THE DESIGN AND OPTIMISATION OF CROSS LAYER ROUTING AND MEDIUM ACCESS CONTROL (MAC) PROTOCOLS IN COGNITIVE RADIO NETWORKS

By

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DISSERTATION

Submitted in fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in the

FACULTY OF SCIENCE AND AGRICULTURE

(School of Mathematical and Computer Sciences)

at the

UNIVERSITY OF LIMPOPO

Supervisor:

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2021

DEDICATION

This dissertation is dedicated to my beloved people.

To my parents Isaiah Madiba and Agnes Basambilu Madiba.

To my siblings Tintswalo, Tsakani and Tshepo Madiba.

To my nephew Mpho Gladwin Madiba.

Lastly, to Tshwarelo Khosa.

DECLARATION

I, ***Miyelani Silence Madiba*** hereby declare that this dissertation titled: **THE DESIGN AND OPTIMISATION OF CROSS-LAYER ROUTING AND MEDIUM ACCESS CONTROL PROTOCOLS IN COGNITIVE RADIO NETWORKS** submitted at the University of Limpopo for a master's degree is my original work and has not been previously submitted to any university or institution of higher learning. I further declare that all the sources cited are acknowledged and correctly referenced.

Signature: ____________________ Date: ____________________

ACKNOWLEDGEMENTS

I would firstly like to thank the almighty God for strengthening me throughout this journey. The perfect love that God has given me, “Give thanks to the Lord, for he is good; his love endures forever.” 1 Chronicles 16:34.

To my supervisor, Professor Mthulisi Velempini. Thank you for your guidance throughout this journey. It was not simple for me, but your availability every time I needed help made the journey much lighter. Your feedback, comments and advices have grown me so much. *Imisebenzi yakho emihle iyabonakala*.

My father, Isaiah Madiba, *mmina tau ka sebele.* Thank you for being an amazing dad that you are, your support and love has done wonders in my journey.

My mother, Agnes Basambilu Madiba, *ngwetse ya ditau.* Thank you, your prayers and words of encouragements throughout my studies, you are the best.

My siblings, Tintswalo, Tsakani and Tshepo Madiba. Thank you, *bantase,* for being caring and loving. You always told me not to give up and always put more effort into my studies.

To Tshwarelo Khosa, thank you for your dearest support, love and encouragements in this journey, and for showing interest in my research and correct me were possible, I appreciate it.

My friends, Nokuthula Mnisi, Kagiso Bapela, Mmathapelo Chego, Khutsisho Maatli, Priscilla Moshomane. Thank you, a lot, the journey was much easier when I thought of you guys.

To all my colleagues in the department of computer sciences, thank you for your amazing support. I also like to acknowledge the University of Limpopo for this opportunity granted to me. Lastly, the Council for Scientific and Industrial Research (CSIR) supports me financially. I appreciate it and continue doing it to those who need this kind of support as I did.

ABSTRACT

Cognitive Radio (CR) is a promising technology designed to solve many issues, especially spectrum underutilisation and scarcity. The requirement for spectrum effectiveness was essential, and consequently, the possibility of CR arrived along and introduced the unlicensed Secondary Users (SU). SU can operate on the unlicensed and licensed spectrum bands on a condition that they avoid interference with the licensed Primary Users (PU). This approach is called the Dynamic Spectrum Allocation (DSA) and has solved the underutilisation of spectrum using the spectrum holes. The United States of America's telecommunication regulator Federal Communication Commission (FCC) introduces spectrum bands by unlicensed users looking at the rapid growth of wireless applications and devices; therefore, the Fixed Spectrum Allocation (FSA) become inadequate because of the spectrum crowded issues. Accomplishing this design requirement while meeting the Quality of Service (QoS) of SU is a challenge; thus, the cross-layer design (CLD) was introduced to enhance the efficiency and effectiveness of Cognitive Network (CN). CLD arrangements in Cognitive Radio Network (CRN) are empowering; however, there are yet numerous issues and difficulties that must be addressed, such as resource allocation and others that may negatively impact network performance. Routing in CRN also necessitates the cross-layering approach. Therefore, in this work, designing a protocol that will solve routing issues and channel selection will also maximise spectrum opportunistically. In this study, we propose the Optimised Cognitive Cross-layer Multipath Probabilistic Routing (OCCMPR) protocol, which is the optimised version of Cognitive Cross-layer Multipath Probabilistic Routing (CCMPR). We used MATLAB simulation installed in the Windows 10 operating system (OS) tool to generate comparison results. We compared the OCCMPR protocol with the existing protocols, the Cognitive Ad-hoc On-demand Distance Vector (CAODV) and the CCMPR protocols.

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ABBREVIATIONS

AODV – Ad-hoc On-demand Distance Vector

BER – Bit Error Rate

CAODV – Cognitive Ad-hoc On-demand Distance Vector

CCMPR – Cognitive Cross-Layer Multipath Probabilistic Routing

CE – Cognitive Engine

CLD – cross-layer design

CLRP – Cross-Layer Routing Protocol

CN – Cognitive Network

CR – Cognitive Radio

CRN – Cognitive Radio Network

CSMA – Carrier-Sense Multiple Access

CSMA/CA – Carrier-Sense Multiple Access with Collision Avoidance

CSS – Cooperative Spectrum Sensing

CU – Cognitive Users

DSA – Dynamic Spectrum Allocation

ECN – Explicit Congestion Notification

FCC – Federal Communications Commission

FSA – Fixed Spectrum Allocation

IEEE – Institute of Electrical and Electronics Engineers

IPC – Information Processing Centre

IPSec – Internet Protocol Security

MAC – Media Access Control

MANETS – Mobile Ad-Hoc Networks

NDMA – Network- Assisted Diversity Multiple Access

OCCMPR – Optimised Cognitive Cross-layer Multipath Probabilistic Routing

OS – Operating System

OSDRP – Opportunistic Service Differentiation Routing Protocol

OSI – Open Systems Interconnection

PDR – Packet Delivery Ratio

PHY – Physical

PPSH – Pure Proactive Spectrum Sensing

PU – Primary Users

QoS – Quality of Service

RERR – Error Route

ROSA – Routing and Spectrum Allocation

RREP – Route Reply

RREQ – Route Request

RSS – Receiving Signal Strength

SDN – Software Defined Networks

SOP – Standard Operating Procedure

SSH – Secure Shell

SSL – Secure Sockets Layer

SU – Secondary Users

TCP – Transmission Control Protocol

TCP/IP – Transmission Control Protocol/ Internet Protocol

TDMA – Time Division Multiple Access

Wi-Fi – Wireless Fidelity

CHAPTER 1 – INTRODUCTION

1. Introduction

What is a Cognitive Network (CN)?
A CN is a system with a cognitive procedure that can consider the present system condition, plan upon the considered system condition and act towards those conditions. It is commonly known that CN can think, learn, and recall past actions [1] [2].
FSA was popular in most wireless networks, but it was not advantageous because the spectrum was underutilised, only the PU could access the spectrum PU [3] [4]. CRN is an encouraging technology considering the spectrum sensing opportunities to enhance the remote systems' spectrum efficiency [5]. CRN comprises two kinds of users, the PU, authorised (licensed) users and SU, unauthorised (unlicensed) users. PU only occupy the licensed spectrum bands where the SU occupy both the unlicensed and licensed spectrum bands. As per FCC SU sense the primary or licensed spectrum to check the actions of PU regularly. When a PU involves the licensed spectrum band be "busy", therefore, SU cannot use the spectrum at that time, and SU must wait for the sensing of PU to be completed or spectrum band to be "idle" then take advantage of the channel [1] [5] [6] [7] [8] [9]. CRN introduced the phenomenon of using the opportunity of spectrum holes when the PU is not accessing the spectrum, and this development was called DSA. CR's real attributes are that the actions of PU vary progressively, and channel accessibility is not quite the same from time to time. Therefore, the SU need to effectively utilise accessible channels in the dynamic environment [5] [4]. To fulfil the SU's QoS requirements, SU must have the capability to select the best accessible spectrum band, a procedure known as spectrum selection [10].

Figure 1-1 illustrate the CRN environment where SU determine which available channels can be used. SU can access the licensed and unlicensed spectrum bands; therefore, SU can reach the primary base station using the licensed bands. Again, SU can correspond with one another across an ad-hoc association on both licensed and unlicensed bands.

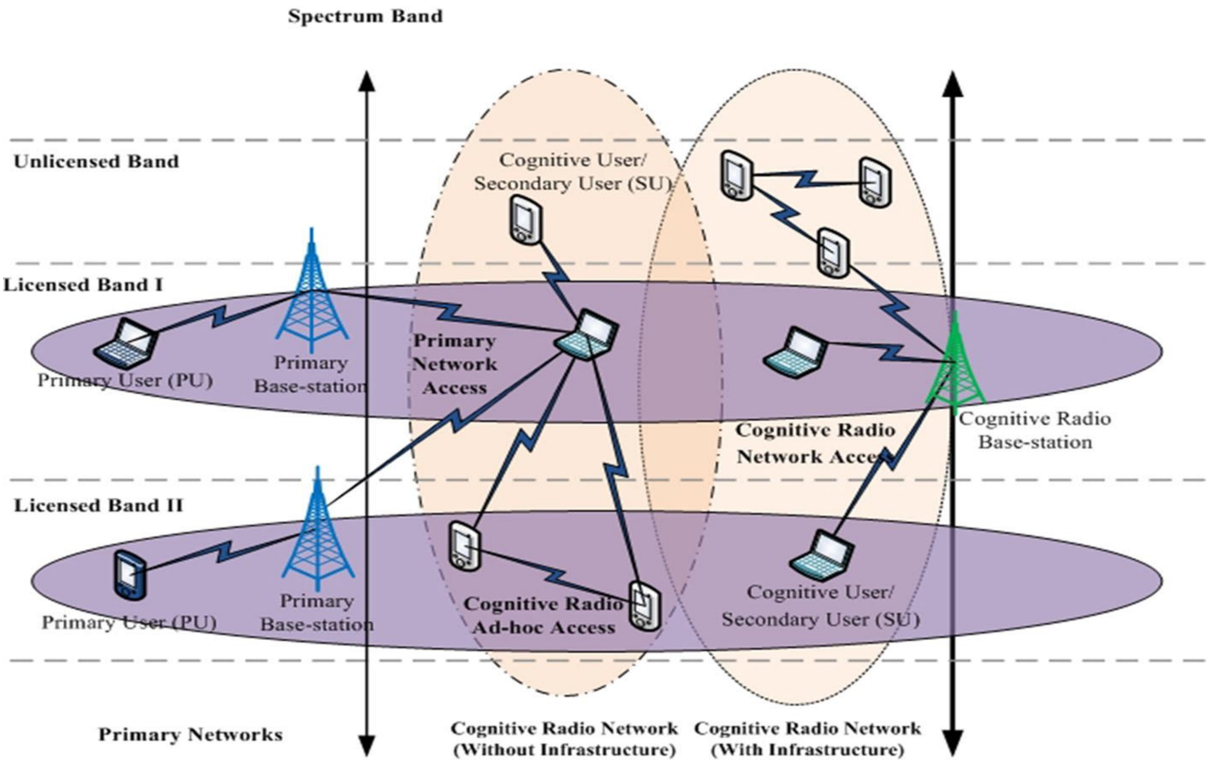


Figure 1-1: CRN *[11]*

Figure 1-2 illustrates a concept of spectrum holes. The blocks indicate that the spectrum is in use while the empty spaces indicate the spectrum holes, which means that the spectrum is not busy, and SU can use the opportunities.

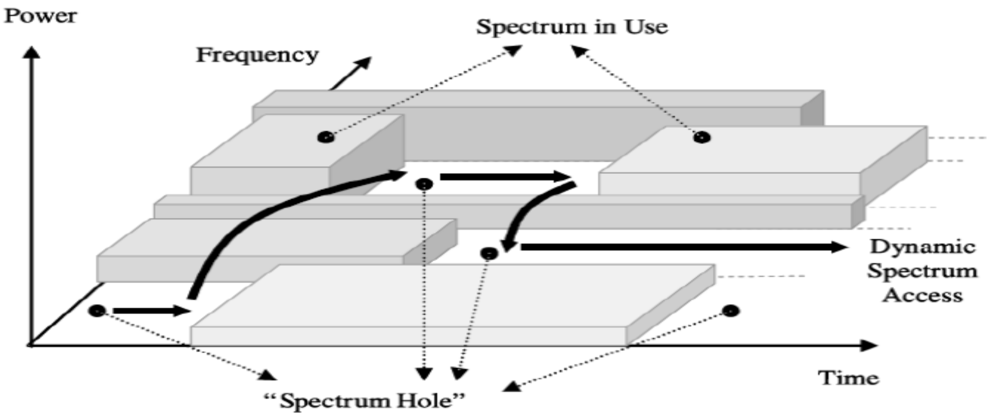


Figure 1-2: Spectrum holes concept *[4]*

CR's main objectives include spectrum sensing, handoffs, sharing, and decision [1] [12].

Figure 1-3 demonstrates the cognitive cycle. SU senses the spectrum; SU must move and sense another available spectrum whenever PU is accessing the spectrum. Whenever PU is not available after SU senses the spectrum, the decision is taken on which SU must access the spectrum according to the QoS requirements. Transmission between the SU should be coordinated for the spectrum to be shared accordingly and to avoid collisions.

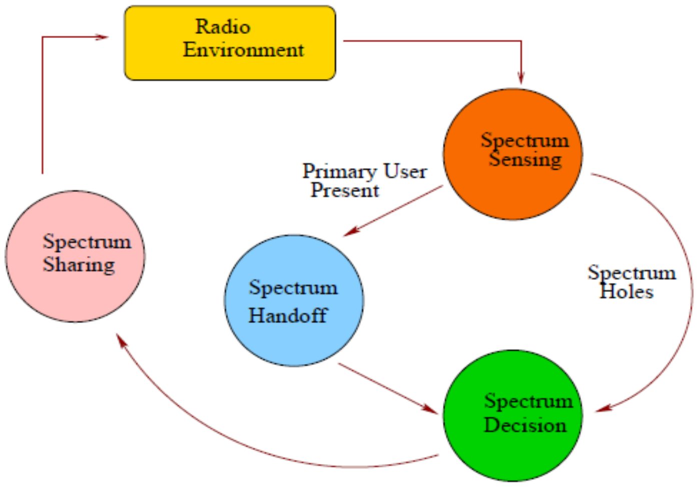


Figure 1-3: Cognitive cycle *[1]*

1.1. Routing

The main objective of routing in any wireless network system and the packet routed is the elementary component of information in computer networks. Routing is utilised for packet delivery using the best selected route from source to destination [13]. The routing procedure faces numerous difficulties in CRN, for example, the absence of centralised framework, the coordination amongst the spectrum administration and routing modules, regular link failures resulted from the unexpected appearance of PU, adjusting to the dynamic changes of spectrum accessibility because of the stochastic conduct of the PU and the SU for example [9] [14].

