THE DESIGN AND IMPLEMENTATION OF THE ROUTING ALGORITHM OPTIMISED FOR SPECTRUM MOBILITY, ROUTING PATH DELAY AND NODE RELAY DELAY

By

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DISSERTATION

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DECLERATION

I declare that **THE DESIGN AND IMPLEMENTATION OF THE ROUTING ALGORITHM OPTIMISED FOR SPECTRUM MOBILITY, ROUTING PATH DELAY AND NODE RELAY DELAY** is the work that I created and the information that helped me to create this document has been acknowledged by being referenced. No one has submitted this work before at any institution.

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Full names	**Date**

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ABSTRACT

Spectrum scarcity is one of the major problems affecting the advancement of wireless technology. The world is now entering into a new era called the “Fourth Industrial Revolution” and technologies like the Internet of Things (IoT) and blockchain are surfacing at a rapid pace. All these technologies and this new era need high speed network (Internet) connectivity. Internet connectivity is reliant on the availability of spectrum Channels. The Federal Communication Commission (FCC) has emphatically alluded on the urgency of finding quick and effective solutions to the problem of spectrum scarcity because the available spectrum bands are getting depleted at an alarming rate.

Cognitive Radio Ad Hoc Networks (CRAHNs) have been introduced to solve the problem of spectrum depletion. CRAHNs are mobile networks which allow for two groups of users: Primary Users (PUs) and Secondary Users (SUs). PUs are the licensed users of the spectrum and SUs are the unlicensed users. The SUs access spectrum bands opportunistically by switching between unused spectrum bands. The current licensed users do not fully utilize their spectrum bands. Some licensed users only use their spectrum bands for short time periods and their bands are left idling for the greater part of time. CRNs take advantage of the periods when spectrum bands are not fully utilized by introducing secondary users to switch between the idle spectrum bands. The CRAHNs technology can be implemented in different types of routing environments including military networks. The military version of CRAHNs is called Military Cognitive Radio Ad Hoc Networks (MCRAHNs). Military networks are more complex than ordinary networks because they are subject to random attacks and possible destruction.

This research project investigates the delays experienced in routing packets for MCRAHNs and proposes a new routing algorithm called Spectrum-Aware Transitive Multicasting On Demand Distance Vector (SAT-MAODV) which has been optimized for reducing delays in packet transmission and increasing throughput. In the data transmission process, there are several levels where delays are experienced. Our research project focuses on Routing Path (RP) delay, Spectrum Mobility (SM) delay and Node Relay (NR) delay. This research project proposes techniques for spectrum switching and routing called Time-Based Availability (TBA), Informed Centralized

Multicasting (ICM), Node Roaming Area (NRA) and Energy Smart Transitivity (EST). All these techniques have been integrated into SAT-MAODV. SAT-MAODV was simulated and compared with the best performing algorithms in MCRHANs. The results show that SAT-MAODV performs better than its counterparts.

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Abbreviations

AODV: Ad hoc On-Demand Routing Algorithm

ARMSCOR: Armaments Corporation of South Africa

BWAR: Backpressure with Adaptive Redundancy

CCC: Common Control Channel

CM: Centralized Multicasting

CRAHNs: Cognitive Radio Ad Hoc Networks

CRNs: Cognitive Radio Networks

CR-VANETs: Cognitive Radio Vehicle Ad hoc Networks

DFSP: Depth-First Search Routing Protocol

DMR: Delay-Minimized Routing

DORP: Delay-motivated on-demand Routing Protocol

DTNs: Delay Tolerant Networks

EIT: Energy Infused Transitivity

EST: Energy Smart Transitivity

ETC: Expected Transmission Count

ETT: Expected Transmission Tiime

FCC: Federal Communications Commission

FIFO: First In First Out

ICM: Informed Centralized Multicasting

IEEE: Institute of Electrical and Electronics Engineers

IoT: Internet of Things

IPSAG: IP spectrum aware geographic routing algorithm proposal for multi-hop cognitive radio networks

LCCLD: Loosely Coupled Cross Layered Design

MAC: Medium Access Control

MANETs: Mobile Ad hoc Networks

MAODV: Multicast Ad hoc On-Demand Distance Vector

MARSA: Mobility-Assisted Routing algorithm with spectrum awareness

MCRAHNs: Military Cognitive Radio Ad Hoc Networks

MSEE: Mean-to-Square Extreme Eigenvalue MSEE

NR: Node Relay

NRA: Node Roaming Area

NS2: Network Simulator version 2

NS3: Network Simulator version 3

OSI: Open Systems Interconnection

PRoPHET: Probabilistic Routing Protocol Using History of Encounters and Transitivity

PUs: Primary Users

QMS: Queue Management System

QoS: Quality of Service

RP: Routing Path

RREP: Route Response

RREQ: Route Request

RSW: Reduced variable Spray and Wait

SANDF: South African National Defense Force

SARCP: Spectrum Aggregation-Based Cooperative Routing Protocol

SAT-MAODV: Spectrum Aware Transitive Multicasting Ad hoc On-Demand Distance Vector

SEARCH: Spectrum Aware Routing for Cognitive ad-hoc Networks

SM: Spectrum Mobility

SSR: Spectrum-Aware Semi-Structure Routing

SSRP: Stability-based Spectrum-aware Routing Protocol

SUs: Secondary Users

SW: Spray and Wait

TBA: Time-Based Availability

T-test: Studentized test

WCETT: Weighted Cumulative Expected Transmission Time

WSNs: Wireless Sensor Networks

xWCETT: Extended Weighted Expected Transmission Time

CHAPTER 1 INTRODUCTION

1.1. Introduction

Spectrum depletion is one of the biggest challenges facing the wireless technology field. The Federal Communications Commission (FCC) released a statement saying that the current spectrum bands available for wireless transmission are getting depleted [1]. Wireless technology is growing at a very rapid pace and spectrum bands are highly needed to keep up with this growth. This depletion of spectrum bands affects all entities and organizations which make use of wireless communication.

The Cognitive Radio Ad Hoc Networks (CRAHNs) technology was introduced to deal with this challenge of spectrum depletion [2]. In CRAHNs there are two types of spectrum users: Primary Users (PUs) / licensed users and Secondary Users (SU) / unlicensed users. PUs are the rightful owners of the spectrum bands and SUs access the spectrum opportunistically whenever PUs are not using it. This technology proposes that instead of allocating licensed spectrum bands to every user, we can have users accessing the spectrum opportunistically. In this way unused spectrum bands will be recycled and the usage of the allocated spectrum bands will be optimized. This creates a very dynamic environment for SUs as they switch between unused spectrum bands to achieve transmission without losing data packets. Figure 2-1 depicts the CRAHNs structure.

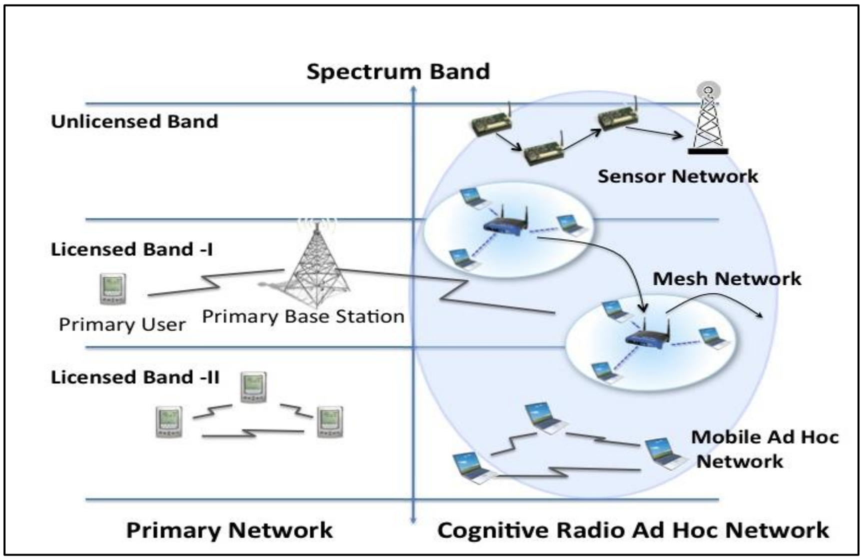

Figure 1-1: CRAHN Structure [3]

CRAHNs technology is now being deployed in many institutions including the military. Military Cognitive Radio Ad Hoc Networks(MCRAHNs) have many challenging factors than normal CRAHNs. They do share common attributes with traditional CRAHNs but they are not entirely the same. MCRAHNs are always faced with the problem of destruction, all the nodes in the network are subject to destruction that can occur at any time and at any given point which makes the networks to be characterized as intermittent. In intermittent networks, there are no guaranteed paths from the source to the destination, at any instance a node or nodes which constitute the routing path may be destroyed [4]. In normal CRAHNs, when a routing path is selected for packet transmission it is often assumed that the routing path won't change and that the nodes which make up the routing path will exist until the packets reach their destination, but that assumption doesn't apply for MCRAHNs because the entire network is subject to unpredictable destruction.

MCRAHNs are composed of different nodes with different sizes and magnitudes. All the nodes in MCRAHNs are connected wirelessly and they use finite stored energy. Figure 2-2 depicts an example of a military network:

Figure 1-2: An example of an ad hoc military network [5]

All the military components shown in figure 2-2 are subject to destruction that can occur at any given point and time. It is important to note that in the case of destruction to some of the nodes in the MCRAHN, the network should still operate with the remaining nodes available.

1.2. Problem Statement

In intermittent mobile networks, there are no guaranteed routing paths from the source node to the destination node due to the destructive nature of the network. MCRAHNs are such kind of networks, with the possibility of nodes like tankers and aircrafts being destroyed, the routing paths are not always guaranteed. As a result, in the process of relaying data packets, transmissions may be interrupted due to the unavailability of relaying paths. This results in delays which degrade the performance of the network. Some packets are dropped due to buffering and timeouts. The delays which are incurred in MCRAHNs due to destruction are Spectrum Mobility (SM) delay, Node Relay(NR) delay and Routing Path (RP) delay. This destruction also reduces the throughput of the network because whenever it occurs most packets end up not reaching their destination.

When designing a routing algorithm for MCRAHNs it is imperative to first start by addressing destruction avoidance and recovery mechanisms because most of the inefficiencies emanate from these two factors. Numerous routing algorithms have been proposed for addressing inefficiencies that are experienced in MCRAHNs. Most of the algorithms designed for MCRAHNs don’t address delays because some researchers believe that the delay incurred in these networks is unavoidable, that is why MCRAHNs are categorized as Delay Tolerant Networks [6]. We are of the view that these delays can be reduced, and the throughput can be optimized.

Spectrum mobility is another challenging factor that should be evaluated in MCRAHNs. Spectrum scarcity in MCRAHNs makes packet transmission even more challenging. In trying to design routing algorithms which deal well with destruction, spectrum acquisition needs to also be included. Spectrum acquisition for MCRAHNs is different from that of normal CRAHNs. In MCRAHNs spectrum acquisition must be quick and robust because the packets must be transmitted quickly before destruction occurs in cases where destruction hasn’t occurred yet. In cases where it has occurred already, spectrum acquisition must happen with an already damaged network and missing nodes.

Our research project proposes a new routing algorithm for MCRAHNs optimized for reducing NR, SM, RP delays and throughput.

1.3. Research aim and Objectives

The aim of this research project is to assess and analyze the current challenges in routing protocols designed for MCRAHNs that are causing inefficiencies of delays and throughput. This project also aims to design a new routing protocol which is optimized for reducing delay and improving throughput. The Objectives that guided this project are:

- Investigate the challenges of MCRAHNs Routing algorithms.
- Investigate the impact of delay in MCRAHNs.
- Optimize Spectrum-Aware Transitive Multicasting On Demand Distance Vector (SAT-MAODV) for node relay delay, spectrum mobility delay, Routing Path Delay and Throughput.
- Investigate and evaluate the performance of the proposed algorithm.

1.4. Research Questions

The inefficiencies of routing protocols designed for MCRAHNs create a wide domain of questions in trying to find the solution to mitigate against them. This research project is only focused on finding answers to questions regarding delay and throughput in MCRAHNs. The following are the research questions which guided this research project:

- Which is the best performing routing algorithm in MCRAHNs?
- What are the shortcomings of the existing routing algorithms designed for MCRAHNs?
- How does spectrum mobility impact on existing MCRAHNs routing algorithms?
- Can spectrum mobility be factored in the optimization of routing algorithms?
- What is the impact of routing path delay and node relay delay on routing in MCRAHNs?
- Can spectrum mobility delay and node relay delay be reduced?

- How can spectrum mobility delay and node relay delay be optimized in algorithms to achieve an improved performance?
- How can throughput be optimized in MCRAHNs which are destruction oriented?

1.5. Motivation

The motivation for this research project emanates from the current challenges of delay and throughput affecting the deployment of MCRAHNs routing protocols. MCRAHNs services are often offered in very unstable and compromised environments which demand robust and genuine tools. The current routing protocols designed for MCRAHNs incur a lot of RP, SM and NR delays and they even offer a low throughput [7].

MCRAHNs combine three main factors that make them to be more challenging than other networks to design routing algorithms for: spectrum mobility, nodes mobility and subjection to destruction. These factors cause a lot of algorithms to falter when deployed and they also make the design of algorithms that can deal with them all to be challenging. MCRAHNs are often categorized as delay tolerant networks because most researchers believe that a lot of delay is bound to be incurred by them and it is unavoidable [8].

This research project was also motivated by the military institutions that have invested in the research for this kind of technology like the South African National Defense Force (SANDF) and the Armaments Corporation of South Africa (ARMSCOR). The frequent calls by the FCC for more research into spectrum recycling also propelled this research project forward [9].

1.6. Research Outline

The succeeding chapters present the background and implementation of this research project. Chapter 2 presents the background of routing in MCRAHNs. It also outlines the challenges that are faced when routing in MCRAHNs. A subset of this challenges is addressed by this research project.

Chapter 3 presents the past literature on studies that have been conducted in MCRAHNs or in similar environments. This chapter outlines the achievements of past studies and the shortcomings of the studies. It is in this chapter where the validity of our research project is presented and justified.

Chapter 4 presents the methodology of the implementation for our research project. The tools used for the simulation and analysis of our research project are also presented in this chapter. This chapter goes on further to present all the algorithms simulated for this research project. The stepwise process of simulating every algorithm and the analysis methods of the results are also provided in this chapter.

Chapter 5 presents the results and analysis of our research project. The contents of chapter 4 are implemented in this chapter. This chapter starts by depicting the graphical results of the research project and then gives a statistical analysis of the depicted graphs. The statistical analysis validates the graphical results.

Chapter 6 presents the conclusion of our research project. This conclusion is based on the findings acquired in chapter 5. This chapter goes on further to give the recommendations for the implementation of our proposed algorithm. These recommendations entail the implementations and modifications that should be done.

CHAPTER 2 BACKGROUND OF ROUTING IN MCRAHNs

2.1. Introduction

Routing in MCRAHNs where nodes (tanks, airplanes, soldiers, etc.) are mobile and subject to destruction is more complex than routing in normal CRAHNs. The unavailability of guaranteed routing paths is the main challenge. Nodes in MCRHANs are forced to buffer packets while alternative routing paths are being discovered at the event of linkages due to node and spectrum mobility. This buffering of packets causes inefficiencies which degrade the performance of the network.

