same transmission channel. However, the transmission rates for the Amplify-and-Forward is a fraction better than those of the other two realying schemes. This is because of the higher channel gains brought by the amplification of the signal during the Amplify-and-Forward action of the MAC scheme. However, Figure 34 shows that in terms of energy conservation, the Store-and-Forward scheme provides the best energy saving patterns for the proposed E^2DRCMAC scheme per node per frame of transmission. This is because

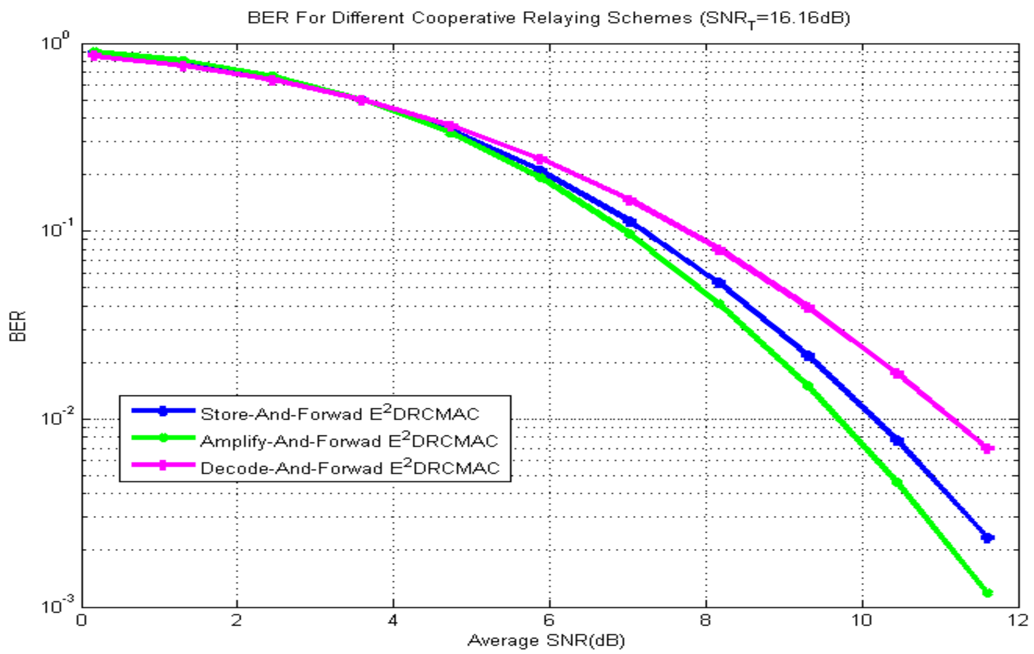

Figure 32: Comparing BERs for the Cooperative Relaying Schemes

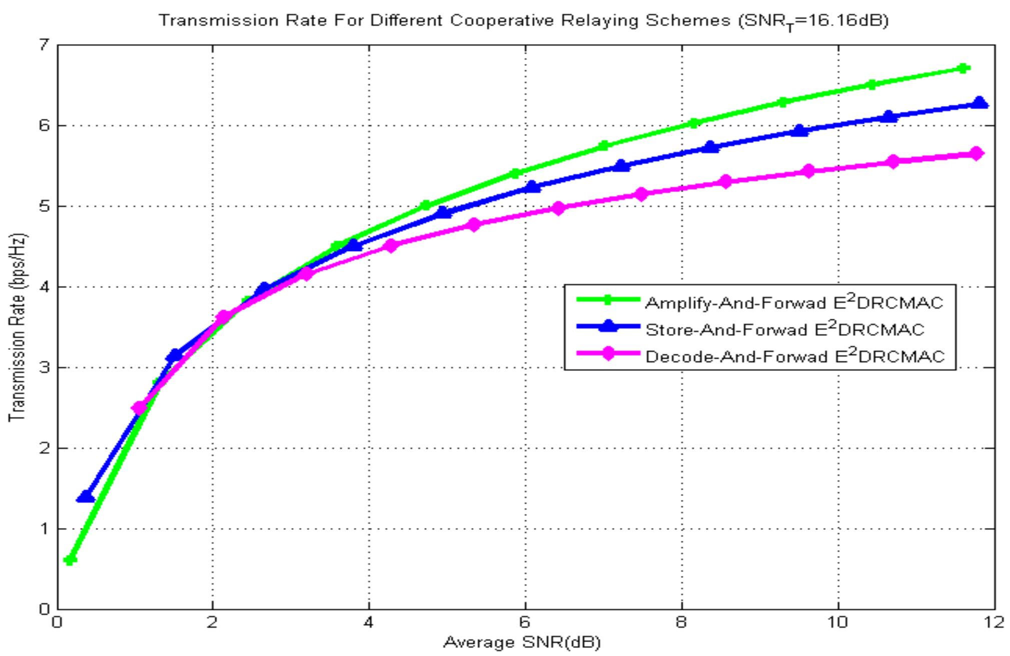

Figure 33: Comparing Transmission Rates for the Cooperative Relaying Schemes

the power consumed to save the signal is much less when compared to the power needed, to either decode (Decode-and-Forward) or amplify (Amplify-and-Forward) a signal. Although the energy consumption in Store-and-Forward is not dramatically excessive when compared to the other two relaying schemes, this analysis led to Store-and-Forward being the main relaying scheme for the E^{2}DRCMAC. This is because the proposed MAC seeks mainly to be an energy efficient scheme.