Routing protocols constitutes of three primary divisions:

- Routing metric which is responsible for selecting the best path from the source node to goal node,
- An information system that comprises of the routing data,

- Messages that trade amongst neighbouring nodes for sharing of routing data [15].

1.2. Media Access Control

Media Access Control (MAC) ensures that the available spectrum is shared fairly amongst users of the spectrum to benefit every user of the spectrum band and in a multi-channel system it is accountable for channel assignment and access control. MAC protocol is also accountable for channel fragmentation, the core feature in CR. The SU and PU in a standard-based MAC are permitted to can the can sense the spectrum concurrently [1] [12].

CRNs enables the MAC layer to utilise DSA to check for accessible spectrum without interfering with to licensed users, the PU. CRs can change transmission parameters as per spectrum accessibility on a scope of channels [16]. The usage of the spectrum holes in the MAC layer has shown greater improvement because it minimises conflict on channels, limits interference between imparting hubs and enhances the average channel productivity [14].

1.3. CLD into CR networks

CRNs are a genuine result of CLD, diverse layers, for example, the physical (PHY), MAC and network layers collaborate to produce an efficient and useful CR system. CLD is an essential concern in CRN because the attributes in a certain protocol could influence the execution of others [1] [2].

CR’s faces issues such as congestion and security prompting decreased QoS and execution issues in the real-time situation. CLD helps overcome these issues by offering a straightforward uncover of internal data, upgrading the security, QoS, mobility, and system execution. Therefore, CLD is utilised within the CRNs to enhance the traditional layered plan by breaking the customary designs and making it possible for any of the layers to communicate to enhance the system [17].

1.3.1. Functions for dynamic spectrum environment in CLD

CR in CLD is responsible for four functions: spectrum sensing, allocation, sharing and mobility to adjust to the dynamic environment. Figure 1-4 presents these four functions.

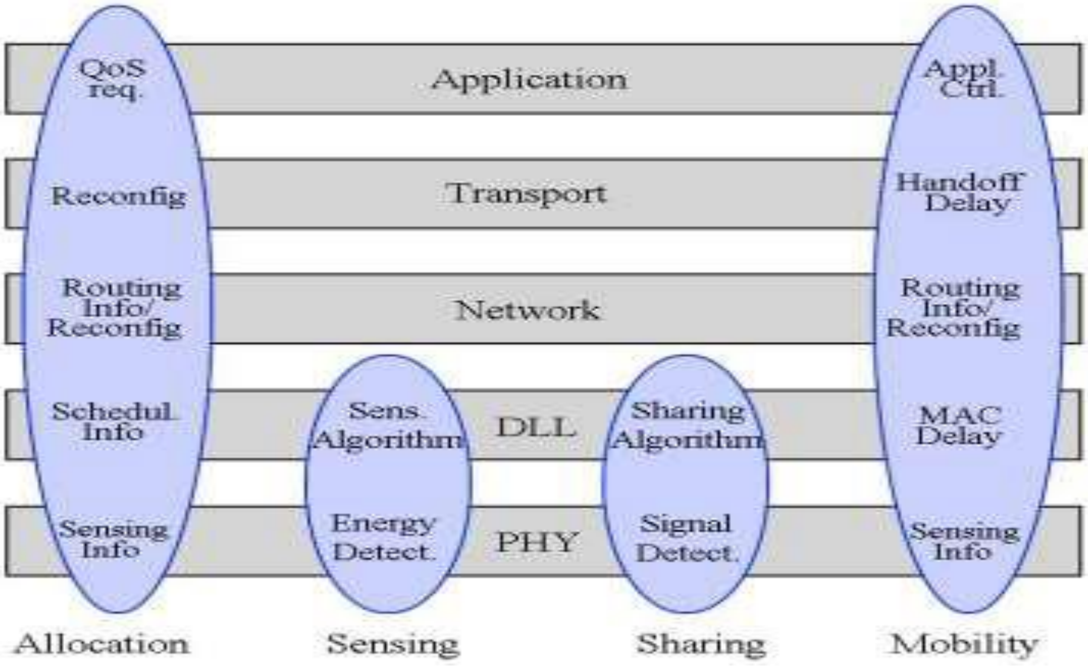


Figure 1-4: CR spectrum management framework *[18]*

1.3.1.1. Spectrum allocation

The principal objective of CR users is to figure out which parts of the spectrum are accessible. Hence, it should screen all accessible bands in the spectrum and distinguish those suitable for communication [18].

1.3.1.2. Spectrum sensing

Spectrum sensing discovers bands in the spectrum that are accessible and allows SU to reach the bands which are accessible and not involved by PU. Several strategies were initiated for this assignment procedure to work. The QoS necessities and applications, the system conditions, and the routing metrics need to be considered in dealing with spectrum decision and the transmissions of messages in the system [6] [18].

1.3.1.3. Spectrum sharing

Upon the completion of spectrum sensing, SU incorporates spectrum sharing among the SU. Therefore, access to spectrum ought to be administrated to prevent collisions between numerous SU and PU interference. Spectrum sharing appoint the proper spectrum among coinciding users and gives the capacity to keep up the QoS of CR users without making obstruction [6] [7] [18].

1.3.1.4. Spectrum mobility

SU are unlicensed users, and they should allow PU to move from one to another spectrum band whenever a PU demands the present spectrum for communication [18]. If PU demands the segment of the spectrum being used should handoff the spectrum and carry on with its transmission in the alternative spectrum else wait for the spectrum to be idle again [6] [7].

1.4. Problem statement

Generally, the mobile ad-hoc networks (MANETs) design depends on the traditional layered approach, where mobile nodes communicate through a wireless medium. This approach is inefficient in handling congestion related problems and the Receiving Signal Strength (RSS) (the power measurement in the radio signal received) correlated complications. This affects the PHY and the network layer, which in turn affect the transport layer. The main constraint of wireless networks is the very high node and spectrum mobility, which causes the link breakages; thus, they need to be repaired to ensure that packets are successfully delivered [19] [20]. Route repair is a time consuming and costly process.

CR is a promising technology designed to solve many challenges, such as the spectrum scarcity and spectrum allocation. To achieve spectrum efficiency in CN, Cognitive Users (CU) access the spectrum opportunistically when the PU is idle. According to the specification, the SU should not cause any interference to the PU [3]. Achieving this design constraint while meeting the QoS of SU is a challenge; hence the CLD was introduced to improve the efficiency and effectiveness of CNs.

CLD solutions in CRN are encouraging; however, there are still many issues and challenges that must be addressed, such as routing, channel and resource allocation, security issues, and energy efficiency, which negatively impact network performance [2].

We propose a CLD scheme that optimises routing and channel selection protocol for minimisation delays, increasing the throughput, and addressing other related issues that may affect a network's performance.

1.5 Research Aim and Objectives

This research aims to design and optimise a CLD multi-routing protocol that maximises the use of spectrum opportunities effectively in a dynamic framework incorporated with channel selection. This is broken down into the following study objectives:

i. Design a scheme which utilises spectrum opportunities efficiently without causing interference to PU.
ii. Minimise the end-to-end delay.
iii. Improve route stability.
iv. Maximise the network throughput.
v. Increase the network lifetime by saving the energy of nodes.
vi. Minimise interference between communication nodes and improve channel efficiency.

1.6. Hypothesis

The following is the research hypothesis based on known facts and theory which this research sought to prove:

The utilisation of CLD scheme that uses multi-routing and efficient channel selection can solve the spectrum related issues such as spectrum scarcity and underutilisation of the spectrum.

The use of spectrum opportunities while avoiding interference with the PU will increase throughput and minimise the delay.

1.7. Research

The research seeks to use the CLD scheme, which will improve the spectrum and channel utilisation. We seek to answer the following set of questions:

i. Can a CLD scheme be used to maximise spectrum efficiency by using spectrum opportunities while avoiding interference to the PU?
ii. How can we minimise the interference between communication nodes to minimise delay, maximise throughput, and improve channel efficiency?
iii. How can we save the energy of nodes; as a result, increase the network lifetime?
iv. How can we improve route stability between the source to the destination node?

1.8. Research motivation

The research is motivated by the high spectrum demands that have resulted in problems such as spectrum scarcity and underutilisation of spectrum due to FSA where only licensed users could access the spectrum. Traditional layered protocol stack has enabled the interoperability of networks to be possible. However, there is a need for CLD which integrate adjustment layers for improved efficiency. This approach was proposed to address these limitations of the traditional layered approach. Its main objective is to maintain the functionalities layers while facilitating the coordination, the communication, and joint enhancement of protocols across distinctive layers. It also addresses the challenges of spectrum mobility [21].

CRN in CLD has possible shortcomings which require attention such as interference to the PU. The merging of different layers to improve the network's efficiency has been one of the most effective solutions used in CLD.

1.9 Scientific contribution

1. M. S. Madiba, M. Velempini and R. L. Moila, “Spectrum handoff management strategies in cognitive radio routing protocols for mobile ad-hoc networks,” in SATNAC, Durban, Zimbali, 2019.

2. M.S. Madiba, M. Velempini, “The Design and Optimisation of Cross-Layer Scheme – Routing and Medium access control for Throughput in Cognitive Radio Networks,” in ICONIC, Inn Mauritius, Mon Trésor, Plaine Magnien, 2020.

1.10. Dissertation outline

This dissertation is outlined in seven chapters. Chapter two (2) discusses the background of CLD and understanding more about CLD communication and information sharing. Chapter three (3) is the literature review where we look at the challenges of CLD, the CLD architectures or methodologies and existing CLD protocols. Chapter four (4) is the research methodology chapter, and we looked at MATLAB in CRN, spectrum sensing model, spectrum handoff technique, channel occupancy, design architecture, and the performance plan. Chapter five (5) is our design and implementation; we illustrate our system model, explain our proposed scheme etc. Chapter six (6) demonstrates results; we look at the comparison results between the proposed scheme and two (2) other existing schemes. Chapter seven (7) concludes that we make a final remark based on our finding and presents recommendations for future research.

CHAPTER 2 - BACKGROUND

2. Introduction

The fast development of technology in the ongoing past has brought new difficulties or challenges and demands for a CLD to help and support it [22]. CRN had received much attention since the year 1999 when it established, and different significant standards were proposed. Studies have proven that results based on CR innovation require CLD for optimum performance, and they have built onto the outstanding enhancement in execution [18] [23]. CLD main goals are to advance communication and control at least two layers of the Open Systems Interconnection (OSI) model to accomplish significant execution enhancement by sharing sources [24].

2.1. Understanding CLD

The term cross-layer implies the interchanges between the OSI model's neighbouring layers and how they perform after and before the sending and receiving the information [22]. Traditionally the framework designs pursue strict layering standards that use the abstraction rule. The execution of information and interior attributes of protocols inside a specific layer is invisible to the rest of the other layers [18]. Therefore, CLD came as a CRN solution and broke the strict layering approach to accomplish certain goals, such as reusing unused spectrum to increment system capacity and sharing sources between different layers [8].

The CLD offers exceptional simplicity, particularly in remote communication. CLD's end goal is to accomplish resource sharing's primary objectives with all the system layers assuming distinctive roles [23]. The sharing of information between the layers in CLD is coordinated to ensure efficient communication between the layers with no loss of information and that the message received at the destination point is the correct message sent by the source node [22].

2.2. Summarised problems with the traditional layered structure

2.2.1. Non-optimal

The traditional layered design does not permit sharing of data between the distinctive layers. Again, the traditional layered structure does not guarantee execution enhancement for the whole system [18] [25].

2.2.2. Not flexible

The traditional layered structure protocol is difficult to work with as it cannot adjust to the system's sudden changes and environment. The other challenge is that the protocol stack cannot use discharged resources in the spectrum and power resources, and it cannot deal with congestion related matters [26].

With the end goal to amend the two issues discussed above, cross-layer scheduling mechanism is brought into a remote system. This mechanism aims to make the system more versatile and ensure improvements dependent on application requirements and system conditions that enhance the entire framework's execution [25].

2.3. CLD at the link layer

This layer is also called the connection layer, which oversees the accessibility and productivity in the accessible spectrum opportunistically. The link layer in CLD accounts for medium access, implementing and monitoring sensing strategies, and control channel.

2.3.1. Medium access

The link layer gives the key administration of organising the entry to a remote medium using the MAC layer. This administration is distinctive compared to the one used by link layer in the layered systems as it seeks an ideal necessitated application for QoS parameters. Dealing with the sensing procedure of the PHY layer and decision of the spectrum acquired from the Cognitive Engine (CE) (which is the agent that settles on decision dependent on its perceptions, experience and administers its execution), the link layer coordinates the nature of communication interface [27]. MAC is an ideal resource assignment among various traffic streams to enhance low inactivity movement over ad-hoc remote frameworks [28].

2.3.2. Implementing and sensing strategies

The access and sharing of spectrum in the CR system will be the outcome of the link layer's decision dependent on systems set by the CE. In this specific situation, the link layer performs two functions: 1) it must sustain the CE with the expected data to describe the ideal techniques and 2) it must actualise such techniques and uphold the subsequent decisions regarding framework parameters, for example, the transmission control, carrier frequency and bandwidth. The link layer's decisions dependent on CE procedures will permit CE and link layer to enhance basic decision making procedure by using the historically verifiable spectrum information and past experiences [27].

2.3.3. Control channel

The link layer supplies the above layers and CE with satisfactory system resources to coordinate signalling, for example, dispersal of sensing results, sharing decision, entry to the radio environmental databases for recovering radio system data, etc. This is done through cognitive control channel selection methods pending CE's contribution best appropriate PU channels for channel control foundation given spectrum history based on sensing decisions and exchanged information [27]. The control channel should have the ability to incorporate the accessibility of resources and modify user's configuration entailing density and adaptability [28].