Most routing algorithms designed for MCRAHNs cause nodes to buffer packets for a long time in the case of route unavailability caused by destruction. The main reason for this is that most of these algorithms don't have a backup plan for route unavailability and they often wait for route recovery until they are able to forward data packets. This causes a lot of delay and packet loss which in turn decreases throughput.

The buffers of nodes in MCRAHNs can hold packets for a specific pre-configured period. When the pre-configured period elapses, the nodes drop the packets. If the buffering period in the nodes is increased, the energy of the nodes in the network will be highly compromised and there will be a lot of routing overhead because some nodes will be required to receive and relay packets whilst they are still buffering old packets. A packet transmission back up plan is very imperative in MCRAHNs because important data packets get dropped and most military information is sensitive and important, so high packet loss can't be tolerated in this kind of networks. The lack of backup routing plans for algorithms designed for MCRAHNs often results in two types of delays called Routing Path (RP) delay and Node Relay (NR) delay which are fully expounded on in chapter 4. The process of spectrum switching by SUs also incurs delay called Spectrum Mobility (SM) delay which is also expounded in chapter 4.

One other common problem in algorithms designed for MCRAHNs is that they don't optimize the configuration of the Common Control Channel (CCC). The CCC must be configured in a way that spectrum channels are acquired, packets are relayed, and the route unavailability plan is always ready. These three factors must be addressed in the

CCC because it is the one which facilitates the operations for packet transmissions. In designing routing algorithms for MCRAHNs, there are three focal points that should be looked at meticulously: spectrum acquisition, destructed route recovery and packet relay. Algorithms designed for MCRAHNs should be optimized for these three factors.

2.2. Spectrum Acquisition

Spectrum acquisition is the first step in packet transmission. In MCRAHNs, spectrum acquisition must be done taking into cognizance two disturbing factors which are PUs activity and route destruction. These two factors make the process of spectrum acquisition to be challenging because at times a spectrum channel may be acquired but a routing path is not available and vice versa. Research studies conducted in MCRAHNs show that there is still room for improvement in current techniques deployed for spectrum acquisition.

Routing schemes designed for MCRAHNs must be optimized for queue management for them to successfully share spectrum channels [10]. Numerous algorithms use modified versions of the traditional real time Queue Management System (QMS) for spectrum allocation which deploys the First in First Out (FIFO) technique. The proposed scheme in [10] called C-eNodeB QMS which uses a “type of service” required by spectrum bands to prioritize spectrum allocation is a good example of optimized queue management using the modified traditional real time QMS. This scheme has proved to be effective as it has reduced the delay for spectrum allocation of the traditional QMS by 30%. In other instances, schemes bond spectrum channels to optimize their QMS [11]. In such kind of schemes, the main assumption is that the central controller can dynamically bond parts of the channels in the system to realize resource saving. When spectrum channels are joint and allocated as bonds to SUs, the spectrum channels can be used according to their availability and Quality of Service (QoS). These bonds equip the SUs with a backup plan for PUs demand of spectrum channels. This mechanism reduces packet delivery ratio because all the packets that would have been dropped due to spectrum channel unavailability would be preserved.

Information sharing is another important factor in MCRAHNs which needs optimization [12]. The information about Spectrum availability and integrity must be shared amongst all the secondary users so that they can sense the spectrum based on that information. The information helps in first considering the spectrum bands that were last sensed to be idle before doing a wholesome sensing. Statistical aggregation techniques like the mean-to-square extreme eigenvalue (MSEE) are used for information sharing [13]. This technique was derived from the concept of the arithmetic to algebraic mean. MSSE deploys a system of sensing through the threshold values of the spectrum bands. A specific threshold value of channel strength is chosen before any sensing can be done and that value is used to grade the available spectrum bands if they are worth acquiring or not.

Routing algorithms deploy different techniques for acquiring information about the network before sharing the information. The Artificial Intelligence Q-learning technique has proved to be effective in this regard [14]. In this technique, SUs constantly use Q-learning to acquire information about the state of the network at given intervals and keep the information in the database of the fusion center of the network. This information is used whenever spectrum bands are needed for transmission. This technique is very imperative for spectrum acquisition because it enables the SUs to navigate the spectrum using information that is updated.

2.3. Destructed route recovery

Military operations often require robust systems because the environment they operate in is very harsh. In designing routing algorithms for MCRAHNs, robust route recovery mechanisms should be set in place because destruction is always likely to occur. The route recovery mechanisms should be coupled with spectrum sensing. An efficient routing algorithm should achieve a good spectrum sensing time and have a robust route recovery mechanism.

In MCRAHNs, the proper running of route recovery is done through the CCC. The CCC of MCRAHNs must often do more work than in normal CRAHNs because of possible destructions. It is therefore very important to choose and configure a CCC to be robust and efficient to cope with the harsh demands of military environments [15]. CCCs can be configured in different ways depending on their area of deployment. The configuration of the CCC is important because some CCCs would falter when exposed to harsh environments and that would in turn degrade the performance of the network [16]. Authors in [17] have attributed a lot of inefficiencies and inconsistencies to the wrong choice of the CCC. Destruction can take place at different stages of packet transmission. It can take place when there aren’t any packets being transmitted in the network or when nodes are still busy transmitting packets. The most challenging state is when it happens whilst there are packets still being relayed in the network. The node that would be the last to receive the data packet would have to decide whether to drop the packet or relay it to another node since the transmitting route would be destroyed. A lot of studies have been conducted to try and come up with methods that can be used to deal with this challenge and different approaches have been proposed too.

In [18] a routing protocol called PRoPHET (Probabilistic Routing Protocol Using History of Encounters and Transitivity) was proposed to deal with this challenge. PRoPHET uses the history of encounters to forward packets when direct relaying routes from source to destination are unavailable. In instances where there aren’t any direct routes from the source node to the destination like in the case of MCRAHNs when route destruction has occurred, PRoPHET uses the record of encounters stored by the nodes to decide which node has the highest likelihood of meeting the desired node. In this way PRoPHET reduces packet loss. Since its inception, PRoPHET has been optimized by many researchers, trying to reduce the delay that MCRAHNs incur [19]. Many research studies are being conducted to optimize existent algorithms like PRoPHET and come with new algorithms that can perform well in MCRAHNs.

2.4. Packet Relay

The last step that succeeds spectrum acquisition and all intermediate processes is packet relaying through the available routes. In MCRAHNs, this step has a lot of complexities: at times routes connecting the source and the destination nodes are destroyed. Algorithms designed for MCRAHNs ought to have a backup mechanism to deal with this factor. In mobile networks like MCRAHNs geographic routing (Geo-routing) algorithms are often efficient [20]. In CRAHNs Geo-routing has two ways of routing packets which are dependent on the activeness of the PUs. If the PUs are very active it uses the distance vector approach of routing. If the PUs are not too active then it deploys the greedy geographic forwarding technique. Geo-routing combines distance vector with greedy geographic forwarding to relay packets. It has desirable features which could improve routing efficiency in MCRAHNs. The only major problem is that it is designed for networks which always guarantees source-destination routing paths.

One of the key techniques in designing routing algorithms for MCRAHNs is the usage of dynamic routes rather than fixed routes. Dynamic routing is a routing system that allows nodes to relay packets using real-time knowledge of the network [21]. The nodes don't follow a predefined system of routing, they only route based on the set of constraints given to them and the state of the network. In a study conducted by Michael and Azar, it was found that dynamic routing reduces routing delay by 44% as compared to static routing [22]. The unpredictable structure of MCRAHNs doesn't complement static routing because if destruction occurs, static routing doesn't offer recovery mechanisms.

One other key factor that cannot be overlooked when designing routing algorithms for MCRAHNs is Energy conservation. Energy is a very limited resource in MCRAHNs because the sources that store it are temporal and are also subject to destruction. Routing algorithms designed for MCRAHNs should use Energy sparingly. [23] proposes a new technique for routing in CRAHNs without consuming a lot of energy. This technique combines geographical location of nodes with an interference mitigating system to reduce energy consumption. Energy consumption is linked to interference between PUs and SUs for the acquisition of transmission bands. SUs often cause interference to PUs during packet transmissions especially when the transmission range of the SUs overlap with the ones for PUs. This interference often causes a lot of unnecessary energy consumption as the PUs try to recover and restore linkages.

2.5. Conclusion

In order for routing algorithms to perform optimally in CRAHNs the three above mentioned attributes (packet relay, destructed route recovery and spectrum acquisition) have to be optimized. The nature of MCRAHNs requires a high level of robustness in these attributes. This research project seeks to explore the different factors affecting these attributes and proposes optimization techniques specifically for MCRAHNs.

CHAPTER 3 REVIEWED ROUTING ALGORITHMS

3.1. Introduction

The sporadic unavailability of routes in MCRAHNs degrades the efficiency of most routing protocols. It is because of this factor that most traditional routing protocols falter when deployed in MCRAHNs. This chapter outlines some breakthroughs of studies conducted to mitigate against SM, RP and NR delays in MCRAHNs or similar networks. The one common outcome in all the studies is that the delay incurred in MCRAHNs has always been higher than in normal CRAHNs. It is for this reason that MCRAHNs are categorized as Delay Tolerant Networks (DTNs).

3.2. Algorithms optimized for reducing routing path delay

One of the most common techniques used to mitigate against delay in CRAHNs is the Loosely Coupled Cross Layered Design (LCCLD). In LCCLD, network layers are merged according to the Open Systems Interconnection (OSI) model and optimized for Quality of Service (QoS) to form stronger and more robust layers which can reduce delay. The authors in [24] proposed a routing scheme that combines routing with resource allocation for mesh CRAHNs. This scheme routes packets based on the resources of spectrum channels that are supposed to provide sufficient quality of service. When routing packets in mesh CRAHNs, depending on the PU activities, traffic load and density, the available spectrum resources vary between mesh transmission attempts [25]. The variations in QoS are caused by PU activities and the traffic load. More PU activities result in less QoS for the channel. This then means that there will be less QoS for the SUs available in the channel.

This scheme joins routing with resource allocation which culminates in a scheme that reduces end-to-end delay. Before a path can be chosen, this scheme considers the resources available in the vacant spectrum channels which should sustain the transmission until it is completed. The channel with more QoS/resources is then selected. The transmission route is chosen with respect to the probability of the transmission link sensing an idle primary channel. These two methods: resource checking and the idle channel probability are joined together in routing packets. This scheme was compared to

Delay-motivated on-demand Routing Protocol (DORP) and a disjoint scheme which routes first and then allocates the resources along the constructed paths. The results of the simulations in [24] show that this scheme outperforms the two other schemes which have been simulated against it.

The LCCLD approach reduces delay by providing QoS for the packets to traverse the network but incurs a lot of routing overhead in the process. The other problem with implementing this scheme in MCRAHNs is that it assumes that the paths available from source to destination nodes are definite and are stored in routing tables, which is not the case in MCRAHNs because routing paths are subject to destruction at any given time. Schemes of this kind are well suited for traditional CRNs but not for MCRAHNs.

One other routing method that is frequently used in mobile ad hoc networks is the shortest path selection based on the Dijkstra algorithm. It is an efficient way of finding the shortest paths to the destination in small and medium sized algorithms. In [26] we are introduced to a routing protocol called Spectrum Aggregation-Based Cooperative Routing Protocol (SACRP) which is based on aggregation cooperative routing and shortest path selection. SACRP has proven to be efficient in reducing end to end delay. For route selection, SACRP uses the shortest path selection method. This algorithm combines these two main features and integrates them into one robust and efficient algorithm. The first step this algorithm takes in route selection is discovering unutilized routes. It calculates the route distance of every unutilized path. The information about the unutilized routes is compared to the stored route information and the shortest path is selected from there. It is important to note that the process of checking for unutilized routes is done through sending packets to neighboring nodes. When the shortest route selection is done, then the route request message is sent from the source to the destination, the source then selects the shortest route from the response message which is from the destination which passes through other nodes. The one distinct feature that SACRP uses in reducing end to end delay is the retransmission of packets done at each hop. SACRP retransmits packets at each hop to increase the packet arrival rate on all the hops that packets traverse.

SACRP also introduces a method of choosing nodes which has better channel conditions. These channel conditions are given priority because good channel conditions increase the chances of successful packet transmission without interference.

Routing based on channel conditions is a good method for reducing spectrum mobility delay. Channel conditions must be considered so that transmissions can always stand a good chance of being successful. This protocol proposes a feature that is very important for the reduction of spectrum mobility delay in CRAHNs, but it wouldn’t be operational in MCRAHNs. It lacks the ability to buffer packets until routing paths are discovered and, in that way, it will drop packets. Its features can be included in an algorithm which is for intermittent CRAHNs for the reduction of spectrum mobility delay.

Spectrum mobility in MCRAHNs makes it more challenging to design efficient routing algorithms. Most routing algorithms fail to cope with the dynamicity of spectrum bands and end up failing to take full advantage of the available spectrum channels. A spectrum-aware routing scheme for CRNs called Spectrum-Aware Semi-Structure Routing (SSR) was proposed to optimize spectrum acquisition. SSR is mainly based on taking full advantage of the spectrum bands since “most of the existing routing algorithms for CRNs either cannot fully take account of the spectrum dynamics or are resource aided which may introduce too much cost” [27]. SSR is a joint routing scheme, joining routing with a power control framework. Power control is often used in Wireless Sensor Networks (WSNs) to prolong the lifetime of a network. It is also very important to consider for MCRAHNs since the unguaranteed paths can make nodes to buffer packets for a long time which demands a lot of energy from the nodes.

SSR relays packets based on the residual power inherent in the nodes. The process starts with the choosing of a source for a forwarding zone, then forwards a packet to a node in that zone. The node in the forwarding zone chooses a node to relay the packet based on the level of the transmission power. If the available power is above the threshold, then the intermediate nodes can transmit to far away nodes. If the power is below the threshold then the intermediate nodes will have to transmit to nearby nodes. The power threshold of the nodes is chosen before the any transmissions can be done and is always constant.

SSR was compared to two joint routing algorithms: the coolest algorithm and the shortest algorithm. SSR outperformed the two algorithms by a margin [27]. The results show that SSR keeps the lowest latency amidst an increasing PU activity. The main factor which makes SSR to be more efficient is that since it starts by choosing a forwarding zone based on the available residual energy, it makes an informed decision before relaying packets by only considering nodes with an above threshold energy level.

3.3. Routing algorithms optimized for reducing NR delay

Node mobility is another challenge which highly impacts the designing of routing algorithms in MCRAHNs. The location and dispensation of nodes in ad hoc networks determines the routing approach. In large networks, factors like the transmission range also adds to this challenge whereby some nodes are outside the transmission range of the sending node. Georouting (Geographic routing) is focused on dealing with this challenge. In Georouting the source node sends packets to the geographic location of the destination, not its network address.

The authors in [28] proposed a protocol called the Internet Protocol spectrum aware geographic based routing protocol (IPSAG) for routing in CRNs using geographic location and spectrum awareness. IPSAG is based on routing with predefined knowledge of the spectrum and of the nodes’ geographical location.

In IPSAG, all the nodes have the required information about the geographic location of all the nodes that are within the specific network. When a node receives a packet, it first starts by checking through its buffer for the location of the destination node, then forwards the packet using the Greedy forwarding strategy: the next hop must be the closest current node’s neighbor to the destination. IPSAG also checks for the nodes which have common spectral quality before it forwards the packets. If the transmitting node has the option of relaying to two or more nodes through the Greedy forwarding strategy, then the spectral features are evaluated. The node that will offer more QoS in terms of spectral quality will be chosen for routing.