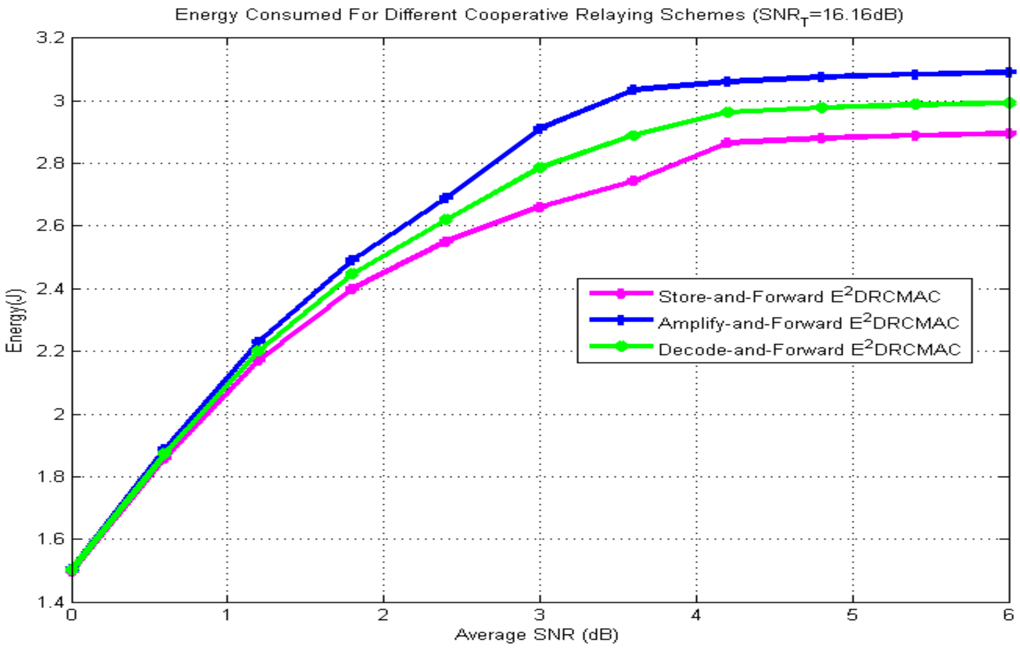

Figure 34: Comparing Energy Consumption Patterns for the Cooperative Relaying Schemes

5.5 Conclusion

The aim of the chapter was to determine which, amongst Store-and-Forward, Amplify-and-Forward and Decode-and-Forward, was the best cooperative relaying technique for forwarding data packets in the proposed E^{2}DRCMAC scheme in terms of energy saving, and Bit Error Rates. This chapter analysed both the Amplify-and-Forward and the Decode-and-Forward techniques when applied to the cooperative transmission of the proposed E^{2}DRCMAC scheme. The numerical results are presented and they show how the cooperative relaying techniques investigated herein compare in terms of Bit Error and Transmission Rates. For this performance criteria, the Amplify-and-Forward scheme proves a slightly dominant cooperative relaying scheme when compared to the Decode-and-Forward and the preferred Store-and-Forward technique. However, in terms of energy conservation patterns, the Store-and-Forward technique shows the best performance for the proposed MAC scheme, which is why it is in the model of the scheme. This is because this work mainly seeks to achieve the best energy consumption patterns rather than other performance criteria.

Chapter 6:

6 Conclusion And Future Work

6.1 Conclusion

This dissertation proposed a new cooperative MAC scheme for wireless sensor networks. The main objective of this MAC scheme is to combine the effects of cooperative communications with that of overhearing avoidance in wireless sensor networks. This, as the results indicated, aimed to reduce energy consumption thereby providing improved network reliability and lifetime. The dissertation presented a simulation and analytical model to evaluate the performance of the proposed protocol. Most MAC schemes for WSNs only look at providing a good medium access and do not pay too much attention to what happens to the nodes′ energy levels as time passes or as load increases and network gets denser. This dissertation also proposed a channel quality estimation method for an Energy Efficient Cooperative MAC scheme (E^2DRCMAC) for WSNs. This allows for the nodes in the network running the E^2DRCMAC scheme to be able to estimate accurately their respective channel quality properties. This, as evident in the results, gives rise to better performance metrics in terms of channel capacity and Bit Error Rates. The channel quality estimation method presented in this dissertation allows the attached MAC scheme to select the best possible cooperative relay channel to be utilized in any cooperative retransmission phase if the direct transmission channel does not have all the adequate resources required to meet the transmission requirements during any particular frame of transmission. This will in turn allow the MAC to provide much improved energy savings thereby extending the network lifetime for the nodes running the attached MAC scheme. Not only was the MAC protocol proposed but its energy analysis model was provided as well. This was in an attempt to show that cooperation in wireless sensor networks can result in both improved performance and improved energy savings. The energy model was provided together with the simulation results which compare energy consumed by direct communications with energy consumed by cooperative communication in the modules that make up the sensor nodes, namely the sensor module and the transceiver module.