2.4. CLD at the network layer

This is the essential layer within the OSI model which manages the routing and communication of the information between all the layers. The CLD is proposed in this layer to accomplish high performance, QoS, better effectiveness, security, handoff latency for example. The network layer in CLD accounts for routing and admission or flow control [22] [27].

2.4.1. Routing

The main objectives of routing are selection, maintenance and refreshing of routes for packets delivery purposes. The CE chooses the routing algorithm and the routing metric because of different layers and the network layer. Such components will be used to decide routes and data given by the CE or lower layers [27].

Re-routing of packets ought to be carried out in a cross-layer form. Given the probability that the connection failure happens because of spectrum mobility, the intermediate CR users can re-route packets using spectrum information accessible from spectrum detection and pick another accessible route [28].

2.4.2. Admission or Flow control

The main aim of admission control is to oversee the network regarding the number of gadgets permitted and packets flow rate adjusting to system conditions and congestion. For this situation, the CE's coexistence necessitates deciding the flow control techniques relayed to the network layer [27]. The flow of admission control guarantees that only movement flows whose QoS parameters can be ensured by the system are admitted [29].

2.5. Sharing plan amongst nodes in CLD

The sharing plan amongst the nodes in the system can be either by centralised or distributed. In centralised, it utilises the focal hub to control the data sharing while distributing the data without utilising the focal hubs [17] [30]. Figure 2-1 demonstrates the sharing plan amongst nodes in CLD.

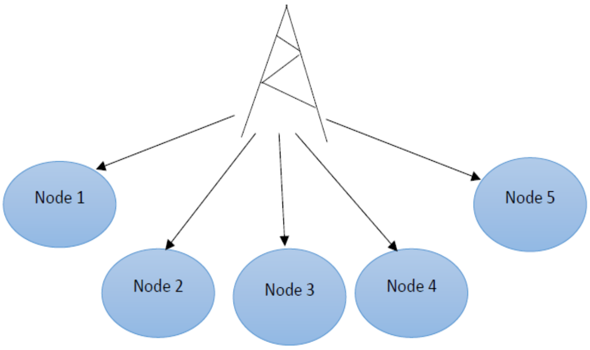
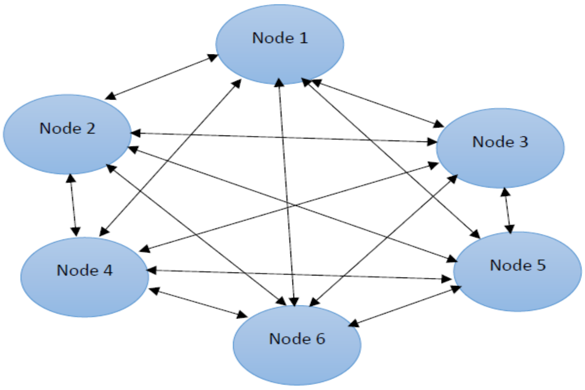
Centralised	Distributed
 Figure 2-1a: Centralised sharing plan The central node shares information with all the subsequent nodes in the system equally.	 Figure 2-1b: Distributed sharing plan. All the nodes in the system share the information amongst themselves; there is no central node to coordinate the sharing.

Figure 2-1: Sharing plan methods amongst CLD nodes (Adapted from *[30]*).

2.6. CLD communication and information sharing amongst the layers.

2.6.1. Shared database

The shared database design presents a database accessible by each layer that requires its service, therefore direct communication between layers [18]. This approach enables all layers to communicate with a control plane that performs cross-layering as per enhancement model. The control plane acts as the centre of the information to the system nodes and can be used to make a new abstraction of the system functionalities, and consequently, the traditional layered structure loses its original content [31].

With this approach, the shared database can act as another new layer to store or recover the layers' data. This method is advantageous since just one single command can help in sending the signal to each of the layers and this exceptionally appropriate for vertical adjustment architecture [22] [25] [28] [32]. The Figure 2-2 shows the shared database communication approach.

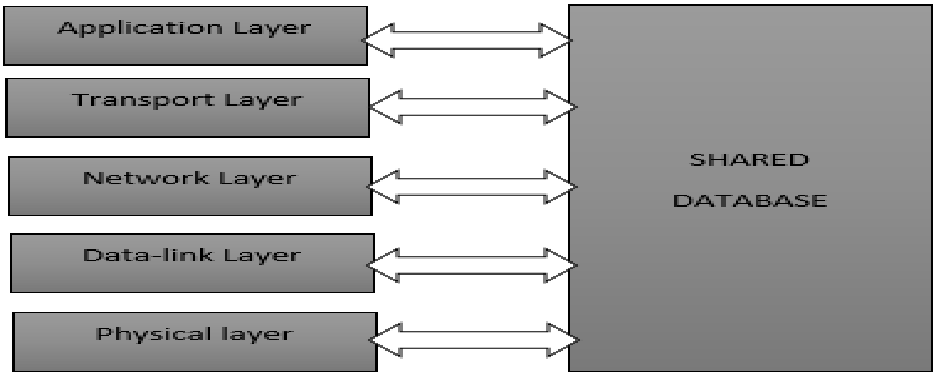


Figure 2-2: Layers communication through a shared database (Adapted from *[8]***)**

2.6.2. New abstractions

The new abstractions design optimises shared database, which can offer applicable information from different layers [8]. It introduces another approach different from layering, which sorts out the protocols in heaps, not in stacks. This approach permits rich communications between the building squares of the protocols, it offers extraordinary adaptability, both during configuration and at runtime [32]. The issues encountered in this sort of communication are that since there are not changing the layer design but rather the protocol itself, there may be a need to construct a radically new framework independently to support this kind of communication [22]. Figure 2-3 shows the new abstraction communication approach.

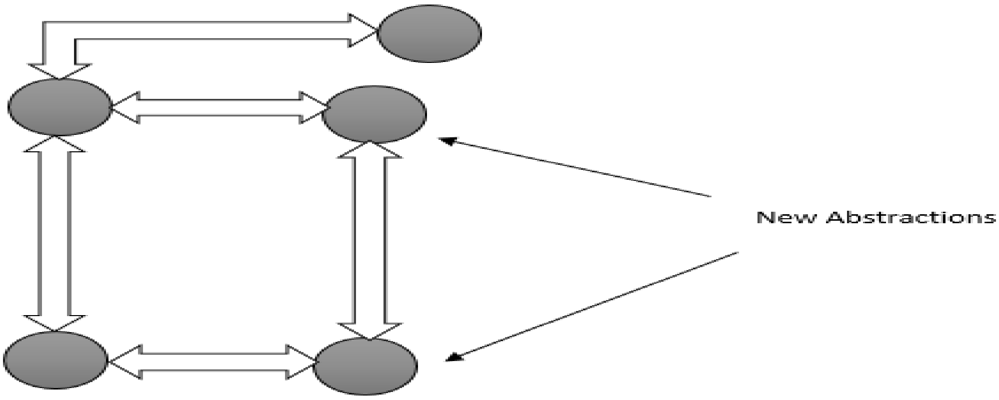


Figure 2-3: Layers communication through new abstractions *[8]*

2.6.3. Direct communication between layers

This strategy enables factors at one-layer transparent to alternate layers at execution time. It is a basic communication strategy between the layers where the layer will communicate directly with its neighbouring layer, and each layer will be working at its factors and variables. The challenge encountered with this approach is shared memory space, i.e., the layers may communicate with one another; however, the memory shared space between the layers may be of an issue [22] [28]. The benefits of this design are that it minimises complexity [18] [31]. Figure 2-3 illustrates the direct communication approach between the layers.

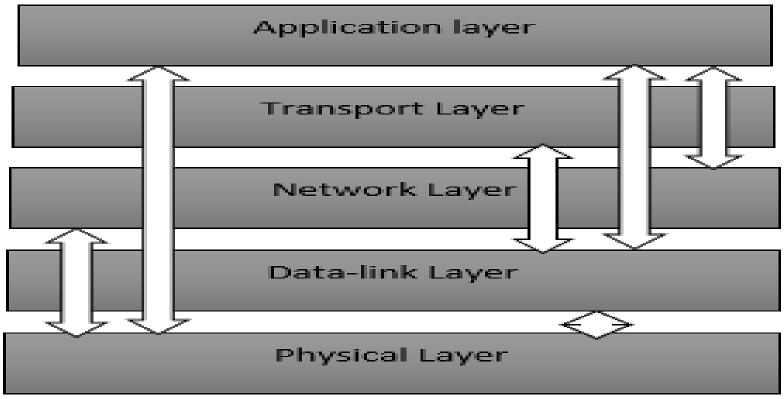


Figure 2-4: Layers communication through direct communication (Adapted from *[8]*)

2.7. Summary

The chapter presented the background of CLD. We understood CLD, presented the challenges encountered with the traditional layered approach, demonstrated the CLD at the data-link layer and at the network layer, and showed the services offered by each layer and methods of sharing data across the layer. We discussed three communication strategies between the layers: the shared database, new abstractions, and direct communication between the layers.

CHAPTER 3 - LITERATURE REVIEW

3. Introduction

CLD violates the traditional layered architecture of the basic layers of the OSI model and considers the relationship between the five (5) layers and the reconfiguration capacity [8] [33]. A lot has been done in CLD, and this chapter reviews the literature.

3.1. Routing / MAC CLD

A routing protocol in a multi-hop remote system finds the best route for packets from source to goal. The routing and MAC cross-layer architecture design should be conjoined protocol since a routing scheme gathers data from the MAC layer, such as traffic load information and link quality to decide on the best available route. With the end goal to optimise the execution of routing and MAC protocols at once, MAC protocol techniques should be investigated and enhanced to conclude the best execution of MAC and routing cross-layer plan.

The current studies indicate that MAC protocols can be reserved or random-access-based. In a MAC that follows a random-access-based, there would not be any system accessible to adjust the MAC layer execution by considering the data from the above layer. The advantage of such a MAC is its simplicity and additional preferred standpoint of being decoupled from the above layers. This type of MAC’s weakness is its low execution, and a routing scheme may experience more dreadful execution since zero possibility of cross-layer advancement is accessible. This kind of challenge demonstrates one in numerous challenges of using the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC protocols in wireless systems.

The resolution to this challenge includes two (2) arrangements. The first arrangement is adjusting the random-access protocol with the goal that it acts more like reserved protocol. This can be done using the 802.11E hybrid channel access control, which incorporates the scheduling procedure and the reservation that will operate with CSMA/CA to enhance the execution of 802.11 MAC. Secondly is to have an overlay protocol that can build up a Time Division Multiple Access (TDMA) protocol overlaying CSMA/CA [34] [35].

3.2. The goals of CLD

Objectives of CLD are to enhance security, QoS and mobility over all the five layers of Transmission Control Protocol/ Internet Protocol (TCP/IP) protocol layer as presented in Figure 3-1.

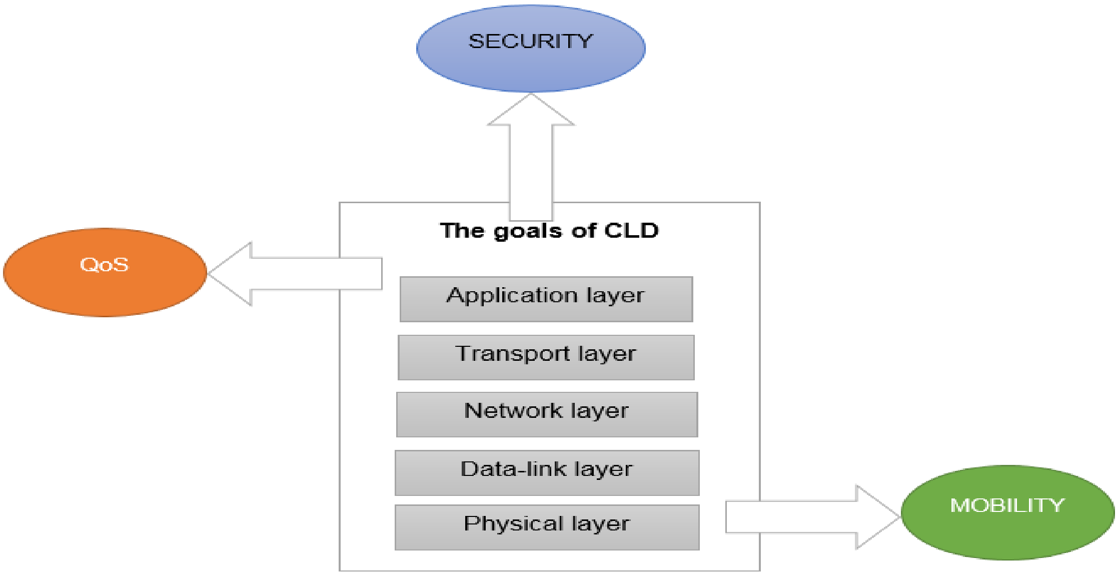


Figure 3-1: The goals of CLD

3.2.1. Security

The security coordination plane confines the protocols regarding the security challenges in the five layers of the TCP/IP. The Secure Shell (SSH) and Wireless Fidelity (Wi-Fi) encryption strategies for secured access may be set up inside this plane for security purposes in a cross-layer procedure. The SSH and Secure Sockets Layer (SSL) encryption techniques at an application layer can be implemented for security in end-to-end encryption, Internet Protocol Security (IPSec) protocol technique can be implemented at the network layer for the end-to-end encryption, and finally the Institute of Electrical and Electronics Engineers (IEEE) 802.11 remote systems can be implemented for security at the PHY and link layer [17] [22] [30].

3.2.2. Quality of Service (QoS)

The QoS coordination plane is focused on accomplishing CLD with the end goal to enhance QoS. This plane enhances the nature of administration in remote communication over the five layers of the OSI model. Because of the characteristics of PHY and link layers in the remote systems, the above layers should know about the data in the two lower layers with the end goal to enhance the QoS in specific conditions. The data sharing specifications amongst the two (2) bottom layers and the three (3) above layers is not backed-up in the present waterfall design of remote system architecture [17] [22] [30].

3.2.3. Mobility

The mobility coordination plane is responsible for ensuring continuous and undisturbed correspondence in remote systems. Nodes movements are key in ad-hoc systems. The occasions resulting in the nodes motions, for example, switching of channels and changing of routes are important to be found and corrected for guaranteeing the uninterrupted communications. The fading of the channel, excessive Bit Error Rate (BER) and delays incurred during transmissions, and different disappointments that minimises the QoS can influence mobility too [17] [22] [33] [30].