IPSAG was compared to other best performing algorithms: On-Demand Routing Algorithm (AODV) and Spectrum Aware Routing for Cognitive ad-hoc Networks

(SEARCH). IPSAG outperformed these two routing algorithms in terms of efficiency [28]. The evaluation of IPSAG was done through a proposed scheme called Common Spectrum Opportunities that was developed in the designing of IPSAG. This metric is used to check for common spectral opportunities between the current node and the nodes within the routing path. The node with similar spectral opportunities with the transmitting node is given preference based on this metric.

Though IPSAG outperforms two common best performing protocols, if it were to be deployed in intermittent military networks, it would drop packets doe to time-outs because there wouldn't be guaranteed routes. IPSAG in some instances wouldn't be able to buffer packets until candidate nodes are available since its buffering capacity is not configured for long waiting times in the case of unavailable routes.

3.4. Routing algorithms optimized for reducing SM delay

The complexity of spectrum usage is not only in the mobility, spectrum heterogeneity also makes it more challenging to design efficient routing algorithms. In MCRAHNs, spectrum acquisition is mainly dependent on PUs activity and QoS. The design of routing algorithms must address those two major factors.

The authors in [29] proposed a protocol called Stability-based Spectrum-aware Routing Protocol (SSRP) for mobile cognitive radio ad-hoc networks. This protocol is based on three processes: avoiding interference to PUs during route formation and data transmission, performing joint next-hop selection and selecting the best channel at each node to improve route stability for better network performance.

SSRP efficiently coordinates data flows between secondary systems with heterogeneous spectrum availability in ad-hoc cognitive radio networks architecture. Efficient protocol operation as a matter of maximum-possible routing paths establishments and minimum delays is obtained by a coordination mechanism, which was implemented based on a simulation scenario [30]. The simulation scenario focuses on several secondary systems that exploit television white spaces. The validity of the research approach is verified via several experimental tests, conducted under controlled simulation conditions and evaluating the performance of the proposed routing protocol [30].

SSRP is based on Spectrum awareness, but it doesn’t directly address the delay that is incurred by spectrum mobility. SSRP doesn’t offer any mitigation mechanisms for spectrum mobility delay.

Most of the available protocols in MCRAHNs cannot be directly applied to time-critical automation applications due to spectrum mobility, node mobility and unpredictable PUs activities [31]. A protocol called Delay-Minimized Routing (DMR) has been proposed to address this problem. In designing DMR, a model was developed based on conflict probability. This model is used to detect any forms of routing conflicts in the network which may come because of having routing paths which are of the same value [32]. The model helps in resolving the probability conflict. In this study a new routing metric called the minimum path delay was also proposed. This metric is used to evaluate the delay that is incurred in routing protocols. By using the conflict probability model, DMR outperformed related protocols in end-to-end delay, minimum path delay, throughput and packet loss rate.

An algorithm called Mobility-Assisted Routing algorithm with spectrum awareness (MARSA) has been proposed. MARSA is an algorithm for intermittent CRAHNs [33]. It incorporates two factors which are often overlooked by routing algorithms in intermittent CRAHNs: spectrum availability and node mobility. When routing packets in intermittent CRAHNs, the challenge is not only unguaranteed paths, a path can exist at a given time but then the spectrum might not be available. When the spectrum is unavailable at a given time, it creates a problem because there is a great possibility that when the spectrum becomes available, the path would then be unavailable because intermittent paths are not fixed.

MARSA guarantees that whenever a routing path is chosen, there exists at least one spectrum band. The results of MARSA show that it outperforms the current available intermittent CRAHNs routing algorithms. MARSA was compared to the Epidemic, MobySpace and Basic algorithms. In the simulations conducted MARSA achieved a high delivery ratio. In intermittent networks, delivery ratio is very important, most algorithms cannot deliver packets to other nodes because in most cases when there are no available paths, algorithms tend to drop packets to allow the system to flow.

The other metric that is very important to consider in intermittent networks is the delivery latency. MARSA has a low delivery latency [33]. With the combination of high packet delivery and low delivery latency, MARSA is indeed a good algorithm for intermittent networks. The problem with MARSA is that it doesn’t address spectrum mobility delay which is a factor that can greatly improve its latency performance.

A model has been introduced for the predictable contact of nodes in CRAHNs. The problem of routing in intermittently connected networks is mainly caused by the unavailability of fixed routing paths [34]. This model introduces a way of using predictability in the contact of nodes to derive future information about the network with regards to routing.

This model was simulated using the random walk mobility scenario. In the random walk scenario, the nodes are assumed to freely move within a given space at whichever speed without movement restrictions.

Predicting contacts in intermittently connected networks is a good strategy but the problem is that there might be great variations in how the nodes move which causes the model used for nodes contacts to be inaccurate.

A protocol called spectrum and connectivity aware anchor-based routing protocol for cognitive radio vehicular ad hoc networks (CR-VANETs) has been proposed. This protocol has two modes: decision mode and forwarding mode. The decision is taken at the junctions to select the path which is highly connected and which has common idle channels between communicating vehicles. In forwarding mode, vehicles select the next relay node based on channel state (idle/busy), distance, and link lifetime [35]. The scenario that is used is that of a vehicle-to-vehicle communication in a city for both connected and sparse networks. CR-VANET shows improvement in packet delivery ratio in comparison with existing protocol predefining their movement.

This protocol is effective in CR-VANET but wouldn’t adapt well to military networks because not all nodes in intermittent military networks are vehicular, the nodes are different and in all the nodes, the chance of node destruction must be factored in. CR-VANETs do not take this matter into consideration. It doesn’t have buffer features that would hold a message as the node is still trying to locate the best suited candidate to route to.

3.5. Routing algorithms optimized for increasing throughput

One of the most challenging factors in military networks is the dynamicity of the topology that might be caused by the destruction of nodes. Depth-First Search Routing Protocol (DFSP) for mobile military networks was proposed to focus on the adaptability of nodes for routing in military environments where nodes are subject to possible destructions [36]. DFSP uses depth-first search method to navigate through the network for routing paths and nodes.

DFSP guarantees shortest path to the destination, but because of the depth-first search method, it ends up considering paths that are very long which causes routing path delay. DFSP uses hints about the network to navigate in an informed way. Hints are the information about available paths and node proximity that is learned and stored by the nodes in the network. The hints are stored in a special repository in the network, which can be accessed by all the nodes for information retrieval. These hints help in guiding the depth-first search, making the search smarter in choosing routing paths.

In the DFSP, the source node first sends a search message for transmitting. This search message contains the following parameters: source, destination, sequence number, priority, QoS, flag, next Hop and the table of the previous hop. These parameters are used to gather information about the network which will be stored in the hints repository

The subnetworks of military networks often differ in characteristics. It is often possible that the subnetworks differ in capacity or range or mobility. In trying to connect such networks, it is difficult to establish the connections without increasing the routing overhead, DSFP aids in such situations. Routing between such networks requires a change in the routing operation. Since the subnetworks differ, it means the change of routing operations is going to be very dynamic. DFSP offers tools which allow for dynamicity.

DFSP has proved to be effective and has good features that would probably make it more efficient than most traditional CRAHNs algorithms to be deployed in an intermittent environment, but it does not address spectrum mobility delay. If an algorithm like DFSP would factor in spectrum mobility delay, it would greatly lower its delay and increase its efficiency.

In intermittently connected networks, packets are often replicated with the hope of them reaching the destination since the connections are not fixed. This system of routing packets often causes unnecessary congestion in the network and on nodes since some of the packets which have already been received will still be in the network as a result of them being replicated several times. In [37] we are introduced to a routing protocol called Ferry Enhanced PROPHET (Ferry) for mitigating against congestion due to packet replication.

Nodes called ferry nodes are used to control the replication of the packets. The ferry nodes move around the network. When the ferries encounter other nodes in the network, they exchange information. The main information that they exchange is the packets that the nodes are carrying. If the ferry nodes check through the encountered node and finds a packet that has already been delivered, the node must mark the packet as delivered. The node then proceeds to the other nodes and exchanges the information with them. The packet is then deleted when all the nodes have updated their storage buffers.

Ferry was compared with the epidemic algorithm and has outperformed it. Ferry achieved a higher delivery ratio than the normal epidemic algorithm. Ferry was derived from an algorithm called PRoPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) which is an old algorithm that uses transitivity to route packets in intermittent networks [38].

Most intermittent algorithms flood the network with copies of packets. They replicate the routing until the destination receives the packet. In the evaluation of Ferry, this factor is used as a metric. Ferry has lesser packet copies than the epidemic and PRoPHET algorithms.

Ferry is indeed a good improvement of the old PRoPHET, it just lacks spectrum awareness to make it deployable in MCRAHNs. Its features for routing in intermittent networks are considered for our research project, but it cannot be deployed in CRNs, it is not well designed for that, in its design there are no provisions for using the spectrum opportunistically.

The problem of network congestion is one of the main challenges in intermittent CRAHNs as most routing algorithms reroute packets until the destination nodes receive them and that results in many packets loaded into the network that have been rerouted even after the destination nodes have received. The authors in [39] proposed an algorithm which mitigates against packet replication called Reduced Variable Neighborhood Search-based Spray and Wait (RSW). RSW is an improvement of the traditional Spray and wait.

RSW uses a congestion threshold value which determines the rerouting of packets from source nodes. Before a packet can be rerouted, the congestion threshold is calculated to determine if the packet should be sent as an ordinary Spray and Wait (SW) or it must wait for another forwarding opportunity [40].

Each node has a buffer which stores the packets to be forwarded. These buffers are used to calculate the congestion threshold. If the destination node has an empty buffer, then more packets can be sent (sprayed), if it is full, some packets will have to be discarded which will then require the other nodes to wait.

RSW was compared to Spray & focus and the Spray & wait Algorithms and it outperformed them. The evaluation was based on the Delivery Ratio, Overhead Ratio and Average Latency metrics.

One of the routing approaches that have been proposed for intermittent networks is backpressure routing. Backpressure routing is a packet transmitting approach for dynamically routing traffic over a multi-hop network by using congestion gradients. A routing algorithm called Backpressure with Adaptive Redundancy (BWAR) has been proposed, this algorithm improves on the shortcomings of the basic backpressure routing algorithm [41]. BWAR addresses two possible scenarios in intermittent mobile networks. The first scenario is for when the transmission network links are congested, and the second scenario is for when there aren’t many packets in the links. The traditional backpressure algorithms work well when there’s a lot of traffic congestion, but falters when there isn’t much traffic since it uses a lot of energy.

When there isn't much traffic load, BWAR creates replicate copies upon node encounters that are stored in the buffer. These replicated copies are only transmitted when the queue is empty. In this way, destination nodes are more likely to meet packets intended for them because of the many replicated packets and packet looping is reduced.

When there's high load BWAR works like the traditional backpressure algorithms. In such conditions BWAR doesn't duplicate packets because they will cause more load which will increase the delay. In high load conditions BWAR routes packets based on the loads on different queues. It intelligently navigates between queues for the queue with the least of packets. In this way BWAR does not require prior knowledge of locations, mobility patterns, and load conditions which are methods used by most intermittent CRAHN routing algorithms [42].

BWAR also proposes a new method of controlling duplicated packets caused by the process of spraying packets into the network with the intention of one of them reaching the destination. The packets are given timeout stamps. When a packet has reached its timeout, it will be automatically dropped so that it doesn't block the routing progress [43].

The problem of relaying packets is very eminent in Sleep-Wake Cycling Wireless Sensor Networks (WSN) whereby the paths from source to destination are not definite and guaranteed. Due to the limited energy, the nodes must take turns in being active. Each node is given a period for its activeness. In the case of a node relaying a packet, the candidate nodes that it can relay to can either be awake or asleep. Such a network is intermittent as there is no guarantee of fixed available paths. The main challenge is coming up with a routing algorithm that can perform well in such an environment without incurring a lot of end-to-end delay and node relay delay.

Numerous algorithms have been introduced to deal with the delay in these kind of networks [44]. The one common challenge among the algorithms designed for this kind of networks is that they lack the cognitive features required for opportunistic usage of the spectrum. In performing our research project, we shall put into perspective some of the features of Sleep-Wake Cycling WSN as they share some similarities with intermittent CRAHNs.

3.6. Commonly used algorithms in MCRAHNs

One of the most popular routing algorithms for MANETs is the Ad Hoc On-Demand Distance vector (AODV) routing algorithm [45]. AODV is also being deployed in MCRAHNs and it is one of the algorithms that are performing well. AODV only establishes routes when a source node requests for packet transmission to a desired node, which means that it is reactive. This reactive feature is what makes the algorithm to be compatible to MCRAHNs because in all CRNs, the algorithms that cope well with the dynamic spectrum channel switching are the reactive ones.

AODV uses sequence numbers to maintain path freshness. Path freshness is very important in MCRAHNs because there is always a high likelihood that a path still exists if it is still considered “fresh” in the buffers of the network. AODV differs from other on-demand routing protocols in that it uses sequence numbers to determine an up-to-date path to a destination. The entries in the routing table are each allocated a sequence number. The sequence number acts as a route timestamp, ensuring freshness of the route. Upon receiving a Route Request (RREQ) packet, an intermediate node compares its sequence number with the sequence number in the RREQ packet. If the sequence number already registered is greater than that in the packet, the existing route is more up-to-date [46].

AODV has a multicasting version which is also deployed a lot in MCRAHNs called Multicasting Ad Hoc On-Demand Distance vector (MAODV). It is similar to it except that MAODV gives the option of choosing a specific portion of the network for multicasting [47]. Multicasting in MAODV can be done in various ways depending on the nature and state of the network. One of the setbacks for MAODV is that it offers less route repair functionality. In the case of link breakages, instead of MAODV resuming from the last node that held the packet before breakage, it starts transmission from the source node.

One other routing protocol which is widely used in MCRAHNs is the Extended Weighted Expected Transmission Time (xWCETT). xWCETT uses on-demand weighted cumulative expected metric to select the best path between the source node and the destination node [48]. When a route is needed between two nodes, the routing process is initiated, and the source node sends a route request (RREQ) packet across the network. The RREQ packet transmitted by a node on a channel contains the calculated value of weighted cumulative transmission time. When an intermediate node receives a RREQ packet with a valid route to the destination specified in the RREQ, it only sends a route response (RESP) packet to the source if the received RREQ's destination sequence number is less than or equal to the destination node's sequence number in the route entry. When a node receives a RREQ packet destined for the destination node, it only sends back a RESP if the received RREQ's cost is smaller than the previous received RREQ with the same sequence number. The source node will finally use the path having the lowest cost for data transmission and stores locally the other best paths.

Table 3-1 summarizes the strengths and weaknesses of all these algorithms by rating them according to their capabilities in an MCRHANs environment. These algorithms form part of the background for this research project: our proposed algorithm was compared to them to prove its efficiency.

Table 3-2 Analysis ratings of available ICRAHNs algorithms

Routing Algorithm	**Route Recovery**	**Scalability**	**Energy Consumption**	**Spectrum Acquisition**	**Routing Overhead**
MARSA	*Good*	*Average*	*Good*	*Good*	*Good*
AODV	*Average*	*Good*	*Average*	*Bad*	*Average*
MAODV	*Good*	*Average*	*Average*	*Bad*	*Average*
xWCETT	*Good*	*Average*	*Average*	*Good*	*Good*

Rating scale: *Bad-Average-Good-Excellent*

The algorithms in table 3-1 have been rated according to their capabilities in MCRAHNs environments, not traditional CRAHNs or (Mobile Ad hoc Networks) Manets. The capabilities and performances of these algorithms are expounded fully in chapter 4 and 5 where they are simulated.