Chapter 2 of this dissertation presented a literature review of the medium access control schemes for wireless sensor networks. The different MAC protocols discussed in this chapter range from contention based to schedule based, CDMA to TDAMA and non cooperative to cooperative. The literature review was conducted so as to gain a vast understanding on the research subject area so as to understand how to design a cooperative MAC protocol for WSNs. The literature review was conducted by obtaining knowledge on different types of existing protocols, their advantages and disadvantages. This chapter assisted in propelling the research work in the direction that it did.

Chapter 3 of the dissertation presented a new distributed receiver based cooperative MAC protocol for WSNs. The sensor node of the proposed MAC protocol, upon having data to transmit, sense their preamble request for communication with the sink node. This helped minimize the effects of collision in the network, while also providing a higher success in packet transmission and reception. The proposed MAC scheme calculates the CQI for the direct link, between the source and sink node, in every frame. If this CQI is sufficient the communication follows a direct transmission. However, if this CQI for direct link is insufficient then the communication follows a cooperative transmission. In the cooperative transmission, the protocol describes how to select the best cooperative relay node with respect to the possible neighbouring relay nodes on a best CQI basis for the cooperative link. This chapter further provides a protocol comparison to validate the proposed MAC scheme. The proposed MAC protocol was compared with the standard IEEE 802.15.4 MAC and through simulation, the MAC scheme was validated by comparing throughput and the percentage energy consumed per node per frame with that of the standard IEEE 802.15.4 MAC scheme. Lastly, the simulation results showed that the proposed MAC scheme outperfomed the IEEE 802.15.4 MAC protocol in terms of throughput and percentage energy consumption.

Chapter 4 detailed the analytical framework for the proposed E^2DRCMAC scheme. This chapter provides an analysis for the packet delay model, the channel model and the energy consumption model. The analytical framework for the proposed E^2DRCMAC scheme combined a network and node analyisis to solve the channel and energy consumption model. The node model follows a three state Markov process which solves a steady state probability of a node being in either Sleep, Back-off or Active state. But to solve the node analysis, the framework needed to first solve the network model. The network model follows an N state Markov process which solves the steady state probability of having X active nodes at any time t. The channel model estimates the SNR of the direct link for the direct transmissions and the SNR of the cooperative link for the cooperative transmissions. The channel estimated SNR proved of great importance when providing the analytical results for the error analysis such as the channel capacity, Bit Error Rates and Packet Error Rates. The accuracy of the analytical framework is validated by the close relation observed between the analytical and the simulated results. The results further showed that cooperation and overhearing avoidance in wireless sensor networks can result in both improved performance and improved energy savings.

Chapter 5 provided an investigative analysis based on three cooperative relaying schemes applied to the proposed E^2DRCMAC scheme. The aim of the chapter was to determine which, amongst Store-and-Forward, Amplify-and-Forward and Decode-and-Forward, was the best cooperative relaying technique for forwarding data packets in the proposed E^2DRCMAC scheme in terms of energy saving, and Bit Error Rates. This chapter analysed both the Amplify-and-Forward and the Decode-and-Forward techniques when applied to the cooperative transmission of the proposed E^2DRCMAC scheme. The numerical results are presented and they aim to show how the cooperative relaying techniques investigated herein compare in terms of Bit Error and Transmission Rates. For this performance criteria, the Amplify-and-Forward scheme proves a slightly dominant cooperative relaying scheme when compared to the Decode-and-Forward and the preferred Store-and-Forward technique. However, in terms of energy conservation patterns, the Store-and-Forward technique shows the best performance for the proposed MAC scheme, which is why its in the model of the scheme.

Further work on this topic may include an investigation and analysis of how the MAC scheme performs under multi-media traffic such as audio, video or both. This may assist in identifying how the proposed MAC scheme performs subject to hash set of QoS requirements. More future work would be to look at the combination of cooperative diversity schemes together with clustering methods in WSNs. This would evaluate how much more energy conservation patterns would be observed in such systems.

Appendix A

A_1 Relevant Chipcon CC240 Data

Table of the Chipcon CC240 data used for simulation and analysis purposes [46].

Table 5: Parameter and Values for Simulation and Analysis

Parameter Notation	**Notation Definition**	Value
V	Working Voltage	5V
λ_{AS}	Transition Rate from Active to Sleep	192 μs
λ_{SA}	Transition Rate from Sleep to Active	192 μs
λ_{BA}	Transition Rate from Back-Off to Active	2 μs
λ_{SB}	Transition Rate from Sleep to Back-Off	0.6mA
I_S	Transceiver Current in Sleep	20μA
I_B	Transceiver Current in Back-Off	426μA
I_{Rx}	Transceiver Current in Active Rx	19.7mA
I_{Tx}	Transceiver Current in Active Tx	17.4mA

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