Security, QoS, and mobility plays a vital role in CLD. Mobility is the main factor in CLD in CRN, that facilitates SU sharing of the spectrum without interfering with the authorised users, the PU. While avoiding interference between the communication nodes at different layers, QoS should be considered to avoid traffic or congestion related issues by coordinating and making sure that all resources are shared effectively within the layers of the OSI model while factoring in the security issues.

3.3. CLD proposals and architectures

3.3.1. Creation of new interfaces

Most cross-layer architectures demand the formation of new interfaces proposal amongst the five (5) layers, demonstrated by Figure 3-2. This type of proposal is utilised amongst the layers for sharing of data at runtime. Design infringement is forming a new interface that is inaccessible in the traditional design [32] [22]. This proposal is divided into three subcategories as follows:

3.3.1.1. Upward information flow

This design uses the upward direction to form a new interface, from the bottom to above layers. The top layer requesting data from the bottom layer(s) with therefore begin the formation of another interface from the bottom layer(s) to the top layer [34]. When the end-to-end TCP path has connection errors, it is possible to trap the TCP sender in creating incorrect presumptions regarding congestion in the system, resulting in poor execution. Making inferences from bottom layers to transport layer empowers explicit warnings thus reduces these challenges. An example: the Explicit Congestion Notification (ECN) in the transport layer from the router can inform the TCP transmitter regarding the encountered congestion in the system to empower it to distinguish amongst congestion and errors in the network [32] [36] [35].

3.3.1.2. Downward information flow

Downward information flow uses downward direction for building the new interface, from top to the bottom layers. The bottom layer(s) that is need of some data from the above layer(s) will build another interface in a downward manner, from above layer(s) to bottom layer [34].

Some CLD proposals are dependent on using the direct interface from other above layers (s) for positioning parameters on the bottom layer(s) of the stack at execution time. For instance, an application layer can notify data-link layer regarding defer specifications and therefore, the data-link layer would implement delay sensitive when treating those packets. The good methods to use for the downward and upward data stream regard them as hints and warnings discretely. The upward data stream effectively notifies the above layers regarding the system conditions whereas the downward data stream is intended to give indications to bottom layers regarding how application information ought to be refined [32] [36] [35].

3.3.1.3. Back and Forth information flow

This approach enables two (2) layers that carry out distinctive activities or roles to work together. The streaming of data in backwards and forward motions presents an iterative loop amongst the two (2) layers. Therefore, design infringement in this regard is the two complementary new interfaces [34].

For this case, we consider the Network-Assisted Diversity Multiple Access (NDMA) propositions where the MAC and PHY layers work together within the uplink of a wireless Local Area Network (LAN) framework to solve the collisions that may have been encountered. After identifying a collision, the number of users that collided should be evaluated by the base station, and retransmissions will occur between the collided users. The PHY layer signal provides the base station with a chance to isolate the signals from all the colliding clients [32] [36] [35].

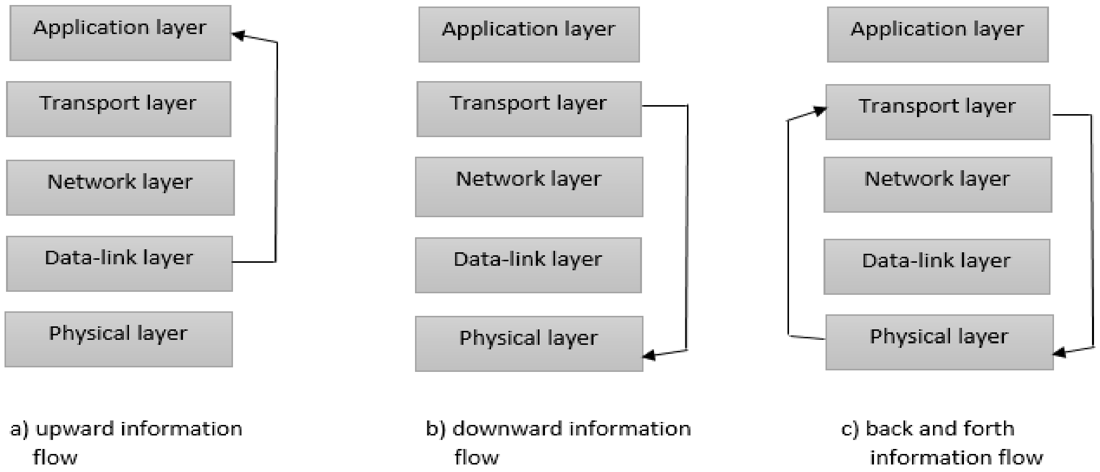


Figure 3-2: Upward, downward, and back and forth information flow (Adapted from *[35]***)**

3.3.2. Merging of adjacent layers

The merging of adjacent layers is one of the simplest approaches for performing CLD to structure at least two neighbouring layers together to such an extent that the services of new super layers are the association of services given by the constituent layers as shown in Figure 3-3. There is no compelling reason for building a new interface in the stack for every layer with this approach. Interfaces can be given amongst the super layer and all other layers. Again, the interfaces from the primary design can be used for the super layer to be interfaced with the rest of the stack [22] [32] [36] [34] [35].

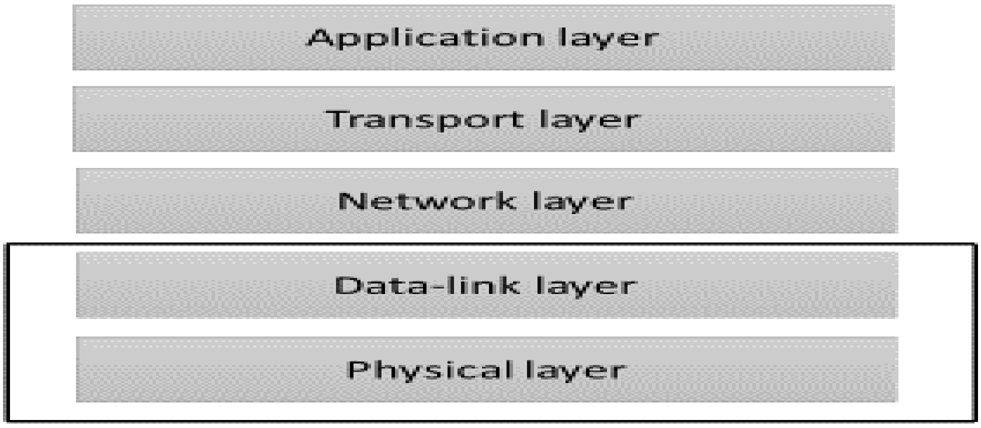


Figure 3-3: Merging of adjacent layers (Adapted from *[35]***)**

3.3.3. Design coupling without new interfaces

Design coupling with new interfaces is a classification of CLD architecture that couples at most two (2) layers in the stack but with no further creation of interfaces for data sharing at execution time as shown in Figure 3-4. Because there are no new interfaces formulated, the challenge with this design is that it might be impossible to substitute one-layer in the stack without making corresponding adjustments to another layer. When one-layer can do more than one task at the same time, the role of another layer must be changed and must be reconstructed [22] [32] [36] [34] [35].

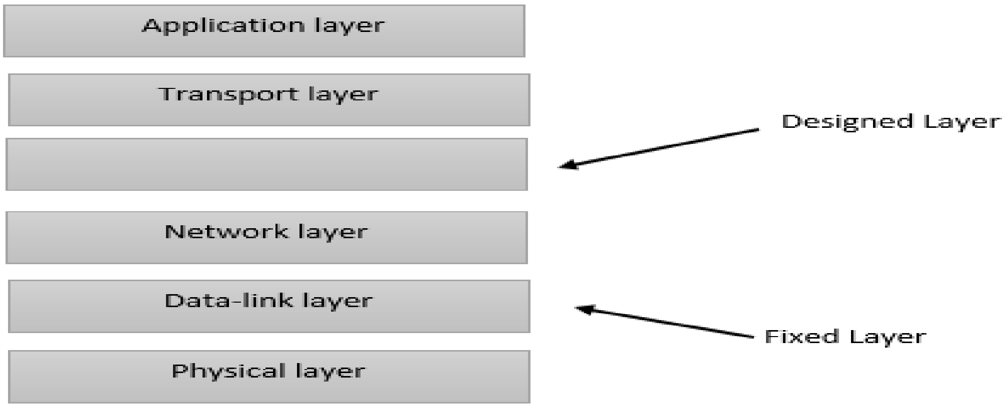


Figure 3-4: Design coupling without new interfaces (Adapted from *[35]***)**

3.3.4. Vertical calibration across layers

The vertical calibration across layers is a design that refers to altering parameters that range crosswise over layers as shown in Figure 3-5. This approach allows the practice of implementing distinct parameters crosswise over various layers. The execution identified at the upper layer is because of the calibration impact at the bottom layers by different parameters. The combined parameters have greater execution over independent parameters [34] [36].

The approach should be possible in a dynamic and static and dynamic environment. Dynamic vertical calibration is performed at execution time and involves the whole convention stack to give varieties in the traffic condition, channel, etc. The static vertical calibration should be possible through reserving some enhancement strategies when positioning parameters across the layers during design time. The parameters in the dynamic calibration can be improved from various layers while in static calibration, they remained untouched after they were adjusted only once during the design time [22] [32] [35].

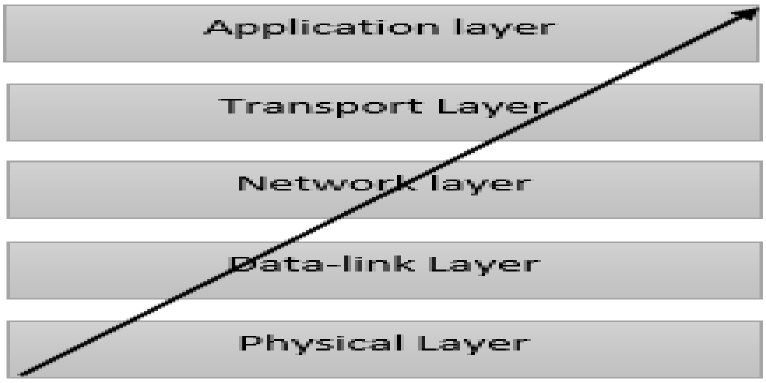


Figure 3-5: Vertical calibration across layers *[35]*

The proposed CLD and architecture discussed above make CLD promising when different data sharing methods at different layers of the OSI model are considered. This was not possible with the traditional layered approach due to strict layering technique; therefore, congestion and RSS challenges were a challenge in this set up.

3.4. Existing cross-layer protocols

3.4.1. Cross-Layer routing protocol (CLRP)

The CLRP considers both the channels that might be inaccessible and the channels that are recognised as accessible at every node. It utilises the stochastic approach to access the latter channels. This protocol also identifies an end-to-end route and shares the data with the first layer from the bottom of the OSI model, the PHY layer. The shared data relates to which channels can be sensed to improve the quality of the route.

The protocol periodically examines a small set of channels. Observed channels are identified as either busy or idle: the probability of availability = 1, or inaccessible, given by the probability of unavailability = 0. The different channels that are not sensed are assigned different probabilities ranging from 0 to 1. These probabilities are important because the routing procedure uses them to determine the nature of a route connecting the source and goal [37] [38].

3.4.2. Cognitive Ad-hoc On-demand Distance Vector (CAODV)

CAODV adjusts the current Ad-Hoc On-demand Distance Vector (AODV) protocol and avoids interference with the PU. This protocol advertises Route Request to all the neighbouring hubs and reserve several routes to the destination. The destination hub will select the best available path, considering the shortest route [39] [40]. AODV protocol is divided into three (3) stages; the Route Request, Route Reply and Route Maintenance phases presented by [40].

3.4.2.1. Route Request phase

In this stage, a route discovery procedure is initiated by a sourcing hub which requires communication with a distant hub and whose path is inaccessible. The source hub floods Route Request (RREQ) parcels until it gets to the goal or a hub having data regarding the goal hub. There is a need for a hub to dispose of all the RREQs that have been seen previously to minimise flooding overhead.

3.4.2.2. Route Reply phase

After the RREQ phase, the goal hub checks the route with a minimum possible count of hops. The packet will create the reverse route with a minimum count of hops. The goal hub will utilise the path with a minimum count of hops and create a Route Reply (RREP) packet and unicasts it to the source hub.

3.4.2.3. Route Maintenance phase

"Hello" messages are frequently used by hubs to notify their existence to their neighbours. This makes it to be possible to observe functioning routes connection status to the next hop. When the hub discovers a connection detachment or failure, it broadcasts an Error Route (RERR) message to neighbouring hubs which will spread the RERR message to the hubs whose paths might have been influenced by failed link. Therefore, the route discovery procedure will be re-initiated by the affected source only if the path is still required.

Minor modifications to convert the ordinary AODV to CAODV, as presented by [41].

- RREQ is communicated by a hub that requires a path to the goal by altering information regarding the spectrum, including the best accessible channel.
- The SU receiving the RREQ will check if it is involved with the PU. If yes, it attaches information regarding the available spectrum then broadcast the packet until it gets to intermediate or goal hub having data to the goal. If there is no available channel, it just drops the RREQ.
- The goal hub selects the ideal route by taking the best shortest path.

The disadvantages of CAODV is that in cognitive routing using the shortest path besides looking at the channel characteristics does not always yield good results and secondly, as the network traffic increases, high overhead is incurred due to flooding of the RREQ packet to all the channels [1] [39] [40].

3.4.3. Opportunistic service differentiation routing protocol (OSDRP)

OSDRP scheme discovers the path with minimum interruptions by considering the accessibility of spectrum opportunities, queuing delay, and switching delay across the PU [5]. It considers Standard Operating Procedure (SOP) to accomplish a successful end-to-end transmission through the route selection process. This protocol's disadvantage is that a SU can abuse the primary band SU irregular access and negatively affect the performance of CRN [42] [43]. This protocol's general targets are accomplished through the four (4) distinct modules: route discovery, decision, opportunistic routing, and maintenance [44]. The OSDRP scheme is illustrated in Figure 3-6.