3.7. Conclusion

The reviewed literature has proven that though many studies have been conducted for the reduction of delay in CRAHNs and intermittent networks, there’s still a need for a research project that should address node relay delay, spectrum mobility delay and routing path delay as a unit and also design algorithms which mitigates all these three different types of delays. The available algorithms only address these delays individually. The other deficiency shown by the literature is that most of the algorithms which address delays in intermittent networks are not for CRNs. In our research project, we combined these three delays in MCRAHNs and designed an algorithm that is optimized for them all.

CHAPTER 4 IMPLEMENTATION METHOD OF THE PROPOSED ALGORITHM

4.1. Introduction

The implementation of our proposed algorithm and comparisons with existent algorithms were carried out on a simulation bed. The simulated algorithms were evaluated on six different metrics. For metrics which were calculated on averages, further statistical analysis was done to evaluate if there is a significant difference in the results. All the findings of this research project are based on the results from the simulations and the statistical analysis.

4.2. Simulation tools overview

The simulations required a network simulator optimized for testing routing algorithms and one that supports setup for MCRAHNs, node-compatibility and single stations. For simulating routing algorithms with those requirements, there are three possible simulators that can be used: Optimized Network Engineering Tool (OPNET), Network Simulator Version 2 (NS2) and Network Simulator Version 3 (NS3). Simulators are chosen based on the specific components that are tested in the routing algorithms as they differ in features and specialties.

NS2 and NS3 are discrete-event network simulators from the same family, NS3 is an Upgraded version of NS2 but they are independent of each other, so, NS2 can’t be implemented in NS3 [42]. They are similar in most of their features, but they differ in simulation implementation and defined libraries. NS2 has more inherent defined routing algorithms meanwhile most algorithms in NS3 are coded from scratch as its library only contains a few algorithms [49].

4.3. Simulation Tools deployed in our research project

The simulation tool chosen for this research project is NS2.31. It was chosen because, its features were found to be the most relevant to the requirements of this research project. OPNET has a wide algorithm library which would be good for this research project, but it lacks full support for CRNs which a key component of this research project. NS3 has more advanced features compared to NS2 and it offers more support for CRNs, but its library doesn’t have many algorithms and requires that most algorithms be coded from scratch. Based on the requirements of our research project, NS2.31 was the most befitting because of its wide library and full support of MCRAHNs. Its Library contains the algorithms required for this research project and those algorithms can be implemented in MCRAHNs as it offers full support for CRNs.

NS2.31 uses C++ and OTcl programming languages. C++ is used for setting up the simulation environment through coding. OTcl is used for visuals since C++ doesn’t offer good visual features. C++ is also used to implement the features of the protocol and OTcl is used for user interfaces to allow users to control the simulation scenarios and schedule the events [50].

For further analysis and visualizations, we used Gnuplot, trace analyzer and Microsoft excel. Gnuplot and trace analyzer were used for graphing the results from NS2.31. Microsoft excel was used for the statistical analysis and for evaluating the level of significance of the results. The process of evaluating the level of significance is very important in the results that are presented as averages because the averages don’t fully reflect the difference between the comparative outcomes.

NS2.31 was installed on a 32-bit computer with a LINUX UBUNTU 12.01 LTS operating system. The computer had a 3gigabytes Random Access Memory (RAM) and 320 gigabytes hard drive.

4.4. Simulation metrics

The metrics that we used to evaluate the performance of the algorithms are spectrum mobility delay, node relay delay, routing path delay, throughput, packet delivery ratio and packet delivery latency. These metrics are for both packet relaying and spectrum bands acquisition.

Spectrum mobility delay: this is the delay that is incurred during the process of switching between spectrum bands due to the PUs and SUs activities. When SUs switch between spectrum bands, the process of routing halts, waiting for the SUs to find a vacant channel for packet transmission to continue [51]. The time it takes an SU to move from one spectrum channel and acquire the next one is called Spectrum mobility delay.

Node relay delay: this is the delay that is incurred whenever packet transmission is done between intermediate nodes. All the factors that contribute in delaying the process of relaying packets from one node to the next constitute into making up node relay delay [52].

Routing path delay: this is the overall delay incurred from source node to the destination. This delay is mostly caused by link breakages in MCRAHNs [53].

Throughput: this is the success rate of packets transmitted from the source nodes to the destination nodes. In MCRAHNs this metric is often challenging to optimize because of the breakages in routes which lead to packet loss [54].

Packet delivery ratio: this is the metric that measures the ratio of packets which have been successfully delivered to their right destinations compared with the ones that couldn’t reach their destinations [55].

Packet delivery latency: The amount of time it takes a data packet to move from one node to the desired node [56].

4.5. Our Proposed algorithm

The algorithm that we are proposing is called Spectrum Aware Transitive Multicast on Demand Distance Vector (SAT-MAODV) algorithm. SAT-MAODV combines multicasting routing, reactive distance vector routing, spectrum awareness and transitivity together to form a more robust and resilient algorithm.

SAT-MAODV uses a multicasting approach which we have enhanced specifically for our proposed algorithm, we termed this approach: Informed Centralized Multicasting (ICM). ICM chooses specific portions of the network for routing based on the information collected by the nodes in the MCRAHN. One of the features of ICM which makes it distinct is that the selection of the network portion is done based on the completeness of the portion with regards to the destination. Even if the portion doesn’t have the destination connected to it due to route breakages and transmission range, the portion of the network selected should have a higher probability of relaying to the destination. This is achieved by another technique that we are proposing called Node Roaming Area (NRA). Every node in the MCRAHN has a specific area that it is most likely to move to since military networks are strategically positioned. Every node in the network has a buffer storage to store the locations of encounters. Whenever nodes meet they exchange location information that is stored in their buffers and would be used to make informed decisions during link breakages. We call the area where a node frequents the NRA.

SAT-MAODV works in a reactive way, it doesn’t pre-plan routing, but routes according to the state of the network. In the case of link breakages SAT-MAODV uses what we have termed Energy Smart Transitivity (EST). EST is an improvement that we are proposing to enhance the old transitive routing method. The old transitive method is represented by the following equation [57]:

$$\forall \; A, B, C \in X, \; if \; A \subset B \; and \; B \subset C \; then \; A \subset C \qquad (4\text{-}1)$$

$where \;\; A, B, C = nodes \; with \; different \; energy \; level$

$X = MCRAHN$

$\subset \, = meeting \; likelihood$

This equation means that if “node a” has a high likelihood of meeting “node b” and “node b” a high likelihood of meeting “node c” then we can infer that “node a” has a high likelihood of meeting “node c”. This transitive method was first introduced in intermittent networks through the algorithm PRoPHET. The core of its routing method is to relay packets which have the highest likelihood of meeting the destination in cases of route breakages/ destruction.

For our research project, we improved on this approach by adding the energy factor. The traditional transitive method doesn’t consider the energy of the nodes. It only relays packets based on meeting likelihood. Our proposed method of EST can be represented by the following equation:

$$\forall \quad A_{i1}, B_{i2}, C_{i3} \in X,\ if\ \ A_{i1} \subset B_{i2}\ and\ B_{i2} \subset C_{i3}\ then\ A_{i1} \subset C_{i3}$$

$$if\ and\ only\ if\ i1, i2, i3 \geq K \qquad (4\text{-}2)$$

$where$:

$A, B, C = nodes$

$i1, i2, i3 = different\ energy\ levels\ of\ the\ nodes$

$X = MCRAHN$

$\subset = meeting\ likelihood$

$K = threshold\ Energy\ value$

The EST approach improves on transitivity by evaluating the energy levels of nodes. In situations where it is inferred through transitivity that “node A” has a high likelihood of meeting “node C” we first check the energy level of “node C”. If the energy of “node C” is below the threshold value, then it doesn’t transmit the packet since “node C” won’t have sufficient energy to relay it to the next node and that packet will be lost. The packet is instead relayed to the second-best candidate to meet the desired node. This approach reduces RP delay and NR delay because in the case of route breakages candidate nodes with a high likelihood to meet the desired node are chosen and new routing paths are formed in the process. Packet transmissions hardly come to a halt unlike in other algorithms that don’t have a backup system for route breakages. EST also improves the throughput because packets are hardly lost due to energy failure in nodes. ICM, NRA and EST in SAT-MAODV can be presented by the following stepwise algorithm:

Algorithm 4-1 The Stepwise Algorithm of ICM, NRA and EST for SAT-MAODV

```
For all nodes in the MCRAHN
IF nodes encounter each other (1cm proximity)
Record location in the buffer
When node $A_{i1}$ must relay a packet to node $l_{i2}$
Send node $l_{i2}$'s location request to all the nodes
Then two nodes with the highest encounter record send the location record of node $l_{i2}$
Let the network portion from source to destination be considered for centralized Multicasting
If there is route destruction in the chosen network portion
If node $A_{i1} \subset$ node $H_{i3}$ and node $H_{i3} \subset$ node $l_{i2}$
If $i1i2i3 > K$
Let node $A_{i1}$ relay packet to node $l_{i3}$
Else let node $A_{i1}$ buffer the packet and look for the second candidate node with high encounter probability of node $l_{i2}$
```

SAT-MAODV uses a more integrated system of spectrum acquisition that we have termed Time-Based Availability (TBA). Spectrum bands are often used by the PUs at specific times which can be patterned. The PUs can utilize their bands at any time, but the time patterns of the PUs activity per spectrum band can be modelled. There are some spectrum bands which are mostly used at certain periods and are vacant at certain time intervals. SAT-MAODV uses TBA to first start by checking the time when a spectrum band is needed. The nodes will then retrieve from their information buffer of the bands which are usually available at that specific time interval. This approach reduces spectrum mobility delay because instead of navigating the whole spectrum, only a specific group of bands is considered depending on the time of transmission. Our TBA technique can be Modelled and presented by the following equation [58]:

$S = \{s_1,\ s_2, \ldots, s_t\}$ (4-3)

Where:

$S =$ set of spectrum bands availability states.

It is important to note that since this equation is derived from the Markov Chains model, the state of each spectrum band is not dependent on its predecessor's state of availability. Each state is independent of its predecessor:

$k_{tm} = k_{tt}k_{mt} + k_{ti}k_{mi} + \cdots + k_{tm}k_{mm}$ (4-4)

Where:

k_{tm}= the availability state of the spectrum Channel.

$k_{t\ldots}$= the vacant spectrum channel when the routes are unavailable

$k_{m\ldots}$= the vacant spectrum channel after route recovery

The overall state of availability for the spectrum channels can be summarized by the following formula:

$k_{tm}^{(2)} = \sum_{i=1}^{p} k_{ti}\, k_{mi}$ (4-5)

Where:

$k_{tm}^{(2)}$= the availability state of the spectrum Channel.

$k_{t\ldots}$= the vacant spectrum channel when the routes are unavailable

$k_{m\ldots}$= the vacant spectrum channel after route recovery

The above formulae show how the availability of the spectrum states are independent of each other because the determining factor in their availability is time, not the activity of their predecessor's availability.

The main features of SAT-MAODV are ICM, NRA, EST and TBA. The relationship of SAT-MAODV and its optimizers follow a linear regression model of four constituting variables [59].

$$Y_{i\dots} = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \varepsilon_i \qquad \text{(4-6)}$$

$where$:

$Y_{i\dots} = SAT - MAODV\ performance\ efficiency$

$\alpha = intercept\ of\ performance\ efficiency$

$\beta_{1\dots} = the\ slope\ of\ the\ model$

$x_{i1} = ICM$

$x_{i2} = NRA$

$x_{i3} = EST$

$x_{i4} = TBA$

$\varepsilon_i = Standard\ Error\ (constant)$

To further prove the efficiency of SAT-MAODV we use a statistical t-test analysis to see if there's a significant difference in our results. The following are the formulae and variables that we have used for our t-test analysis of all our results [60]:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad \text{(4-7)}$$

$\bar{x}_1$ = mean of values of the first algorithm

$\bar{x}_2$ = mean of the values of the second algorithm

s_1= standard deviation of values of the first algorithm

s_2= standard deviation values of the second algorithm

n_1 = total number of values of the first algorithm

n_2 = total number of values of the second algorithm

$$S = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \qquad (4\text{-}8)$$

Where,

x = the values of either of the two algorithms

$\bar{x}$ = mean/average

n = total number of values.

The algorithms were simulated for 6, 35 and 70 nodes with 100, 300 and 500 seconds for each set of nodes respectively. The simulation times are directly proportional to the number of nodes because more nodes require more time to fully study the behavior of the network and the efficiency of the algorithm. Table 4-1 contains all the other parameters of our research project.

Table 4-1 Simulation Parameters

Number of Nodes	6,35,70
Simulation Time(s)	100s,300s,500s
Packet Size (bytes)	512
Environment size (m X m)	500 X 500
Traffic Rate/ Rate	Constant Bit Rate (CBR) 4 packets/s
Nodes Velocity (m/s)	12~15
Transmission Range (m)	90,120,150,180
Maximum Number of connections	15,25,35
Pause Time(s)	0,50,100,250,350,500
Number of Radios	2
Simulated Algorithms	SAT-MAODV, AODV, xWCETT, MARSA
Antenna	Omni-directional
MAC Standard	IEEE 802.11b
Number of PUs	2,10,30
Number of SUs	4,25,40 (For each set of nodes)

4.5. Conclusion

This chapter gave us the background layout of the implementation of our research project. It also introduced SAT-MAODV which is our proposed algorithm. SAT-MAODV integrates multicasting with spectrum awareness, reactive and transitive routing. The main features of SAT-MAODV which make it distinct are ICM, NRA, EST and TBA.

SAT-MAODV was simulated with the other algorithms using the same set of simulation parameters. The next chapter will present the results of the simulation to evaluate the performance of SAT-MAODV compared to the other algorithms.

CHAPTER 5 RESULTS AND ANALYSIS

5.1. Introduction

In the previous chapter, we gave the premise for our simulations. In table 4.2 we outlined the parameters and the network structure that our simulations will be done under. In this chapter, we visualize and analyze the results of the simulations discussed in chapter 4. There are many Reactive Routing algorithms designed for MCRAHNs but for this research project, we have only picked four of the current best performing as mentioned in chapter 4. We took these four algorithms and simulated them against our proposed algorithm (SAT-MAODV) to see how it fairs against them on six different performance metrics.

5.2. Simulations

The simulated algorithms are Multicast On-Demand Distance Vector algorithm (MAODV), On-Demand Distance Vector (AODV), Extended Weight Cumulative Expected Transmission Time (xWCETT), Spectrum-Aware Transitive Multicast On-Demand Distance Vector (SAT-MAODV) and Mobility-Assisted Routing algorithm with Spectrum Awareness (MARSA).The analysis of our results is divided into two sections: in the first section we support the choice of our base algorithm for enhancement (MAODV) by proving why multicasting is more efficient than normal routing in MCRAHNs. We do this by simulating AODV against MAODV. In the second section we compare our proposed algorithm to other best performing ones. We used six metrics to asses the performance of the simulated algorithms: Routing Path (RP) delay, Spectrum Mobility (SM) delay, Node Relay (NR) delay,Throughput, packet deliver ratio and packet delivery latency.

5.2.1. Proving the choice of multicasting over normal routing for MCRAHNs

In this section we prove why multicasting is more efficient than normal routing and why we chose MAODV as our base algorithm.

5.2.1.1. RP delay simulation results for MAODV and AODV

The first set of results for our simulations is depicted in Figure 5-1, these are the Routing Path (RP) delay results of AODV and MAODV.

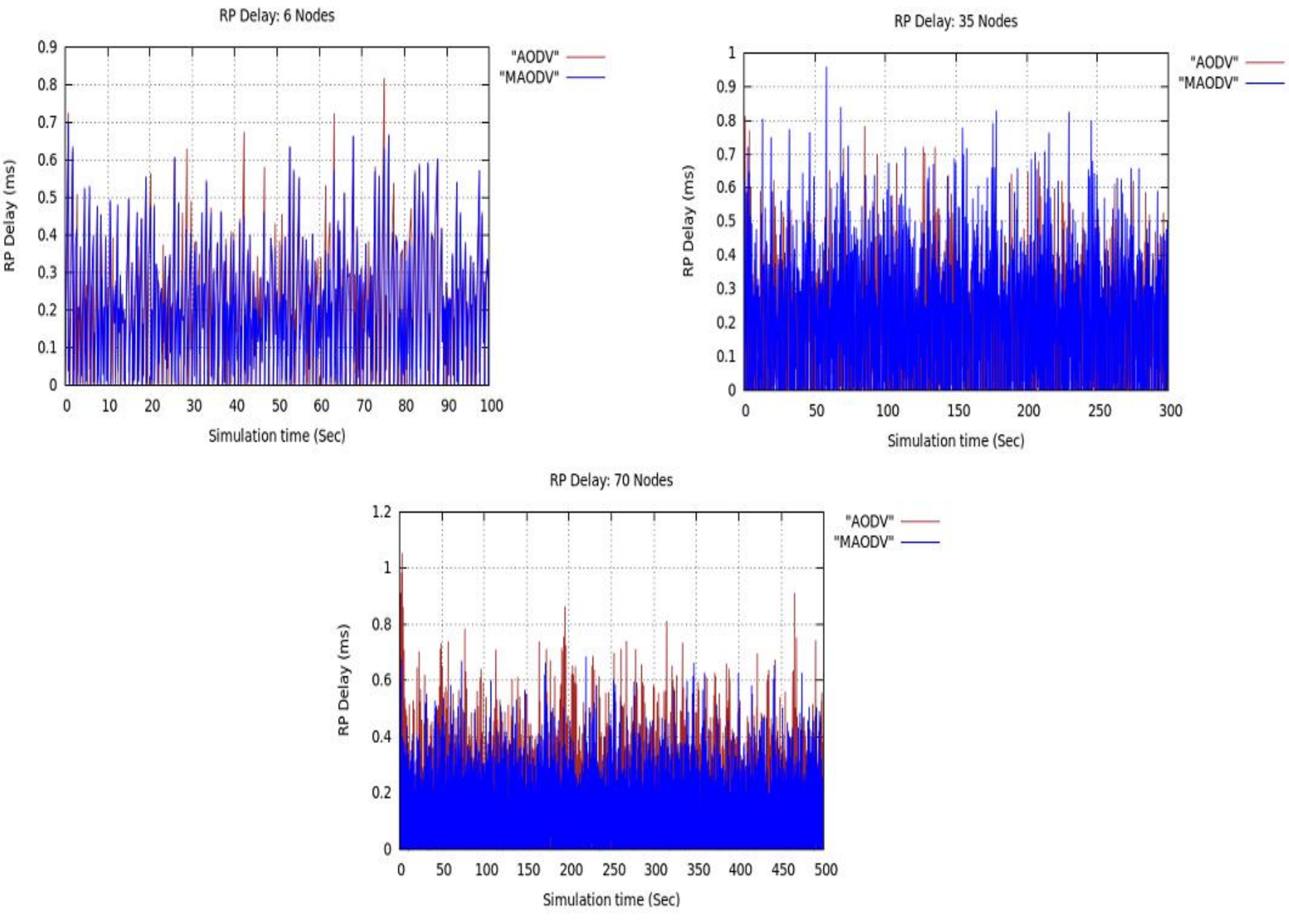

Figure 5-1 RP Delay results for the simulation of MAODV vs AODV

Figure 5-1 clearly shows that for 6 and 70 nodes AODV incurs more delay than MAODV as shown by the maroon curves representing AODV which are higher than the blue ones for MAODV. MAODV incurs less RP delay than AODV because it chooses a specific portion of the network to relay packets to. When multicasting packets to network portions, only portions with complete routes and nodes which lead to the destination are chosen [61]. In MAODV only a portion of the whole network is used for packet transmission, not the whole network. In MCRAHNs, there's always a possibility of route destruction and if we consider the whole network when sending data packets, delays and routing overheads are incurred. The graphs in figure 5-1 are a bit clustered, especially for 35 and 70 nodes, because of this clustering, used the averages of the graphs to further interpret and prove the results. Figure 5-2 depicts the averages of the line graphs from figure 5-1.

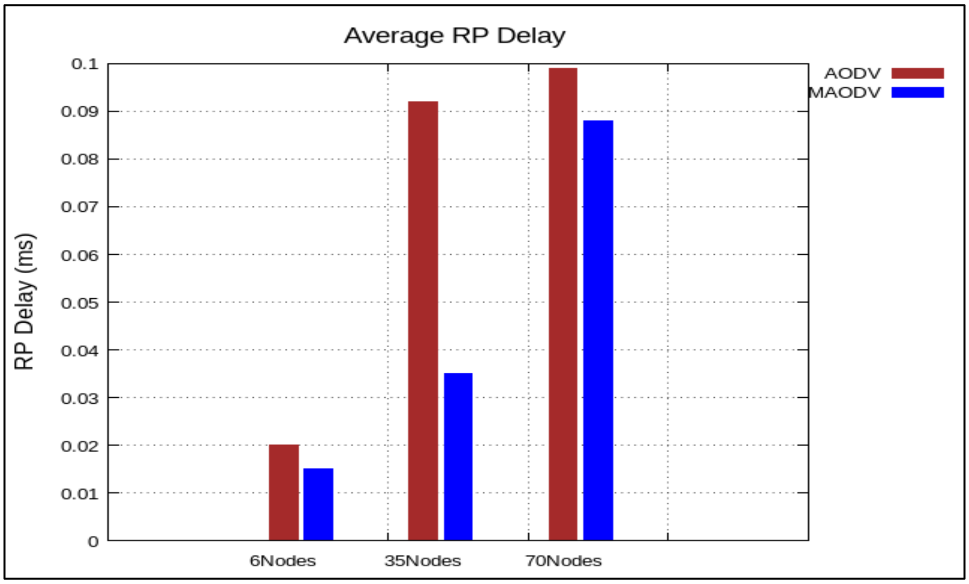

Figure 5-2 Resulting averages of RP Delay for MAODV vs AODV simulation

The averages show that for 35 nodes AODV still incurred more RP delay than MAODV just like it was for 6 and 70 nodes. Figure 5-1 and 5-2 show that for all sets of nodes simulated, AODV incurs more RP delay than MAODV. The main reason for this is that MAODV chooses specific subnets of the network to relay packets to and only consideres nodes and routes within those specific subnets. The method of choosing subnets for packet transmission guarantees that the subnet chosen, has all the routing paths intact or is the least damaged since we are dealing with a MCRAHNs.

5.2.1.2. Throughput simulation results for MAODV and AODV

The next metric that we simulated for was throughput which shows us the success rate of packet transmissions from source to destination nodes. Figure 5-3 displays the results of the simulations.

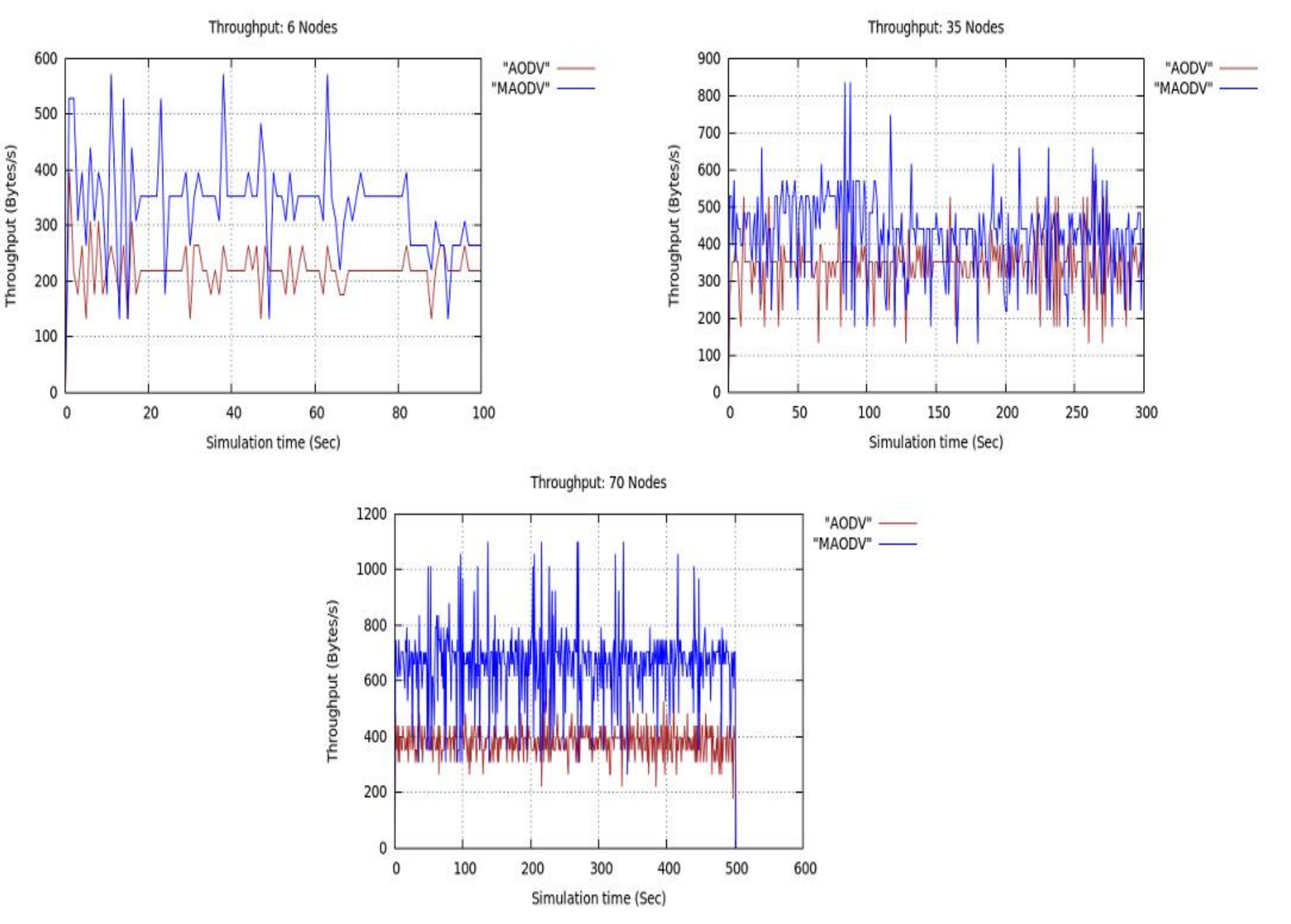

Figure 5-3 Throughput results for the simulation of AODV vs MAODV

The simulation results depicted in figure 5-3 show that for all the sets of nodes, MAODV yields a higher throughput than AODV. The reason is that through multicasting in the subnets of MCRAHNs, we work with smaller networks and that increases the packet transmission success rate [62]. In smaller subnets, there aren't as many nodes and routes as there are in the full network and because of that more packets reach their destinations as route discovery and recovery can be quickly done. The other advantage for multicast routing is that less packets are dropped because of the directness of the network.

Figure 5-3 shows that MAODV experiences three big troughs for the 6 nodes graph: between 0-20 and between 40-60. They are caused by the unavailability of routes within the chosen subnet at that specific period. The same troughs are experienced for 70 nodes simulation. We’ll see more of these troughs in the coming results for other algorithms also, they are mainly caused by the destruction of nodes and routes.

5.2.1.3. The SM delay simulation for MAODV and AODV

The subsequent metric is spectrum mobility delay. Figure 5-4 depicts the results of the simulation.

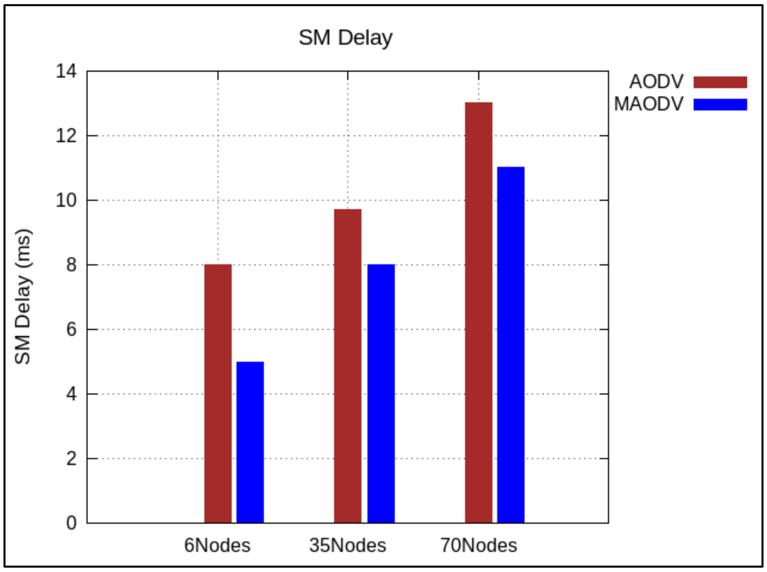

Figure 5-4: SM delay results for the simulation for AODV vs MAODV

The results in figure 5-4 show that for all the sets of nodes, MAODV incurs less SM delay than AODV. This is because spectrum mobility is dependent on route availability. MAODV and AODV sense the spectrum in the same way, the multicasting feature of MAODV only applies to routing not spectrum channel selection. What makes MAODV more efficient is route availability. MAODV has a high likelihood of route availability than AODV. When a spectrum channel is acquired after sensing, there is still a possibility of that channel being relinquished before transmission can take place due to route unavailability. In MCRAHNs spectrum channels are not permanently available, if a channel is acquired and there are no available routes at that given period, then the channel might be requested back by its PU. The selection of specific subnets in MAODV increases the chances of route availability for the greater part of the transmission time, hence from our results MAODV incurs a lower SM delay.

5.2.1.4. The NR delay simulation for MAODV and AODV

The last metric simulated for in this section is Node Relay delay. The results of this simulation are displayed in figure 5-5.