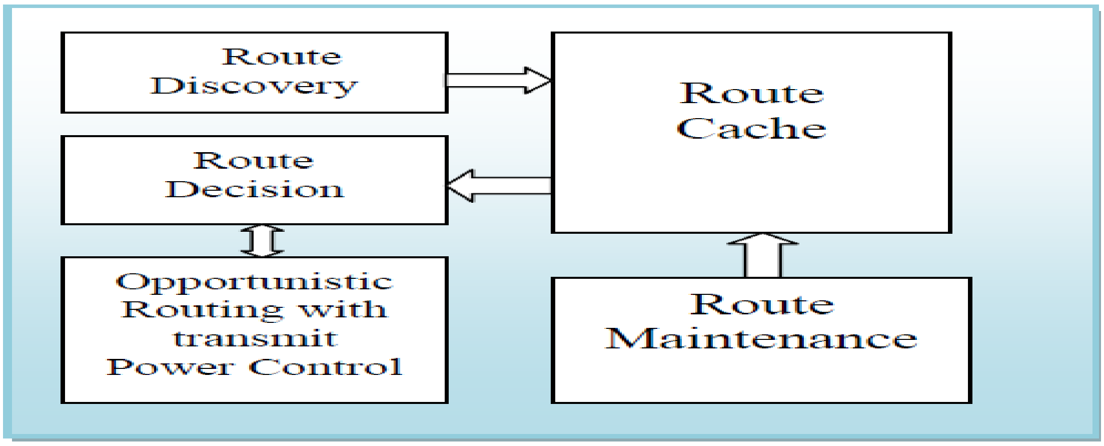


Figure 3-6: Opportunistic service differentiation routing protocol flow diagram *[44]*

The route discovery hub finds all paths available from a sourcing hub to a goal hub. The accessible paths are arranged through delay to be implemented by the route decision module to choose the best path considering end-to-end traffic movement. When the path has been determined, the routing process chooses a sending hub as per packet need. The route maintenance module oversees the entire system and erases the stale sections from the route cache to maintain the workable size [44].

3.4.4. Routing and spectrum allocation (ROSA)

ROSA algorithm enhances achievable throughput utilising joint routing, efficient scheduling, transmission power control, and dynamic spectrum distribution. This algorithm dynamically appears the spectrum resources to avoid interference and ensures that resources are utilised proficiently and distributed using cross-layer plan [45].

The localised and distributed algorithms for spectrum assignment and joint dynamic routing in multi-hop CRNs depend upon the locally gathered spectrum and power allocation data. This protocol also uses the timeslots for the control channel to gather network measurements and the channel information for communication purposes. ROSA algorithm uses the spectrum and queuing signals to opportunistically compute the next hop; thus, every packet chooses its distinctive route [44].

3.4.5. Cognitive Cross-layer Multipath Probabilistic Routing (CCMPR)

The CCMPR protocols have the following characteristics as discussed by [46]

- The cognitive routing technique uses the route and spectrum diversity jointly and uses spectrum holes for information transmission.
- A cross-layer procedure whereby the routing technique implements the spectrum holes while choosing hub and spectrum. It likewise uses the channel history to choose a transmit control level for every hop within the path.
- Multipath routing plan that sets up different routes to a goal. Due to mobility and inaccessibility of a route, another route may be utilised in such circumstances and thus one advantage of multipath routing.
- Probabilistic routing strategy which has the likelihood of choosing each route that will assist through load balancing.
- Reactive routing which only searches the paths when the hub has information to send.

We consider the following phases in CCMPR, as discussed below.

3.4.5.1. Route discovery

Whenever a hub has information to send to a goal, it creates the RREQ message. A goal hub or an intermediate hub that receives the RREQ message computes the previous link cost then updates the header by summing the previous link to the route costs. The off chance that an intermediate hub has a route to goal sends the RREP message to the source hub that initiated RREQ; otherwise, it further broadcasts the RREQ packet. When the RREQ is received at the goal hub, it sends a RREP message.

3.4.5.2. Route maintenance

Route Maintenance phase is computed utilising RERR messages. At whatever point a connection disappointment is identified, the RERR message broadcasted to all functional source hubs in that connection. Occasional “hello” messages are utilised to distinguish connection disappointments. Upon the arrival of the RERR message in the source hub, it can start another route discovery procedure. The paths which are unused in the routing table are removed using a clock-based procedure.

The existing protocols discussed in this section implemented CLD approach using different techniques and architecture in CRN. SU were introduced as means of solving spectrum underutilisation and spectrum scarcity. The main issue in some of these protocols is that SU can interfere with the PU which is a disadvantage in this regard because it results in ineffective utilisation of network resources and other challenges that may degrade the performance network. Therefore, there is a need for protocols that are designed to avoid the interference between the cognitive users to enhance the network performance.

3.5. Summary

In this chapter, we reviewed the literature. We have looked at the Routing and MAC in CLD. We also looked at the goals of the CLD. We discussed the CLD proposals that create new interfaces, merging adjacent layers, design coupling without new interfaces, and vertical calibration. The most important thing in the literature is the last section’s existing protocol on the literature because it is important to review what other researchers have developed in CLD.

CHAPTER 4 – METHODOLOGY

4. Introduction

This study the quantitative experimental approach, whereby our experiments are done using the simulations. We are using MATLAB R2019a installed in Windows 10 OS.

4.1. MATLAB tool in CRN

Figure 4-1 demonstrate the setup of the simulation environment in MATLAB.

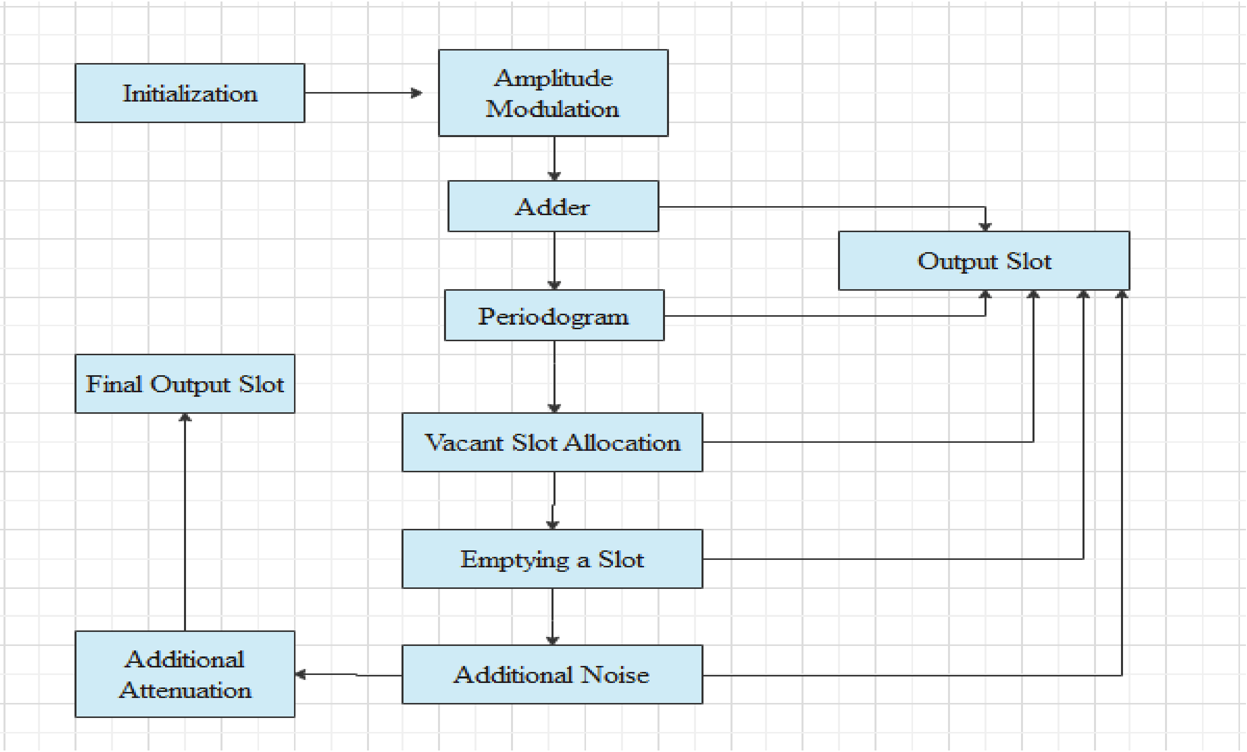


Figure 4-1: Simulation setup of CRN in MATLAB

Initialisation – The first step initialised the message frequency, user's carrier frequency bands, and the sampling frequency.

Modulation – Using the amplitude modulation it modulates user data over the respective frequency band.

Adder - The modulated signals are all added to produce a transmitting signal.

Periodogram- The received signal power spectral density is estimated.

Vacant Slot Allocation- When the new user arrives, the user will be allocated to the first spectral hole.

Emptying a slot – When all the slots are engaged, the user is asked to empty a specific slot.

Addition of noise - the addition of noise amount.

Attenuation - In this last stage we introduced the percentage of attenuation.

4.2. CLD Architecture, communication and information sharing for the proposed scheme.

4.2.1. Merging of adjacent layer design architecture

Merging of adjacent layers is the simplest and straight forward approach for CLD which merge at least two neighbouring layers of the OSI model. We merge the network layer accountable for routing and the data-link layer where MAC is located and responsible for signal transmissions and channel allocations as shown in Figure 4-2. A routing protocol gathers data from the MAC layer. The gathered data can be information related to the interference level, the quality of the link, or traffic load to decide on the best path for data transmission.

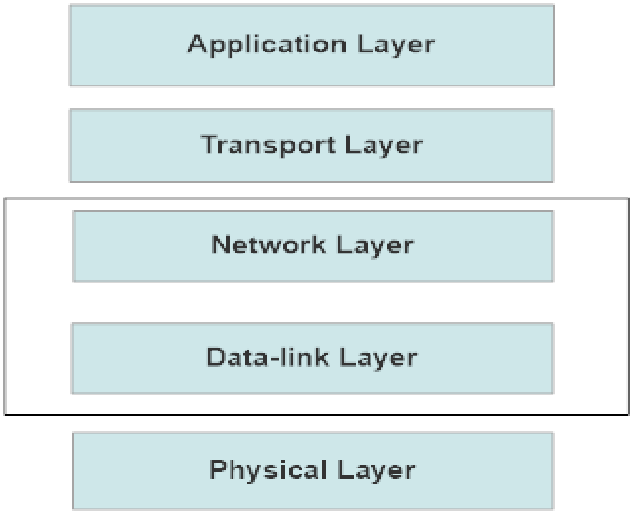


Figure 4-2: Merging of adjacent layers (Network and Data-link layers) design architecture

4.2.2. Direct Communication between the layers

The possible communication for information distribution amongst the merged network and MAC layers will be through direct communication as shown in Figure 4-3. This approach is the basic strategy for communication between the layers. The layer will communicate with its neighbouring layer, and each layer will be working at its factors and variables. The benefits of this communication design are that it minimised complexity and the convenience to improve parameters utilising data from non-nearby layers

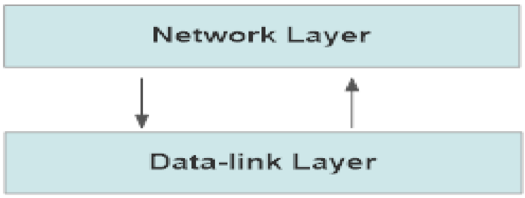


Figure 4-3: Direct communication between layers

4.3. Spectrum sensing model

The wireless hubs in CRN frequently change their parameters to avoid PU or SU interference through efficient communication. This adjustment of parameters depends on observing the radio environment, e.g., user behaviour, radio frequency spectrum and the network state. Figure 4-4 shows the spectrum sensing model in CRN for our study. During the spectrum sensing holes, the first step is the SU scan for the destination frequency band using the energy detection and then sending the results to the cognitive node called the Information Processing Centre (IPC). Lastly, the IPC will then decide whether the PU exists the spectrum bands, called the Cooperative Spectrum Sensing (CSS).

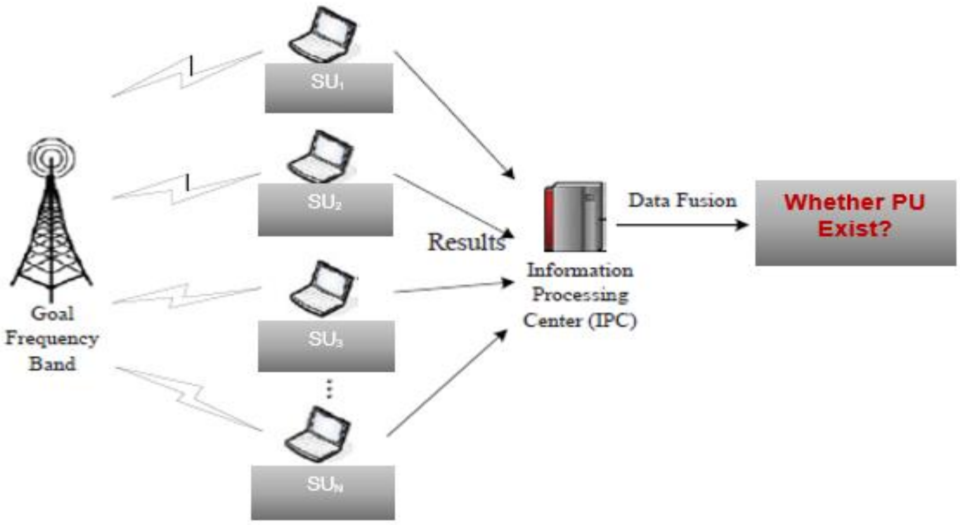


Figure 4-4: Spectrum sensing model *[47]*

4.4. Spectrum handoff management strategy

To avoid interference with the PU in CRN, a spectrum handoff strategy should be implemented when the SU needs to hand off the spectrum to give full access to the PU. This study will use the Pure Proactive Spectrum Handoff (PPSH) strategy because it suits the cross-layering.

We chose to use the PPSH approach because it performed better than a hybrid, non-handoff, and pure reactive approaches, as indicated by the contribution we made in this study [48]. With the PPSH, the objective channel is pre-selected before spectrum handoff happens dependent on long-term measurements. Yet, issues regarding this plan may be that the pre-selected targeted channel might not constantly be reachable. With this handoff procedure, SU utilises proactive spectrum detecting and proactive handoff activity strategies. The SU implements the spectrum detection to discover a backup targeted channel before handoff activation phase. Given the PU traffic model's information, SU can anticipate PU entry so that SU clears the channel before. The targeted channel determination and handoff activities are implemented proactively before the activating occasion.

The proactive spectrum handoff technique is increasingly reasonable due to mobility, and it does not consume time on detecting. In this way, handoff delays and complete administration time are shorter in proactive plan than a reactive plan [49] [50] [51] [52].