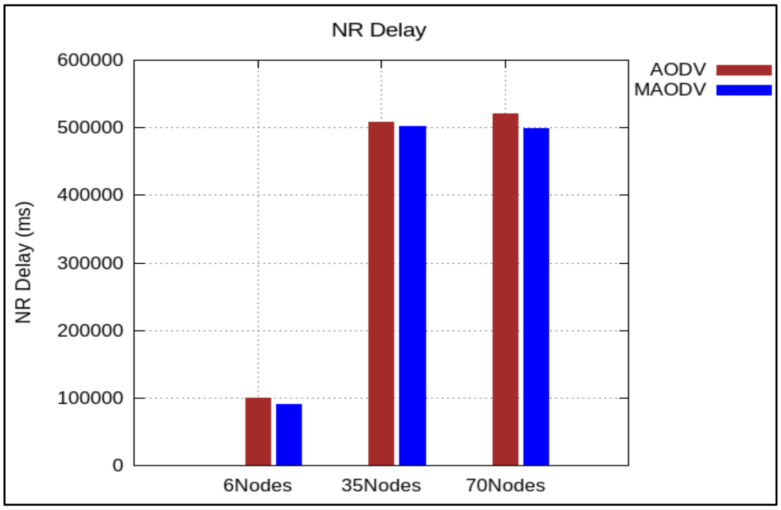

Figure 5-5 NR delay results for AODV vs. MAODV simulation

Figure 5-5 shows the continuation of the superiority trend of MAODV over AODV. The main reason why MAODV incurs less NR delay than AODV is because in MCRAHNs smaller networks are conducive for quicker route discovery, route requests and route recovery. Through choosing smaller subnets from the whole MCRAHNs by multicasting in MAODV NR delay is minimized because routes will be discovered quickly and Route Requests (RREQ) won’t take a lot of time.

The other reason for a low NR delay in MAODV is that NR delay is dependent on SM delay. For a node to relay a packet to another node, the process first starts with successful spectrum channel acquisition. So, all the factors affecting SM delay will also affect NR delay because a node cannot relay a packet without a spectrum channel.

The simulation results depicted in figure 5-1 through to 5-5 justify our choice of MAODV as a base algorithm for our research project over the normal AODV. The results clearly that in MCRAHNs, MAODV outperforms AODV. The main special feature of the MAODV which makes it optimal for MCRAHNs is multicasting. Through multicasting, we divide the network into smaller complete subnets, which contain the source node and the destination node then we relay packets within those subnets.

5.2.2. Comapring SAT-MAODV to the best performing algorithms in MCRAHNs

5.2.2.1. RP delay simulation results for xWCETT, MAODV and SAT-MAODV

In this section we compare our proposed algorithm: SAT-MAODV with other best performing algorithms in MCRAHNS. For the sake of our visualizations we had to perform the simulations of this section in parts: for every performace metric, we first started by comparing MAODV with xWCETT and then took the best one and compared it with SAT-MAODV. This was done to avoid clustering.

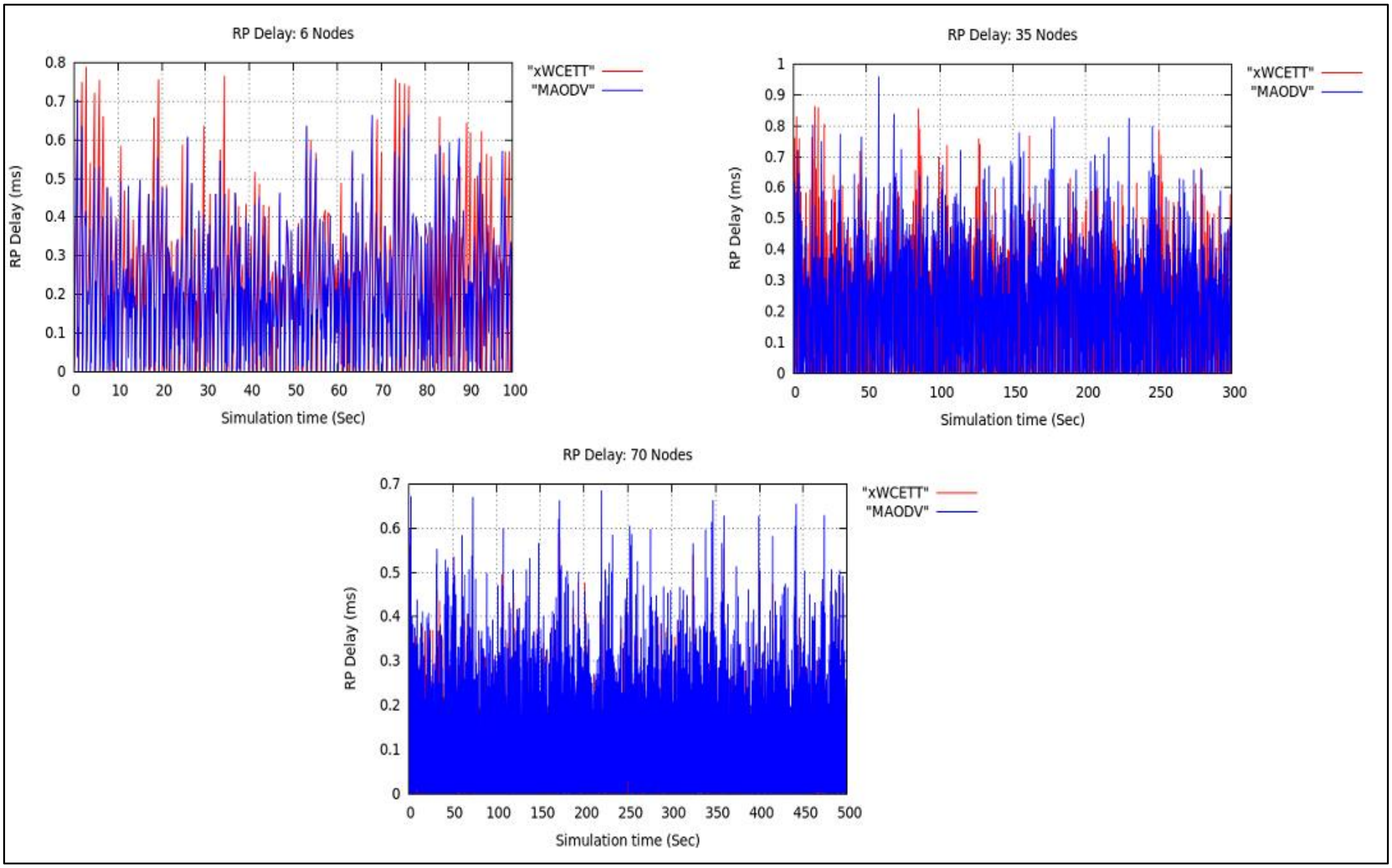

Figure 5-6: RP delay results of xWETT vs. MAODV simulation

The graphs in figure 5-6 are clustered and it is not clear as to which one performs better than the other. It is only for 6 nodes where we see that xWCETT incurs more delay than MAODV. The reason for that is because xWCETT doesn’t differ much with AODV in packet transmission between nodes. When a packet has to be relayed from source to destination the entire network is considered. RREQ and Route response packets(RRESP) are sent to all the nodes in the network, meanwhile MAODV only relays to the nodes in the chosen subnet. The other factor is that in xWCETT, RREQ and RRESP are sent through two routes that are incomplete due to the spontaneous destruction of routes in MCRAHNs. The only time when routes are noticed to be incomplete is when the RREQ reports an error in that specific route. MAODV only considers the optimal complete subnets so incomplete routes are unlikely to be chosen because the subnet is checked beforehand [63]. SAT-MAODV was the compared to the best performing counterpart algorithm for this metric which is MAODV. This best performing algorithm was chosen based on the results of the averages depicted in figure 5-8. Figure 5-7 depicts the results of SAT-MAODV vs. MAODV

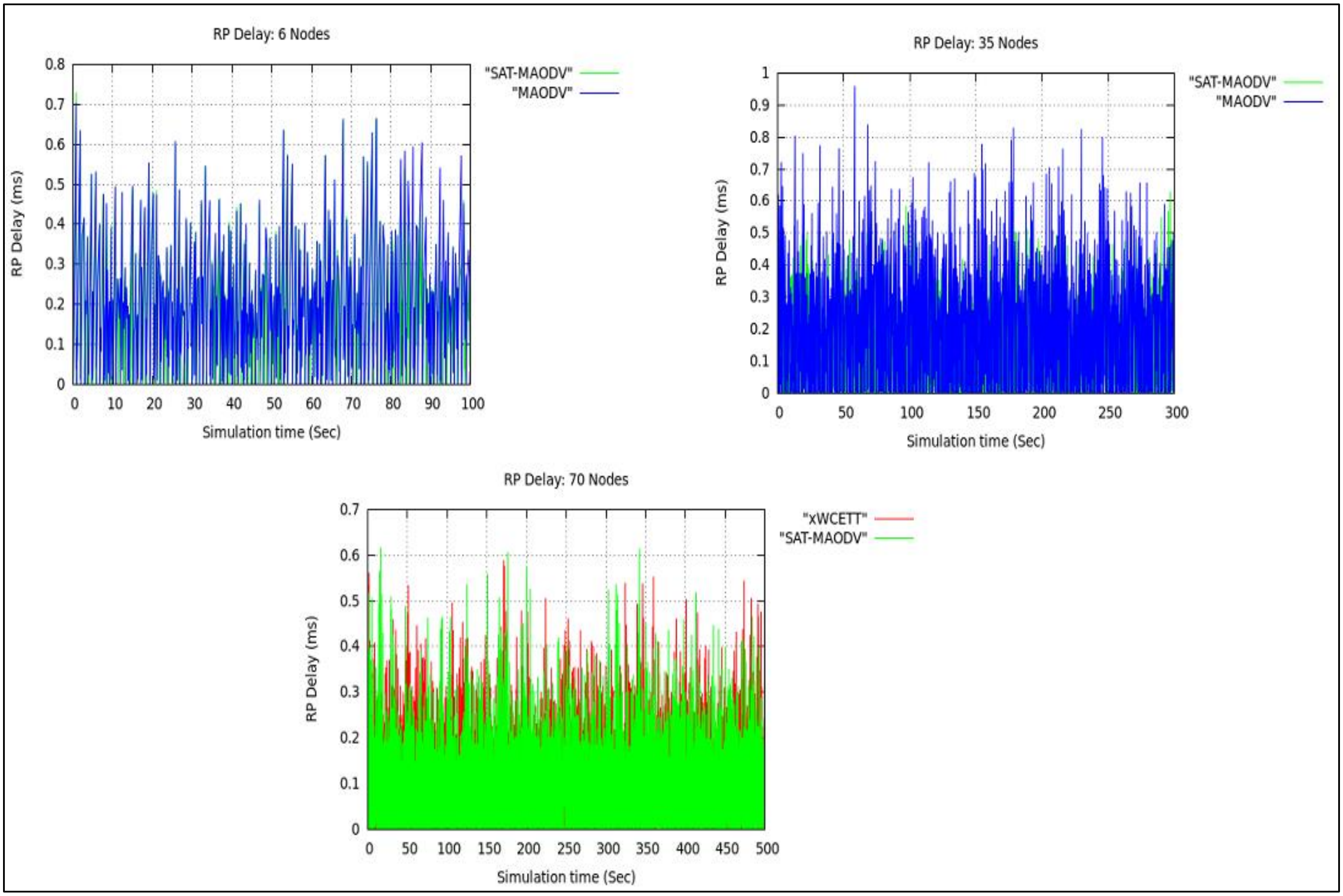

Figure 5-7 RP delay results for SAT-MAODV, MAODV and xWCETT simulation

In figure 5-7 it is also not clearly visible which algorithm is more efficient, the graphs are too clustered. To analyze these results we’ll use the averages displayed in figure 5-8.

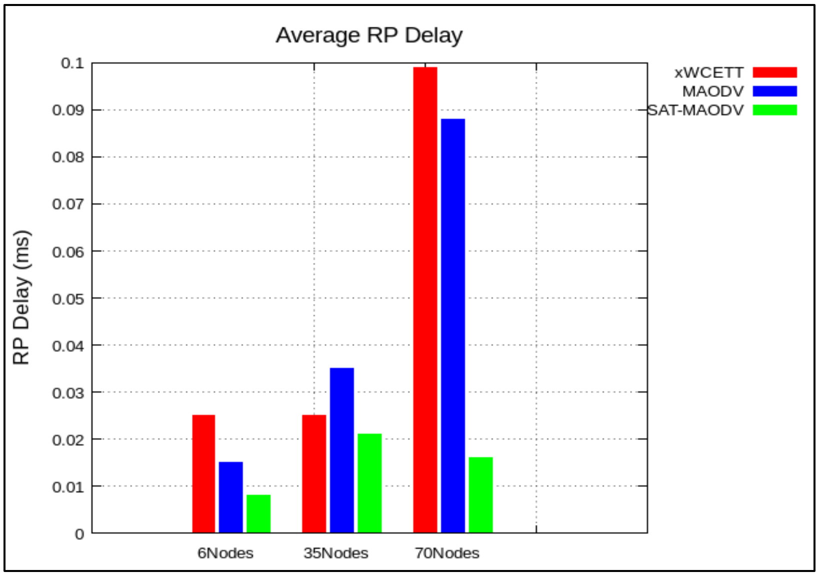

Figure 5-8 The resulting RP delay averages for xWCETT, MAODV and SAT-MAODV simulation

Figure 5-8 shows that our proposed algorithm (SAT-MAODV) incurs the least RP delay. The reason is that SAT-MAODV uses transitive routing and a centralized multicasting approach. The choosing of specific subnets for routing is not the only thing that SAT-MAODV does, in SAT-MAODV the likelihood of the node that is being relayed to meet the destination node (transitivity) is also considered. For RP delay that system makes a great difference because there might be nodes in the subnets which are within a close proximity in transmission range and their routing paths are complete, but their likelihood of meeting the destination node or the node that is closest to the destination node is low, such nodes are the last to be considered. The results also depict that xWCETT incurs the most delay on 35 nodes, this is mainly because by the xWCETT is depedant on the completeness of the network. The network instance in which the simulation for 35 nodes happened was very disintegrated in terms of route availability. In such instances xWCETT struggles to route packets in time since it has to wait for the full route recovery.

5.2.2.2. Throughput simulation results for xWCETT, MAODV and SAT-MAODV

The next metric that we simulated for was throughgput. The results for this simulation are contained in figure 5-9.