Figure 4-5 shows the prediction of PPSH. SU starts by preparing the backup channel, then SU foresees the PU A arrival and temporarily halt the transmission on the channel's PU arrival. The spectrum handoff occurs after PU A will begin its transmission and SU resumes its transmission after PU no longer occupies the channel.

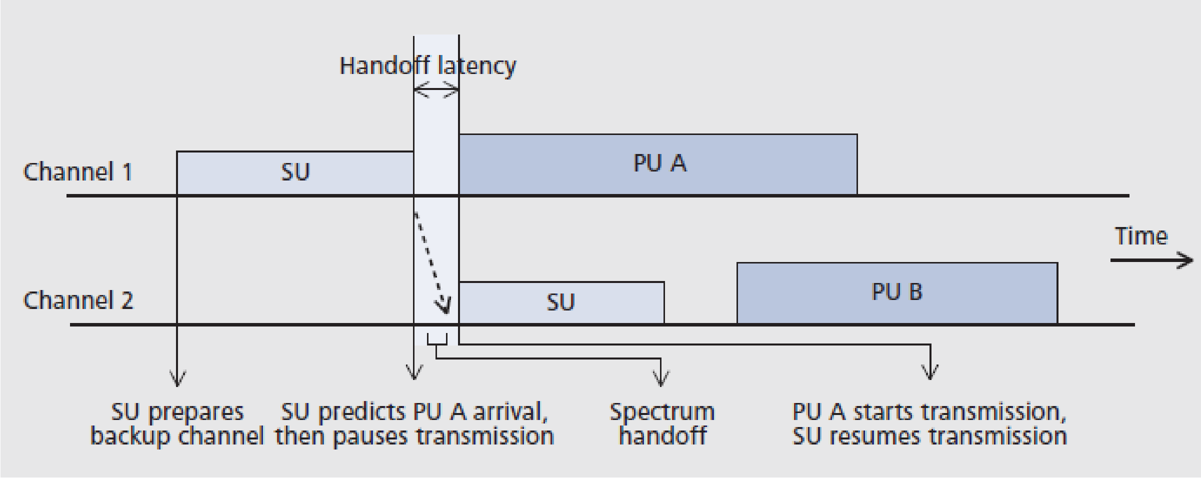


Figure 4-5: Pure proactive approach *[52]*

4.5. The algorithm for CR operation

Figure 4-6 demonstrates the algorithm for CR. SU waits for the beginning of the time slot and checks if PU is accessing that slot. If YES, SU it goes back to the initialisation stage and if NO it waits for the beginning mini slots. The SU again checks whether the time slot is occupied by another PU, if NO it checked if there is a packet in the queue, then checks again if it is the last mini slot.

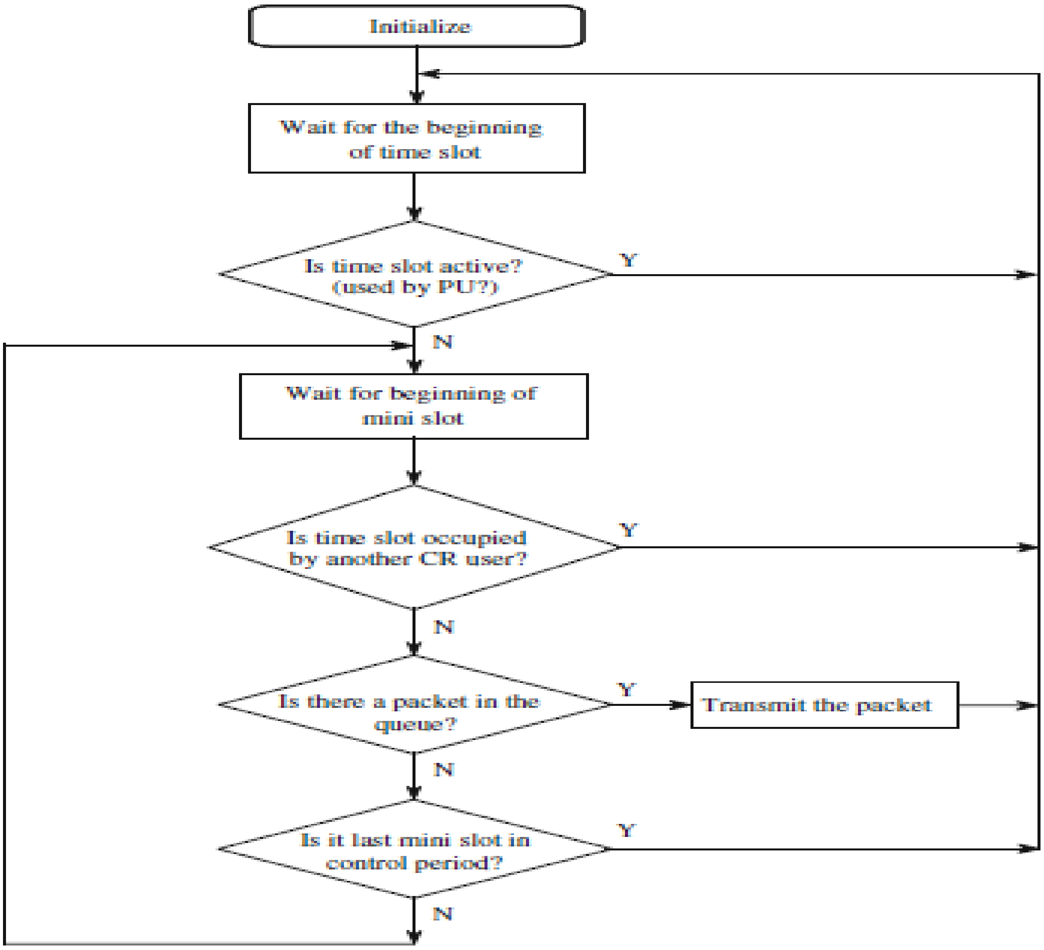


Figure 4-6: The algorithm for CR user operation *[53]*

4.6. Performance plan

4.6.1. Evaluation metrics

The study objectives stated in chapter 1, and some were to minimise the end-to-end delay, maximise throughput, increase the network lifetime by saving hubs' energy, etc. To see if we achieved what stated on our objectives, we will use the following metrics.

i. Energy consumed per packet,
ii. Throughput,
iii. End-to-end delay, and
iv. Packet Delivery Ratio (PDR).

4.6.2. Simulation tools and parameters for evaluation

We use Windows 10 as our OS and MATLAB as our simulation tool for performance evaluation. We choose to use MATLAB because it is easy to use. Researchers in the related study also used MATLAB. The proposed scheme is compared with existing protocols, the CAODV and CCMPR. We chose to use these protocols because they are the best performing schemes that have been developed in CLD already. Table 4-1 presents the simulation parameters and the respective values.

Table 4-1: Simulation parameters

PARAMETER	SETTING
Network simulator	MATLAB R2015a
Operating system	Windows 10 OS
Simulation area	1000m x 1000m
Simulation time	250s
Antenna type	Omni-directional
Cognitive radio model	CRAHN
MAC protocol	IEEE 802.11 with extension to support CR networks
MAC type	802.11a
Packet size	512 bytes
Channel data rate	11Mbps
Traffic type	CBR
Propagation	Stochastic
Primary user detection	Energy detection
Propagation model	Two-Ray Ground
Mobility type	Random waypoint model
Sensing type	CSS

4.7. Summary

This chapter presented the methodology of the study. We have shown the methods we are using, including the sensing strategy, the handoff strategy method we will implement, and channel occupancy. We also presented the performance plan, which includes the evaluation metrics we will use to compare our schemes with the existing schemes. Lastly, the simulation tools and plan or environment together with the simulation parameters and their settings.

CHAPTER 5 – DESIGN AND IMPLEMENTATIONS

5. Introduction

This chapter presents the design and implementation of our study. We present the proposed OCCMPR protocol. We will present the CR model for our study and how SU can switch from one channel to another. We will further show the PU behaviour on the licensed spectrum. Lastly, we will present the routing matric, channel selection model, the transmission power control and the proposed TDMA together with the CSMA/CA protocols.

5.1. Proposed OCCMPR protocol

OCCMPR was highlighted and presented in [54]. OCCMPR is a scheme which is optimised from the CCMPR scheme and utilises cognitive routing, and this approach concurrently takes advantage of the route together with the spectrum varieties by opportunistically utilising spectrum holes for transmission of data. Multi-route routing is also used as the routing technique that sets up various routes for one destination. We set up various routes to the destination since our protocol uses the CRN environment where SU is involved. This means that spectrum may be inaccessible for a SU or spectrum mobility may need to occur when PU wants to make use of the spectrum. If this happens, one route may not be accessible to SU. In such circumstance, other routes can be utilised. The likelihood of selecting a path is inversely proportional to the cost of that path, and the path probabilities are computed using the below equation:

$$PathProbability = \frac{\frac{1}{PathCost}}{\sum \frac{1}{PathCost}} \qquad (1)$$

Route discovery of OCCMPR follows the CAODV protocol; if a hub has any data to transmit, it will create an RREQ message as illustrated in Figure 5-1. The destination node and the intermediate that will receive the RREQ will evaluate the previous link cost and restore the header by summing the route cost and the last link cost. The RREP message will be relayed to the source hub initiated the RREQ through intermediate node only if it has the path to the destination hub as illustrated in Figure 5-2. If the intermediate node has no path to the goal, it further broadcast the RREQ packet, and when the RREQ reaches the destination hub, RREP message will be generated and sent by the goal to the source node.

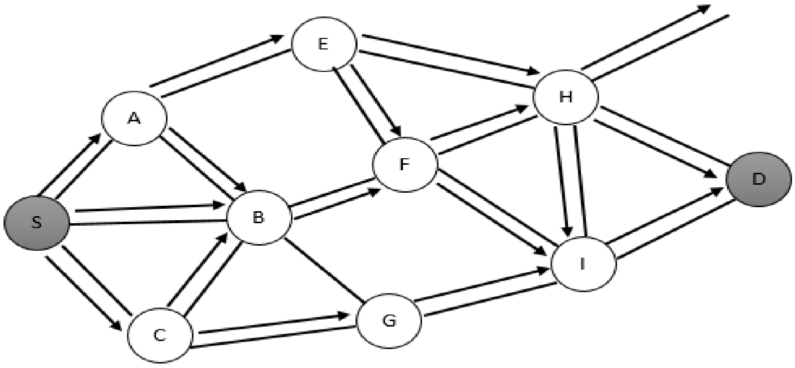


Figure 5-1: Propagation of RREQ packet

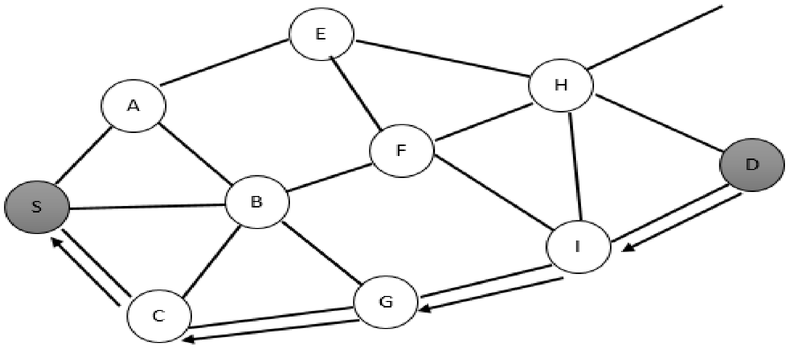


Figure 5-2: Propagation of RREP packet

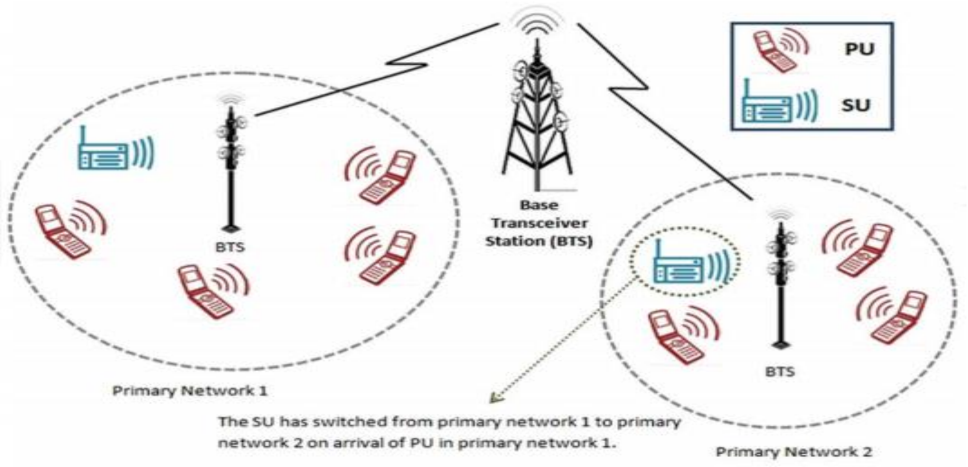
The path and the route maintenance are generated using the RERR message. The RERR message will be created and sent to the link’s active source if the link failure is identified. Many reasons can cause link failure, and one may be due to spectrum unavailability linking or connecting the nodes. The link failures are detected by frequently sent hello messages. Immediately a source received an RRER message it will start another route discovery procedure. The routing table will identify all the routes which are not utilised, and they will be terminated using the timer-based procedure.

Our proposed scheme utilises the cross-layering procedure by using the spectrum opportunities and choosing the spectrum and the node simultaneously. Also, it uses the channel history to choose the transmission power intensity for every hop in the path. The goal of our scheme is to use the spectrum effectively and efficiency. This can be enabled by proposing a schedule-based MAC algorithm, the TDMA for the PU's to access the spectrum bands and a contention-based MAC algorithm, CSMA for the SU or the CU to access the time slots of the spectrum when the PU's are idle, this will further be demonstrated.

5.2. CRN model

We consider the licensed network of PU in the spectrum and SU's unlicensed network in the spectrum bands. SU utilises both the networks but uses the licensed network in the absence of the PU in the spectrum, and when PU arrives, SU needs to hand over the spectrum and consider another accessible spectrum.

Figure 5-3 demonstrate the background network environment for our proposed protocol. The model consists of two (2) networks, primary network 1, and primary network 2. To avoid PU interference, SU must change from primary network 1 to primary network 2 upon the appearance of PU in primary network 1.