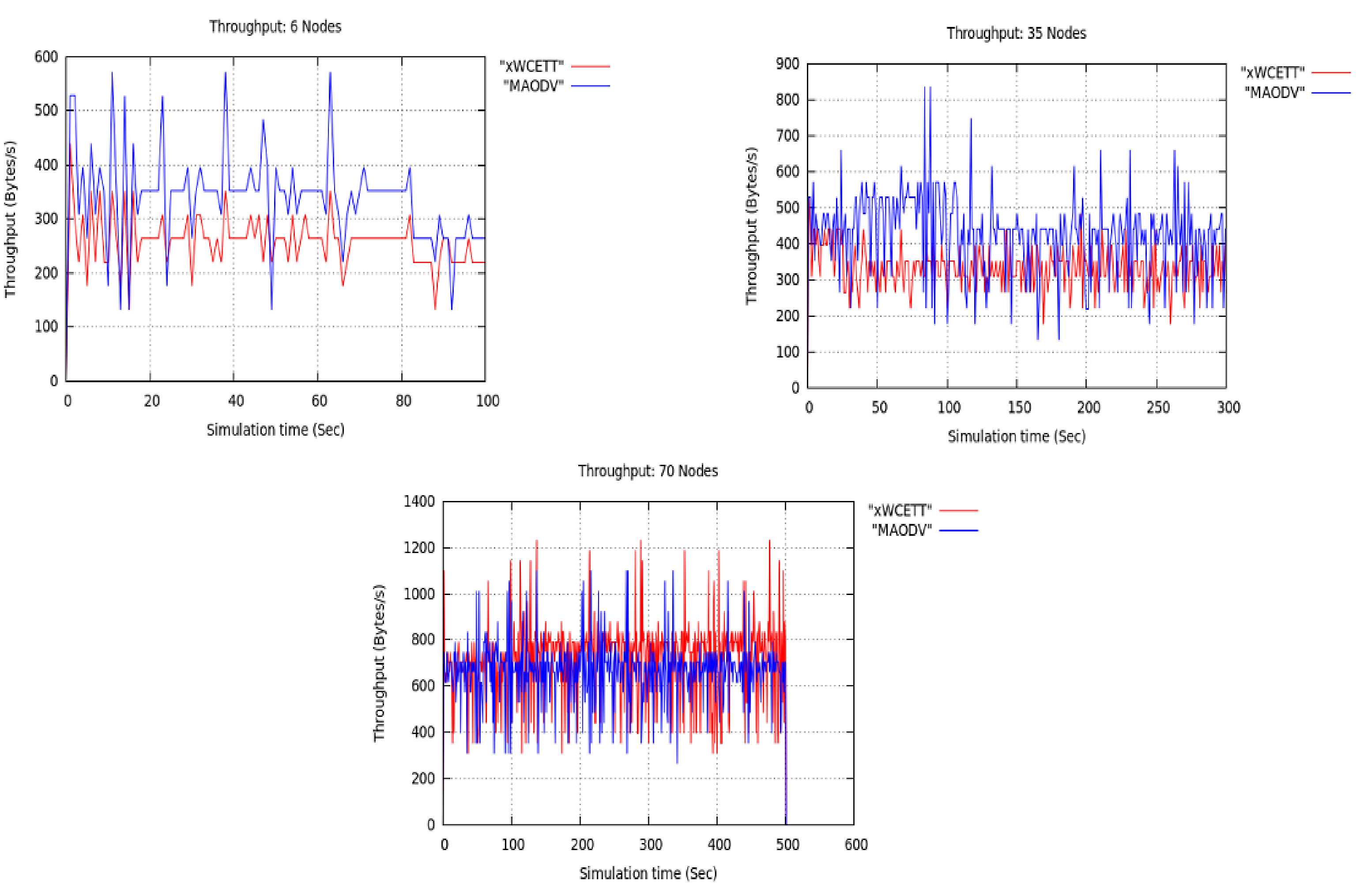

Figure 5-9 Throughput simulation results for xWCETT vs. MAODV

Figure 5-9 shows that for 6 and 35 nodes MAODV outperforms xWCETT. The reason is that MAODV has a quick destination location mechanism called “ Sequence Numbers approach”. The sequence numbers help in maintaining an up to date information on routes. MAODV notices broken routes faster than xWCETT, especially in small networks, which then results in more throughput because broken routes are avoided. For 70 nodes xWCETT outperforms MAODV. From the our observation of the results, whenever there is high PU and SU activity, xWCETT copes better. xWCETT is designed for CRAHNs and its special feature of calculating the Expected Transmission Count (ETC) and the Expected Transmission Time (ETT) despite the PU and SU activities makes it efficient in large CRAHNs. These two values are packaged in the RREQ packets between the source and destination. The ETC and the ETT are used to select the best path based on path availability, the expected hops to the destination and the time interval when the transmission is expected to take place. With that information, the shortest path with the spectrum channel guaranteed of being present at ETT and ETC is chosen. The ETT and ETC increases the likelihood of the presence of spectrum channel throughout the transmission. This feature is helpful mostly in large networks when there is a lot of PU and SU activity like for our 70 nodes simulation.

The results in figure 5-9 show that MAODV outperforms xWCETT for 6 and 35 nodes, but for 70 nodes xWCETT outperforms it. These results are carried to figure 5-10 to compare them with SAT-MAODV.

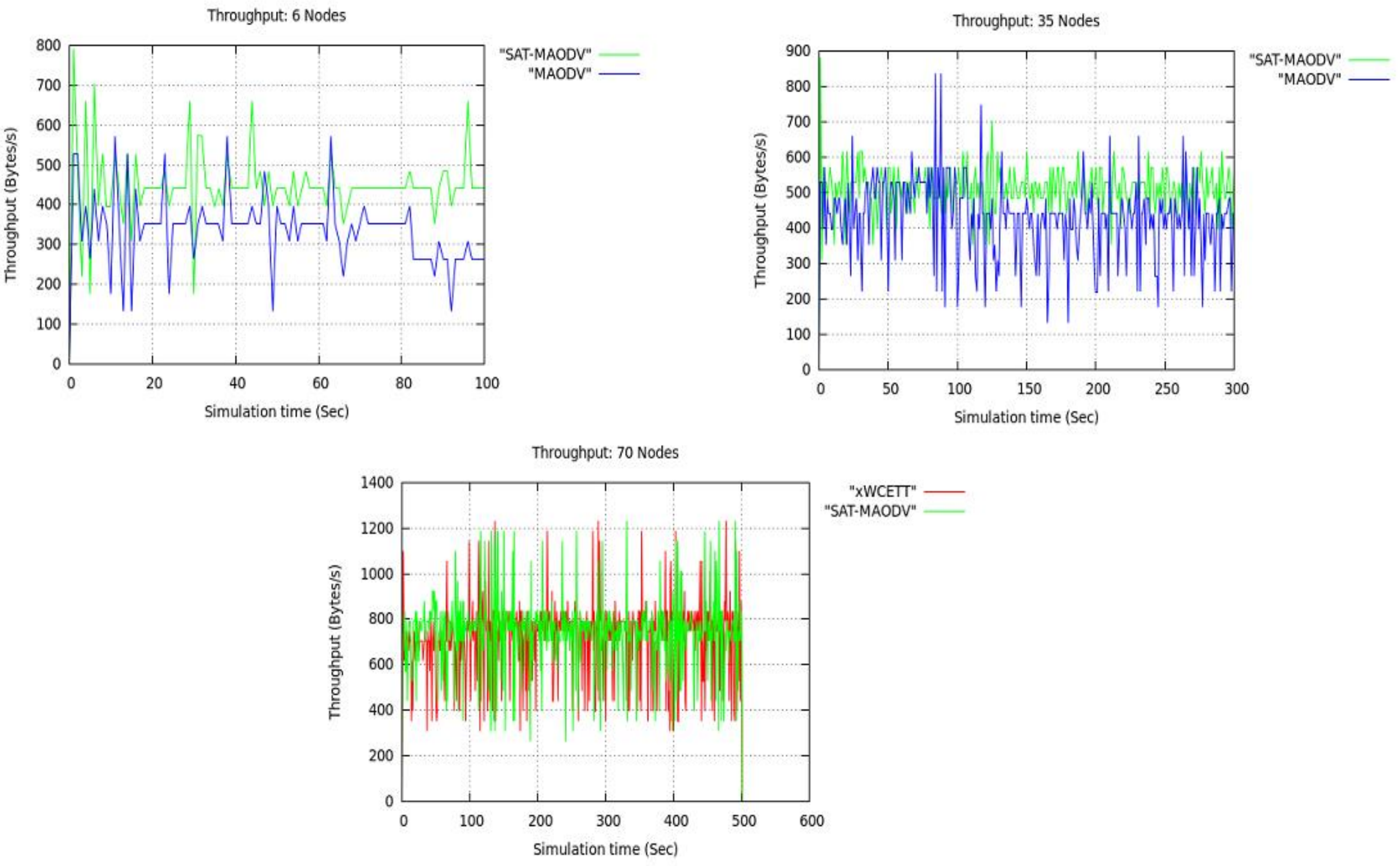

Figure 5-10 Throughput simulation results for SAT-MAODV, xWCETT and MAODV

In figure 5-10 it is clear that for 6 and 35 nodes SAT-MAODV outperforms MAODV which was the most efficient when compared to xWCETT. The reason is that SAT-MAODV uses an energy infused transitivity approach. When a path is broken within the chosen subnet through multicasting, in choosing the node to relay to, the energy infused transitivity is used as explained in chapter 4. This system maximizes throughput as it assures that the nodes chosen for packet relaying will indeed have enough energy to buffer the packet until they meet the nodes that they have been chosen for, based on their high meeting probabilities. For 70 nodes xWCETT comes very close to SAT-MAODV. In this case, SAT-MAODV averages 823 Bytes/s, meanwhile xWCETT averages 810 Bytes/s.

5.2.3. The NR delay simulation for xWCETT, MAODV and SAT-MAODV

The ensuing metric that we tested for is node relay delay. The results are depicted in figure 5-11.

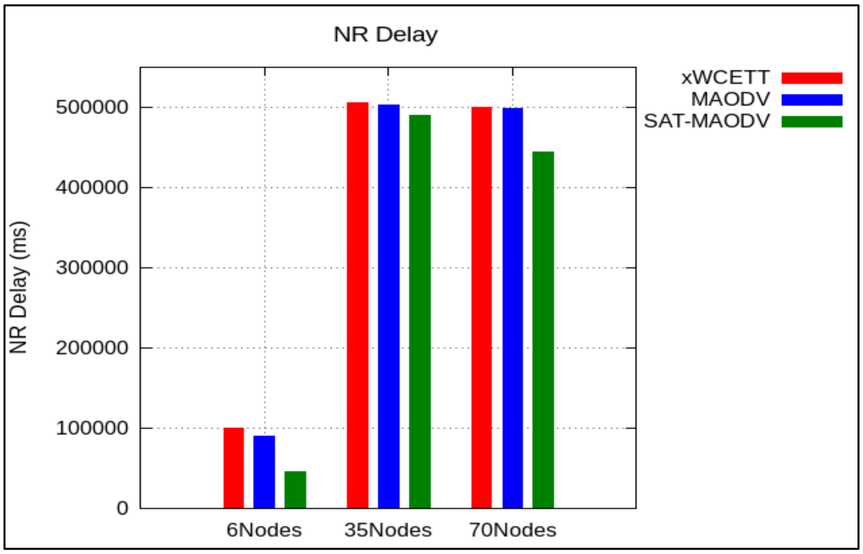

Figure 5-11: NR delay simulation results for xWCETT, MAODV, SAT-MAODV

Figure 5-11 depicts the NR delay results of xWCETT, MAODV and SAT-MAODV. The results show that SAT-MAODV is more efficient than all the other algorithms. Two features of SAT-MAODV which makes it more efficient for NR delay are Centralized Multicasting (CM) and EIT. In CM, packets are transmitted to specific subnets, one at a time and a controlling agent is chosen to compute all the transmissions [64]. CM reduces NR delay because the controlling agent which is the sender in our case chooses the paths the packets take even though it is outside the multicast group. The good thing with this method is that the controlling agent doesn't have to have the energy to transmit the packet all it does is to facilitate the transmission from one multicast group to the next. In this way the controlling agent acts like a coach from the time the packet leaves the sender until it gets to the destination and all broken paths or likely to break paths will be avoided which results in less delay from one node to the next and from sender to destination.

Unlike in most cases of delay, our results show that for 70 nodes the delay slightly decreases. This is because NR delay is not solely dependent on the number of nodes, even amongst many nodes, delay is still measured from one node to the next. The delay only goes up by the measurement of the combined delay for all the nodes involved.

Table 5-1 shows the t-stat results for NR delay. We only tested SAT-MAODV against MAODV because from figure5-11 for all simulations performed for every set of nodes, MAODV comes second best to SAT-MAODV so there is no need to test against xWCETT which has already been outperformed by MAODV.

Table 5-1: t-test table for the NR delay of SAT-MAODV vs. MAODV

t-Test: Paired Two Sample for Means

	MAODV		*SAT-MAODV*
Mean	366033.3333		313333.3333
Variance	53881403333		52233333333
Observations	3		3
Pearson Correlation		0.997857993	
Hypothesized Mean Difference		0	
df		2	
t-Stat		5.891180053	
P(T<=t) one-tail		0.013812536	
t Critical one-tail		2.91998558	
P(T<=t) two-tail		0.027625073	
t-Critical two-tail		4.30265273	

For evaluating the significant difference between SAT-MAODV and MAODV we consider two values from the table: t-STAT and t-Critical two tail values. If the t-STAT value is greater than t-critical two tail value, we conclude that there is significant difference otherwise there is no significant difference [65].

Form table 5-1 we see that the t STAT value is greater that the t Critical two-tail value which means that there is a significant difference in the performance of SAT-MAODV over MAODV. The results from figure 5-11 and 5-1 prove that SAT-MAODV significantly outperforms MAODV for NR delay.

5.2.4. The SM delay simulation for xWCETT, MAODV and SAT-MAODV

The next metric that we simulated for was spectrum mobility delay whose results are depicted in figure 5-12.

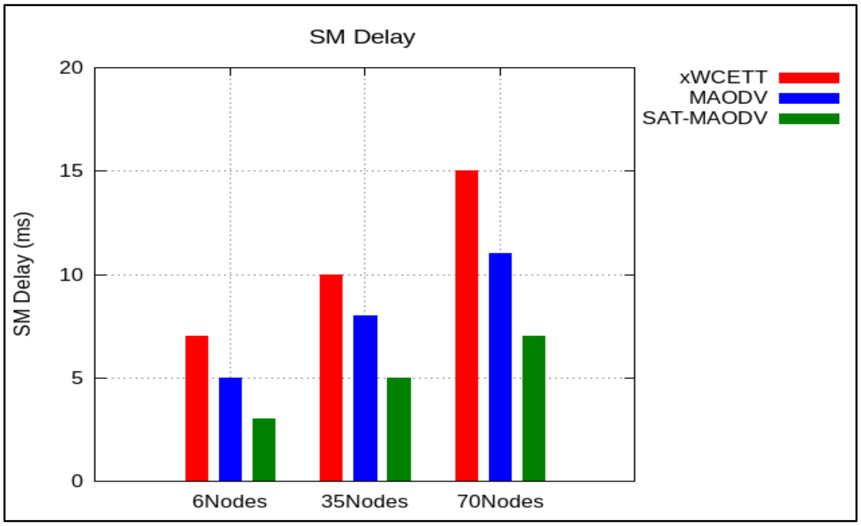

Figure 5-12: SM delay simulation results for xWCETT, MAODV and SAT-MAODV

In figure 5-11 we see that SAT-MAODV outperforms xWCETT and MAODV for SM delay. SAT-MAODV has a special feature for spectrum mobility. For every packet transmission two spectrum channels are chosen. The spectrum channels are chosen using two criteria: the availability of the spectrum and the history of time availability of that spectrum as explained in chapter 4. In this way there is always a backup channel for a specific time, which is known to be the time when mostly the backup channel is free [66]. The movement between channels is done quickly. SM delay increases with the number of nodes because more nodes lead to more PU and SU activity.

We then went on to further prove the significance of the results using the t-test. Table 5-2 depicts the results of the t-test analysis.

Table 5-2: t-test table for the SM delay of SAT-MAODV vs. MAODV

t-Test: Paired Two Sample for Means

	MAODV	*SAT-MAODV*
Mean	7.833333333	4.666666667
Variance	9.083333333	4.083333333
Observations	3	3
Pearson Correlation	0.971509518	
Hypothesized Mean Difference	0	
Df	2	
t-Stat	4.75	
P(T<=t) one-tail	0.020788391	
t Critical one-tail	2.91998558	
P(T<=t) two-tail	0.041576783	
t-Critical two-tail	4.30265273	

From table 5-2 we can see that t-STAT is greater than t-Critical two-tail, which means that there is a significant difference between the results of SAT-MAODV and MAODV. The results for SM delay follow a similar trend to those of NR delay. From figure 5-12 we can see that MAODV still comes second best to SAT-MAODV, hence we tested SAT-MAODV against MAODV. From the analysis results, we conclude that SAT-MAODV significantly outperforms MAODV.