The SU has switched from primary network 1 to primary network 2 on arrival of PU in primary network 1.

Figure 5-3: CRN system model *[55]*

Firstly, we consider i number of channels available in the CRN, presented by:
$C = \{M_1, M_2, \dots, M_i\}$,

Secondly, a primary network consisting of v number of PU presented by:
$A = \{P_1, P_2, \ldots, P_v\}$, and
Thirdly, a secondary network consisting of w number of SU presented by:
$B = \{S_1, S_2, \ldots, S_w\}$.
The entire spectrum bands in the network are assumed to be independent of each other. Since we are using TDMA for PU, the time in the network is divided into t duration and in every time frame the primary senders operating in $V_i(1 \leq i \leq n)$ licensed spectrum is assumed to be distributed by two-dimensional Poisson X_t^i with density λ_i.

5.3. PU behaviour

We assume that the entire spectrum bands have identical transmission bandwidth. The movement of PU in the spectrum is displayed as alternating patterns of OFF and ON intervals. OFF and ON denotes the band of spectrum is occupied and unoccupied by PU, respectively. Figure 5-2 demonstrate ON and OFF intervals which are conveyed with rate $\propto$ and β.

We use the two phases Markov chain to resemble the behaviour of PU to find the temporal reliance between two successive states. The changes are between neighbouring scheduled slots in a similar channel, and they are autonomous of different channels.
In this manner, for channel M_i, let α_i depicts the likelihood that the channel will be occupied in the next schedule slot, that is, the PU will be available given that it is inactive in the present schedule opening. Equivalently, let β_i signify the likelihood that the channel will be idle that will be, that the PU will be missing in the scheduled opening given that the channel is occupied in the present vacancy.

The PU activity at scheduled slot t on channel i can be presented as $S_v(t), (1 \leq i \leq C)$, given that *C* denotes the number of channels in the CR. When $S_v(t) = 1$, it simply denotes that the PU in ON, therefore the channel is not accessible to the CR nodes.
Again, if $S_v(t) = 0$, it simply means that the PU is OFF; therefore, the channel is made accessible to the CR nodes. Hence, the likelihood that the channel i is inactive in schedule slot t can be acquired regarding the steady state likelihood as depicted in Figure 5-4.

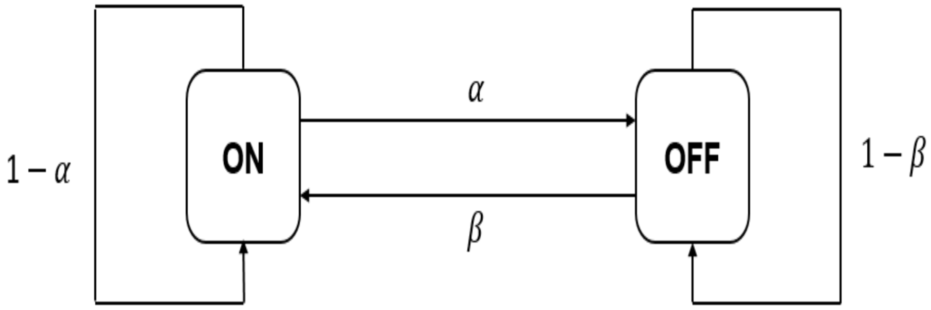


Figure 5-4: PU behaviour on the spectrum band

We implemented the Markov chain model to find the likelihood of the steady phases that the channel is accessible as follows:

$$P_{ON} \cdot \alpha + P_{OFF}(1 - \beta) = P_{OFF} \tag{2}$$

$$Since\ P_{ON} + P_{OFF} = 1, this\ is\ equivalent\ to$$

$$(1 - P_{OFF}) \cdot \alpha + P_{OFF}\,(1 - \beta) = P_{OFF} \tag{3}$$

The two probabilities represent OFF in the same time slot, presented by (3) and again, the channel is ON in the same time slot, presented by (4). We further show the example of time slots matrix versus the channels ID in Table 5-1. The matrix elements are 0 and 1, to show if the PU are present or absent in the channel.

$$P_{i\alpha}^{x} = \frac{\beta_i}{\alpha_i + \beta_i} \tag{4}$$

$$P_{i\beta}^{x} = \frac{\alpha_i}{\alpha_i + \beta_i} \tag{5}$$

Table 5-1: Example of channel availability matrix

Time slots						
Channel ID		*1*	*2*	*3*	…	*t*
	1	0	1	0	…	1
	2	1	1	1		0
	3	0	0	1		1
	…	…				
	l	1	1	0		1

5.4. Binary model hypothesis

There are many methods used for spectrum sensing. We are going to use the basic model for the detection of energy in the spectrum sensing. There are two hypotheses we are going to use for spectrum sensing, the null hypothesis, and the alternative hypothesis.

The null hypothesis:

$$H_0 : y(t) = n(t) \tag{6}$$

This hypothesis (6) denotes that PU is idle in that spectrum band.

The alternative hypothesis:

$$H_1 : y(t) = gs(t) + n(t) \tag{7}$$

(7) States that there is a presence of PU in that spectrum band.

The parameter:

$$s(t) = 0 \tag{8}$$

Indicates that the PU did not transmit anything.

The parameter n demonstrates the sampling ratio $(0 \leq t \leq N)$, $s(t)$ denotes the PU signal transmission, $n(t)$ presents the Additive White Gaussian Noise (AWGN), and g is standard channel compound volume addition. If the channel is not standard, the output $gs(t)$ changes to convolution. This means that the output $gs(t)$ will change after some time regarding the volume increase of the channel at different time flash.

Since we are considered the AWGN model, therefore $n(t)$ can be predicted with mean zero (0) and σ_m^2 variance.

$$n(t) = N(0, \sigma_m^2) \tag{9}$$

5.5. Routing metric

We will use dynamic multi-objective routing and the cost function as a metric for packet routing. The cost transmission for the packet to be transmitted on channel m from nodes i to j is defined as C_{ij}^m with the following parameters:

i. SOP_{ij}^m, the channel availability for transmission of a data packet on channel m from nodes i to j.

$$SOP_{ij}^m = \begin{cases} 1 \; if \; channel \; is \; free \\ 0 \; if \; channel \; is \; busy \end{cases} \tag{10}$$

ii. P_{ij}^m, transmission power for packets sent from nodes i to j on channel m.

iii. E_i, energy that is remaining for node i.

iv. B_m, bandwidth of channel m.

The relationship between the cost function and the parameters are: $C_{ij}^m \propto \frac{1}{SOP_{ij}^m}$, $C_{ij}^m \propto P_{ij}^m$, $C_{ij}^m \propto \frac{1}{E_i}$, and $C_{ij}^m \propto \frac{1}{B_m}$

As stated in one of our objectives to increase the network lifetime, the cost function will pick the high energy nodes. We are going to implement the normalisation procedure for the optimisation algorithm in all these parameters. The range used for the normalisation procedure is given by:

$$f_{norm}(x) = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{11}$$

$f_{norm}(x)$ is going to include values from zero and one. Routing will be generated to find a path π, whereby the path will be minimised for the cost function.

$$minC(\pi) = \sum_{\pi} C_{ij}^m \tag{12}$$

Where:

$$C_{ij}^{m} = \frac{1}{SOP_{ij}^{m}}\{w_1 f_{norm}(P_{ij}^{m}) + w_2 f_{norm}(\frac{1}{E_i}) + w_3 f_{norm}(\frac{1}{B_m})\} \quad (13)$$

The weighing coefficient w_1, w_2, w_3 are defined and are selected also regarding their priorities in such a manner that:

$w_1, w_2, w_3 > 0$ and $w_1 + w_2 + w_3 = 1.0$,

We redefine the cost function looking at individuality cost functions as optimisation for multiple objective goals:

$$C = w_1 f_1 + w_2 f_2 + w_3 f_3 \quad (14)$$

Where: $f_1 = \frac{f_{norm}(P_{ij}^{m})}{SOP_{ij}^{m}}$, $f_2 = \frac{f_{norm}(\frac{1}{E_i})}{SOP_{ij}^{m}}$, and$f_3 = \frac{f_{norm}(\frac{1}{B_m})}{SOP_{ij}^{m}}$ (15)

5.6. Channel selection and cognitive model

We presume that our CR nodes incorporate four radios: the sensing, the receiver, the transmission, and the control radios. We presented the cognitive cycle in chapter one. When the sensing of the spectrum and decision taken regarding the spectrum phases are completed, SU needs to take place or channel switching process if PU is accessing the spectrum. If the PU is not present on the spectrum band or channel switching is completed, control will again go back to the spectrum sensing block.

The network layer takes control of the spectrum selection and to update the receive channel user. The spectrum decision block will send the message to the network layer to update it. The rule of channel selection which minimises the cost function C' as given by:

$$C' = \{w_1 f_{norm}(P_{arv}^{m}) + w_3 f_{norm}(\frac{1}{B_m})\} \quad (16)$$

Where node j selects the channel m in the spectrum opportunities and P_{arv}^{m}. The nodes select the channel with better bandwidth and reduce the average transmission power.

5.7. Transmission power control

The transmission of our protocol is incorporated with routing. The receiver gain RG is calculated immediately when a node receives a packet given by the equation RG, below:

$$RG = \frac{P_{rx}}{P_{tx}} \tag{17}$$

The power update message containing the estimation of RG will be transmitted by the receiving hub back to one hop source. The target transmission power level will be calculated once the node acknowledges the receipt of the power update message, P'_{tx} using the below equations, (17), (18), and (19).

$$RG' = RG * \delta \tag{18}$$

$$RG_{low} = \frac{RXThresh}{P_{max}} \tag{19}$$

$$P'_{tx} = P_{max} * \frac{RG_{low}}{RG'} \tag{20}$$

Where:

δ calculates the likelihood of an error for determining RG, the gain at the receiver from the transmitter. Values of δ ranges from zero and one.

$RXThresh$ is the threshold which is used to measure the receipt of a packet. When signal strength is above the threshold, then it means the packet was received successfully.

P_{max} is the highest that is authorised to transmit the power level.

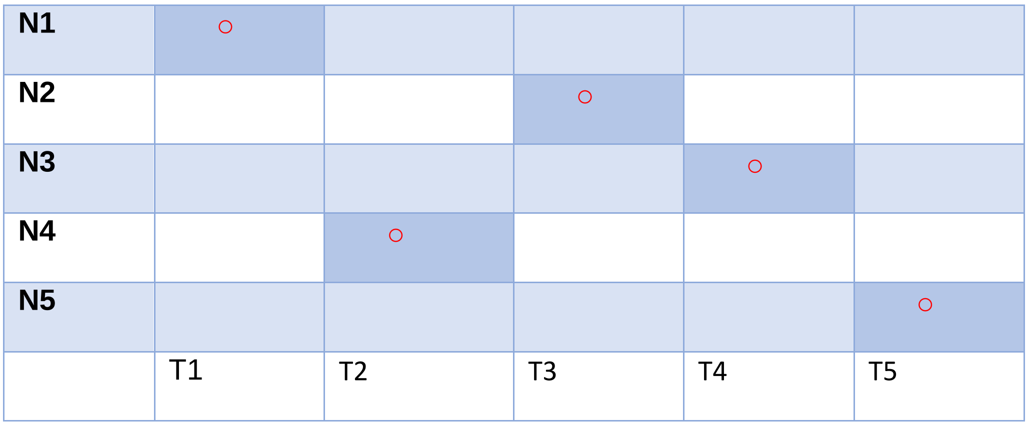
When a node (X) calculates P'_{tx} for its neighbouring node (Y), it will store the digit of P'_{tx} in the neighbouring table. The hub computes the moving average of N when sending the packet and transmission power digits from the neighbour and forward the packet together with computed transmission power.

5.8. MAC protocol model approach

To improve the spectrum efficiency, we optimise the CCMPR scheme by incorporating a schedule-based MAC algorithm, the TDMA for the PU and a contention-based MAC algorithm CSMA/CA for the SU as stipulated in Section 5.1.

5.8.1. Schedule-based approach

In this protocol, the overhearing, collision can be avoided and listen periods have severe time synchronisation requirements. Sensor hubs are distributed schedule slots utilising TDMA. In every scheduled time frame, a hub can transmit without any collisions in a shared medium. Figure 5-5 demonstrate the scheduled based access strategy, where the y-axis presents the nodes numbered N1-N5, and the x-axis presents the time slots numbered T1-T5. TDMA hubs are apportioned various time slots, for example, at time t3, hub N2 utilises the medium. Recipient hubs are synchronised with their sender hubs to wake up simultaneously. This protocol improves energy efficiency by maintaining strategic collision avoidance and overhearing. Another advantage of TDMA is that it guarantees bandwidth and low latency.



N1	○				
N2			○		
N3				○	
N4		○			
N5					○
	T1	T2	T3	T4	T5

Figure 5-5: Schedule access-based protocol

Figure 5-6 depicts the TDMA channel access approach, whereby the base station and a specific hub are responsible for regulating the network's hubs. There are generally fixed time slots for the nodes to access the channel.

The hub in the system is apportioned a specific number of slots for transmission. These slots are generally arranged out in a frame. The base station indicates the beacon, and every hub simply needs to adhere to the base station's instructions. The slots are regularly constructed from base station to hub as downlink and from hub to base station as uplink time frames. The entire communications by every node are directed to the base station. A service slot enables hubs to demand a portion of a connection by communicating with the base station and relaying a connection demand message.