5.2.2.5. The packet delivery ratio simulation for SAT-MAODV vs. MARSA

Having proven that SAT-MAODV is more efficient than AODV, MAODV and xWCETT according to our metrics, we then simulated SAT-MAODV against MARSA. For this simulation we tested SAT-MAODV under the same parameters which MARSA was first simulated in. MARSA was only tested on two metrics: packet delivery ratio and delivery latency. We simulated SAT-MAODV for those two metrics and compared it with MARSA using the results from the research project which first proposed MARSA [28]. Figure 5-13 shows the packet delivery ratio results between MARSA and SAT-MAODV.

5.2.5. The packet delivery ratio simulation for SAT-MAODV vs. MARSA

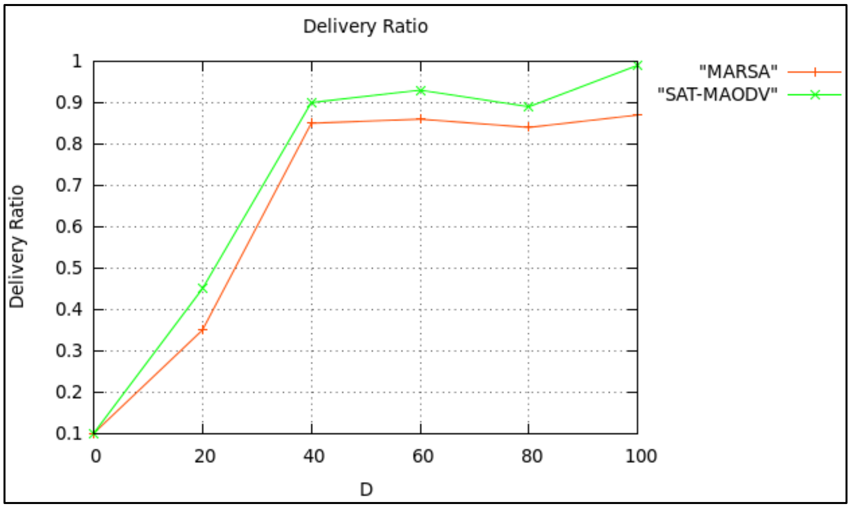

Figure 5-13: Packet delivery ratio simulation results for MARSA vs. SAT-MAODV

From figure 5-13 we can see that SAT-MAODV outperforms MARSA for packet delivery ratio. We can see that the curves follow an almost similar escalating trend from 0 to 40D (Destination zone) although SAT-MAODV is slightly above MARSA. The reason for the similarity in trends is that relaying packets to nodes which are in close proximity to the sender often doesn't incur much packet loss. The mobility of nodes in the network impact on packet delivery. The graph shows that from 0D to 40D the packet delivery ratio constantly increases but from 40D to 100D it fluctuates in small margins. The reason for this is because as the nodes move far apart, packet transmission become more difficult because some of them move out of the transmission range and some relaying nodes lack the energy to relay to distant candidate nodes.

The main reason why SAT-MAODV outperforms MARSA is that SAT-MAODV relays packets based on the transitivity feature and MARSA uses the traditional buffering system to store packets. In cases where routes are unavailable, most packets for MARSA get timed out meanwhile SAT-MAODV uses transitivity to relay to the nodes which have the highest likelihood to meet the destination nodes. Table 5-3 gives the t-test statistical analysis to see if there is any significance difference between the averages of the results in figure 5-13.

Table 5-3: t-test table for the packet delivery ratio of SAT-MAODV vs. MARSA

t-Test: Paired Two Sample for Means

	SAT-MAODV		*MARSA*
Mean	0.71		0.645
Variance	0.127		0.11219
Observations	6		6
Pearson Correlation		0.994424429	
Hypothesized Mean Difference		0	
Df		5	
t-Stat		3.763244767	
P(T<=t) one-tail		0.006556837	
t Critical one-tail		2.015048373	
P(T<=t) two-tail		0.013113675	
t-Critical two-tail		2.570581836	

From table 5-3 we see that the t-STAT value is greater than the t-Critical two-tail value which means that SAT-MAODV significantly outperforms MARSA for packet delivery ratio.

5.2.2.6. The packet delivery latency for SAT-MAODV vs. MARSA

The last metric that we simulated SAT-MAODV and MARSA on was delivery latency. Figure 5-14 shows the results.

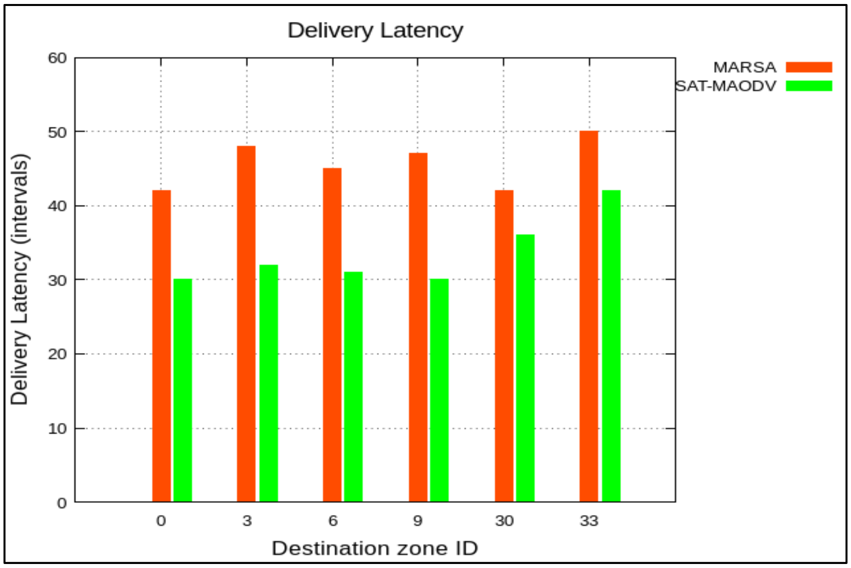

Figure 5-14: Delivery latency results of SAT-MAODV vs. MARSA simulation

From figure 5-14 we see that SAT-MAODV incurs lower delivery latency than MARSA for all the destination zones. Delivery latency is closely linked to packet delivery ratio in terms of the factors which influence it. If a packet takes too long in the network without reaching the destination, it gets timed out and then gets lost. The delivery latency is inversely proportional to the packet delivery ratio.

The outcome of delivery latency is also influenced by transitivity in SAT-MAODV. Packets move more quickly in SAT-MAODV because in cases where there are no routes SAT-MAODV still relays the packets to other nodes which are likely to encounter the destination. For MARSA the packets are buffered until another route is reconstructed. The reconstructed route at times becomes available when the acquired spectrum band is needed by its primary user which will mean that the process of sensing an available spectrum band must start over. Packets take a lot of time in the network and some are even lost.   The results from figure 5-14 are also supported by a t-test analysis. Table 5-4 depicts the results of the t-test analysis.

Table 5-4: t-test table for the delivery latency of SAT-MAODV vs. MARSA

t-Test: Paired Two Sample for Means		
	MARSA	SAT-MAODV
Mean	45.66666667	33.5
Variance	10.66666667	22.3
Observations	6	6
Pearson Correlation	0.440902051	
Hypothesized Mean Difference	0	
Df	5	
t-Stat	6.772044388	
P(T<=t) one-tail	0.000533595	
t Critical one-tail	2.015048373	
P(T<=t) two-tail	0.00106719	
t-Critical two-tail	2.570581836	

The t-STAT value in table 5-4 is also greater than the t-Critical two-tail, which means that there is a significant difference between the performance of SAT-MAODV and MARSA. SAT-MAODV significantly outperforms MARSA.

For the two metrics that MARSA was simulated for, SAT-MADV has proven to be more efficient. Looking at the results and the statistical analysis we can conclude that SAT-MAODV is more efficient than MARSA.

5.3. Summary of Findings

Our results have shown us the performances of the four algorithms we simulated: AODV, MAODV, xWCETT and SAT-MAODV. For our first scenario we saw that in MCRAHNs, given the parameters of our research project, MAODV performs better than AODV. For all the metrics we used we saw that MAODV outperforms AODV. It is important to note that in other networks which are different from ours, AODV outperforms MAODV but in MCRAHNs, MAODV performs better. The main feature that makes MAODV better than AODV in MCRAHNs is multicasting. Due to the unavailability of guaranteed paths from source to destination nodes, our results have shown that it is better to multicast packets to specific subnets in the network and relay from one subnet to the next.

The second Scenario proves our proposed algorithm right. The results show that in most cases MAODV outperforms xWCETT in smaller networks, but in larger networks xWCETT proves to be more efficient. This kind of behavior is caused by the ETC and ETT of xWCETT which work best when the network is large and there is a lot of PU and SU activity. In the four metrics that we used, our proposed algorithm SAT-MAODV performs better than all the other four algorithms. Its main features which make it distinct are ICM, NRA, EST and TBA. The performance of SAT-MAODV continues to be superior even when time and nodes increase. We kept on increasing the time and SAT-MAODV kept on outperforming its counterparts. Equation (4-6) models the perfomance of SAT-MAODV with respect to time and node increases. The simulations we ran for this study prove that even if we had to simulate for 24 hours or more, the performance of SAT-MAODV would still follow the model represented by equation (4-6).

Chapter 6 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

6.1. Summary

The motive of this research project was to find the best routing algorithm for MCRAHNs. Routing in MCRAHNs is challenging due to the intermittent nature (subject to destruction) of the network. We had to find routing algorithms which would cope and show resilience in a topology like MCRAHNs. We identified four best performing routing algorithms in MCRAHNs: AODV, MAODV, xWCETT and MARSA. We simulated them to see which one is the most efficient. In analyzing the performance of these algorithms, we used six metrics; RP delay, NR delay, SM delay, throughput, packet delivery ratio and packet delivery latency

We took the best performing algorithms for each metric and compared it to our proposed algorithm: SAT-MAODV. SAT-MAODV is mainly composed of four unique features: ICM, NRA, EST and TBA. We compared SAT-MAODV with the best performing algorithms for each metric under the MCRAHNs parameters and SAT-MAODV proved to be more efficient than all of them.

Our simulations were partitioned into two sections. The first section was to prove why we chose a multicasting algorithm as a base algorithm over a non-multicasting algorithm. In that way we were showing the importance of multicasting in MCRAHNs over the normal traditional routing in MCRAHNs. We compared the normal AODV with Multicasting AODV (MAODV). In all the simulations MAODV outperformed AODV given that the network setup is MCRANs.

In the second section we compared xWCETT with MAODV for all the metrics. The best performing algorithm for each metric was then compared to SAT-MAODV. We went on further to compare SAT-MAODV with a new routing algorithm designed for intermittent CRAHNs called MARSA. The designers of MARSA only tested it for two metrics: packet delivery ratio and packet delivery latency. We also simulated SAT-MAODV against MARSA for these two metrics and SAT-MAODV performed better with a big margin. The summary of the results is outlined in the next section.

6.2. Recommendations

Delay and packet loss are some of the major inefficiencies caused by the intermittent nature of MCRAHNs. These challenges impact on both spectrum channel selection and packet relaying. In chapter 2 and 3 we elaborated just how packet transmission is highly dependent on spectrum channel selection in MCRAHNs. In addressing spectrum channel selection and packet transmission, three components of MCRAHNs must be modified: the radios of the systems, the CCC and the buffers of the nodes.

One of the techniques which have been overlooked in MCRAHNs is the usage of timestamps for both PUs and SUs. If PUs could always send their time intervals of channel usage through the CCC to the SUs, these time intervals records could be used to forecast spectrum channel availability which would bring into cognizance how SUs search for available spectrum channels. The SUs could also use time stamps of interactions to predict the neighboring nodes they could relay packets to with respect to the direction of where the packets should go.

Looking at all these modifications we recommend that the normal standard MCRAHNs radios should be adjusted in a way that they will allow time-stamping from PUs. The radios should process the time stamps to produce time patterns of PUs usage of the spectrum channels [67]. The information from these radios should always be available to the SUs. We also recommend that the CCC in MCRAHNs should be modified in a way that the information from the interaction of the SUs should be communicated amongst them without any interference in routing and not compromising the security of any node at any time. We recommend that the buffers of the nodes in MCRAHNs should have cognizance through an algorithm which will select the best nodes to relay packets to based on the information acquired through time stamping, transitivity and EIT. If those amendments are implemented in MCRAHNs, delay would be greatly reduced.

Future studies can be directed to the MAC layer in MCRAHNs. We only looked at channel selection and didn’t address channel sensing. We only assumed the normal CRAHNs standard of channel sensing as per the IEEE 802.111 protocol [68]. More efficient ways of sensing the spectrum channels quickly could be researched on [69]. These new ways would reduce the overall end-to-end delay of our algorithm and could integrate algorithms like SAT-MAODV to make them robust on both the MAC and network layers of the OSI model.

6.3 Final conclusion

In the first section of our simulations we observed that in MCRAHNs, a multicasting approach is more efficient than normal routing. We observed this by comparing AODV with MAODV. For all the simulations, MAODV outperformed AODV in MCRAHNs. We also observed from figure 5-1 and 5-3 that for RP delay and throughput, there are major peaks and troughs occurrences in the results. The troughs in throughput and peaks in RP delay are caused by route breakages due to the destruction of nodes. The results show that even though MAODV experiences those peaks and troughs it can recover quickly through the system of multicasting to subnets of the network than AODV.

For SM and NR delay the results show us a trend of an increasing delay being directly proportional to the number of nodes. For SM and NR delay MAODV still outperforms AODV. The main reason for this is that MAODV only considers robust routes than AODV through multicasting to subnets which have complete routes. The robust routes also reduce SM delay since a channel has a high likelihood of being fully used upon its acquisition.

In the second section of our simulations we observed fluctuating performances between xWCETT and MAODV. For RP delay and throughput, we observed that MAODV performs better than xWCETT for 6 and 35 nodes because of the minimal PU-SU activities. xWCETT outperformed/came very close to MAODV for 70 nodes. The reason for that is its special features of ETT and ETC which makes it more robust in MCRAHNs where there is a lot of PU-SU activity. For NR delay, we observed a normal trend of delay being directionally proportional to the number of nodes except for 70 nodes because NR delay is not mainly dependent on the number of nodes, NR delay is calculated from one node to the next.

SAT-MAODV experienced the same trends for all the metrics but always incurred lesser delay and achieved a very high throughput compared to all its counterparts. The efficiency of SAT-MAODV was validated by the statistical t-tests which showed a high level of significant difference for the averaged simulations. For RP delay xWCETT came very close to SAT-MAODV for the 70 nodes simulation but still couldn’t match it. The same also happened for throughput of 70 nodes but still MAODV achieved a much higher throughput. As we have previously stated, the ETT and ETC features of xWCETT make it efficient in large MCRAHNs but even though it performed well, it couldn’t match SAT-MAODV. SAT-MAODV also outperformed MARCA for packet delivery ratio and packet delivery latency by significant margins which were also proved by the statistical t-tests.

SAT-MAODV has proven to be efficient in all the metrics that we used. It has outperformed all the routing protocols that we chose for this research project. Its distinct features: ICM, NRA, EST and TBA make it a very robust and ideal algorithm for MCRAHNs.

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