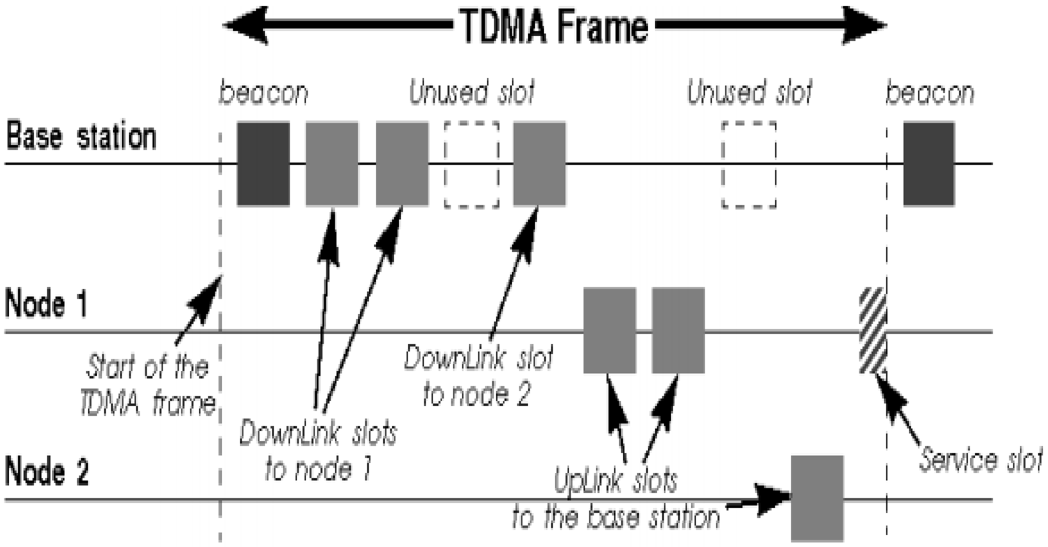


Figure 5-6: TDMA channel access technique *[56]*

5.8.2. Contention-based approach

This protocol loosens up time synchronisation requirements and can adjust to the topology changes as some new hubs may join, and others may die after a certain deployment time. We are going to implement the CSMA with CA. The main key of CSMA/CA is listening before talking together with contention. The contention-based technique is an asynchronous message relaying technique, meaning that it is connectionless, distributing the best effort administration; however, CSMA/CA's disadvantages are no latency and bandwidth guaranteed. The protocol indicates how the hub utilises the medium; when to listen and when to transmit.

Figure 5-7 demonstrate the CSMA techniques whereby you first listen on the channel, and if it is seen as inactive, it transmits the first packet in the transmission queue. If the channel involved, the hub pause until the current transmission ends and starts the contention. Towards the contention clock's edge, the hub is free to send the packet if the channel is still not active. The hub that picked the most shortened delay will be given the first preference to transmit the packet, and the other hubs will continue to wait for the next contention. This approach gives all the nodes the equivalent opportunities to utilise the channel.

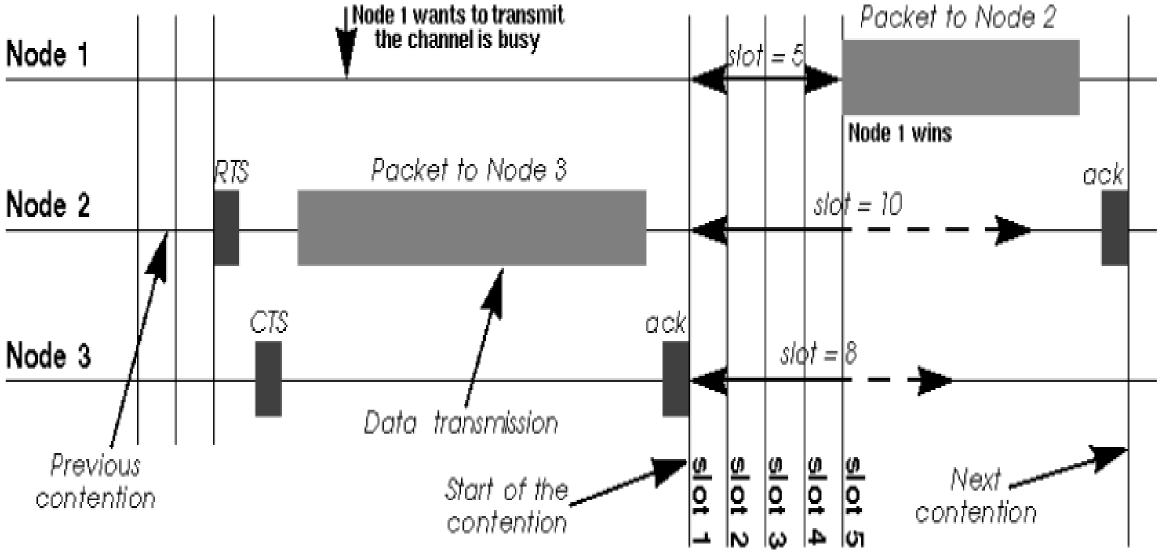


Figure 5-7: CSMA channel access technique *[56]*

5.9. Summary

This chapter presented the design and implementation of our study. We presented the CR model on how SU switch from one channel to the other. We characterized the behaviour of PU on the licensed spectrum band. We also presented the routing metric, channel selection and the transmission power control. Lastly, we proposed the TDMA and CSMA/CA to our protocol to improve the spectrum efficiency.

CHAPTER 6 – RESULTS AND DISCUSSIONS

6. Introduction

This chapter presents the simulation results and discussions of the three comparative protocols: the CAODV, CCMPR, and OCCMPR. The results are based on the four metrics and the simulation parameters presented in chapter 4. We are considered five (5) scenarios for our simulations; scenario 1 with 30 nodes configuration, scenario 2 with 60 nodes configuration, scenario 3 with 90 nodes configuration, scenario 4 with 120 nodes configuration and lastly scenario 5 with 150 nodes configuration.

In this chapter, we illustrate the simulations results for scenario one (1) with 30 nodes configuration, scenario three (3) with 90 nodes configuration and lastly for scenario five (5) with 150 nodes configuration. Scenario two (2) with 60 nodes configuration and scenario four (4) with 120 nodes configuration results are presented in the appendix.

6.1. Energy Consumed per Packet

6.1.1. Scenario 1 – 30 nodes configuration

We set up the network nodes to thirty (30) in scenario one (1), and all the simulations setup parameters are as represented in chapter 4. This scenario's results are presented in Figures 6-1 to 6-4, showing that OCCMPR consumed lesser energy than the other protocols.

The results for scenario one (1) shows unsteady movement for all the protocols and indicates that OCCMPR consumed lower energy per packet. The low energy consumed per packet in the OCCMPR protocol can be attributed to the power control mechanism in routing for CLD. The high energy consumed in the CAODV protocol maybe because this protocol floods the RREQ packets to the neighbouring hubs, increasing network traffic and consuming more energy and degrading network performance.

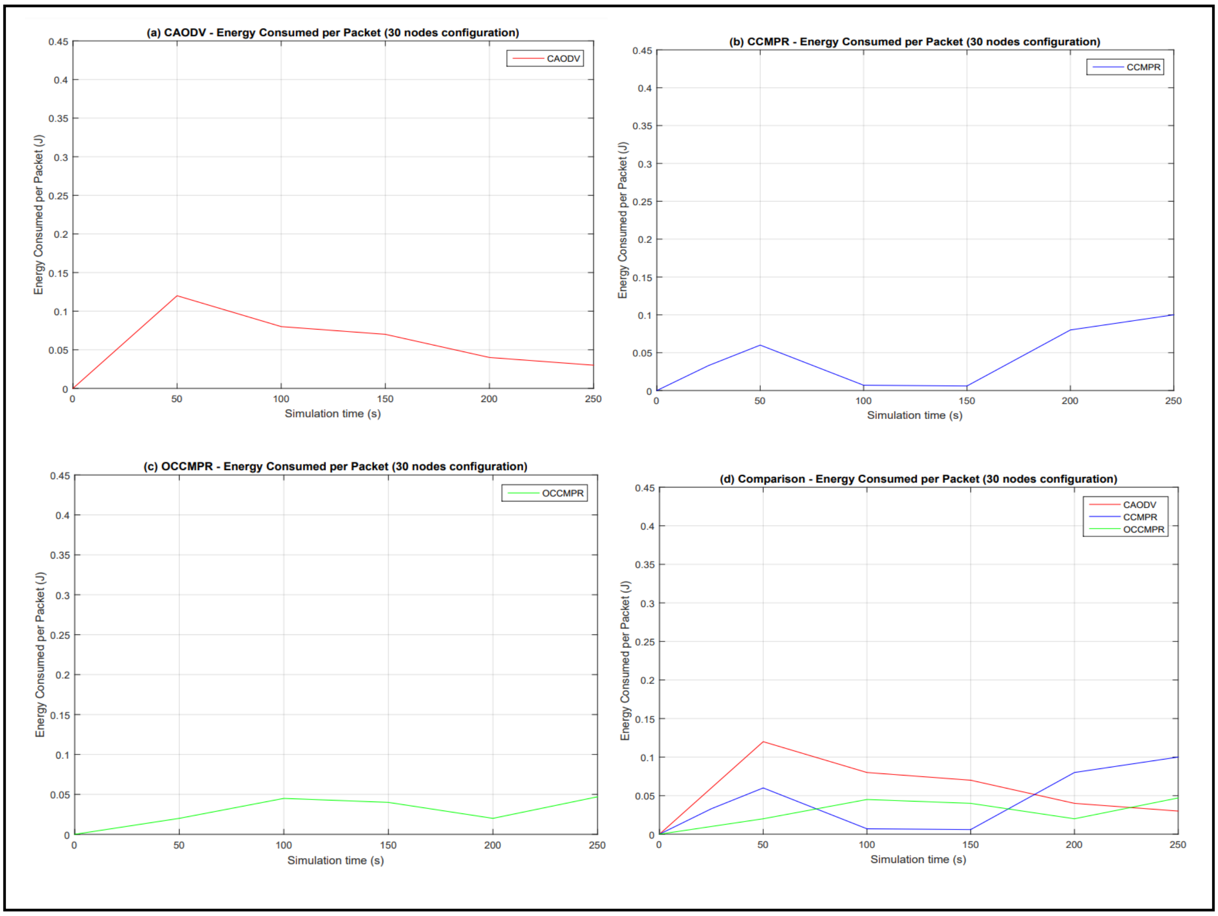


Figure 6-1: Energy Consumed per Packet results (30 nodes configuration)

6.1.2. Scenario 2 – 60 nodes configuration

In scenario two (2), we increased the network nodes to sixty (60) and all the simulations setup parameters were not changed. This scenario's results are presented in Figure A-1 of the Appendix and Figure 6-4, which showed that OCCMPR consumed lesser energy than the other protocols.

6.1.3. Scenario 3 – 90 nodes configuration

In scenario three (3), we have increased the network nodes to ninety (90), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-2 and Figure 6-4, which shows that OCCMPR consumed lesser energy than the other protocols.

The results of scenario three (3) show inconsistency for all the protocols. OCCMPR again under this scenario shows low energy consumption per packet compared to the other protocols because the OCCMPR protocol uses the channel's previous experiences to transmit every packet with the minimum power needed.

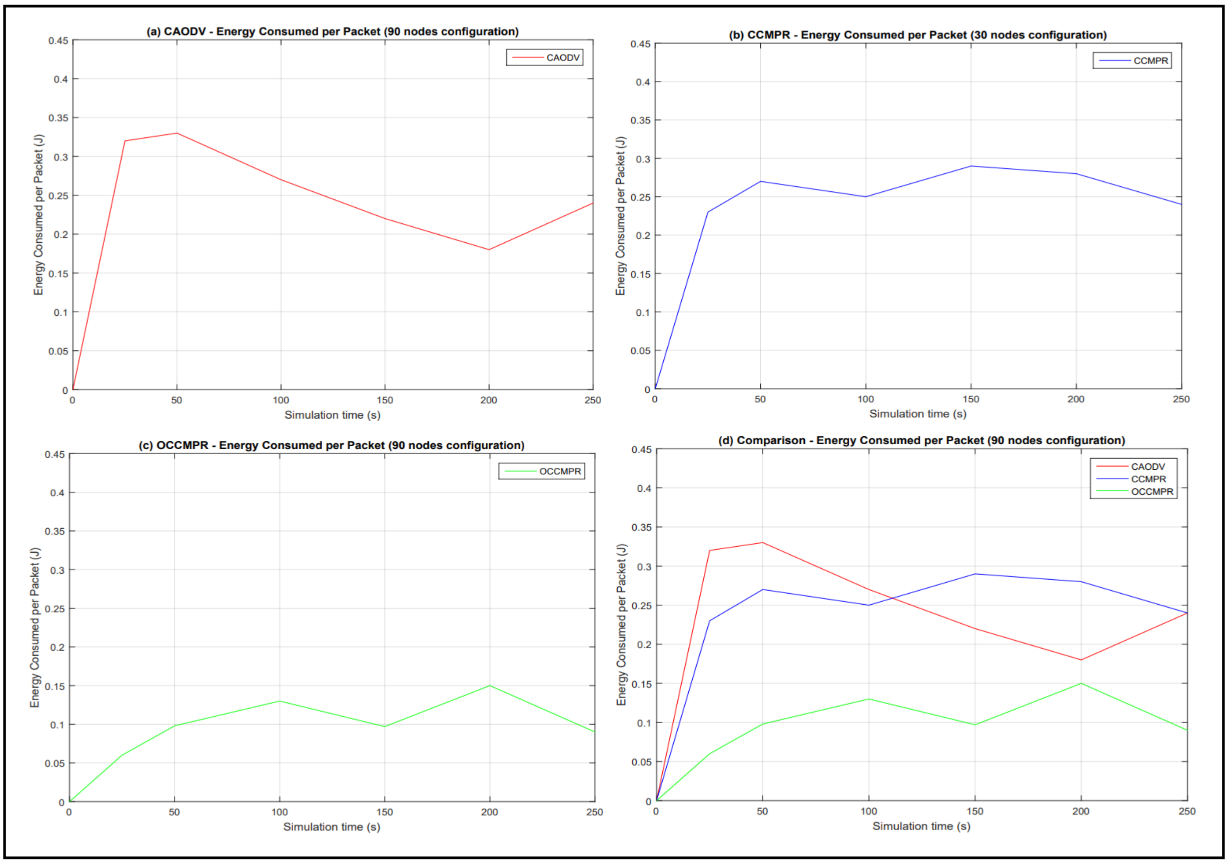


Figure 6-2: Energy Consumed per Packet results (90 nodes configuration)

6.1.4. Scenario 4 - 120 nodes configuration

In scenario four (4), we have increased the network nodes to a hundred and twenty (120), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure A-2 of the Appendix and Figure 6-4, showing that OCCMPR consumed lesser energy than the other protocols.

6.1.5. Scenario 5 – 150 nodes configuration

Lastly, in scenario five (5), we increased the network nodes to a hundred and fifty (150), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-3 and Figure 6-4, which showed that OCCMPR consumed lesser energy than the other protocols.

In scenario five (5) results, we also observe the varying movement of all the protocols. OCCMPR, in this scenario, consumed low energy per packet compared to CAODV and CCMPR. This is since OCCMPR chooses paths considering transmit power needed to send information in each hop, decreasing the transmission of energy consumed per packet.

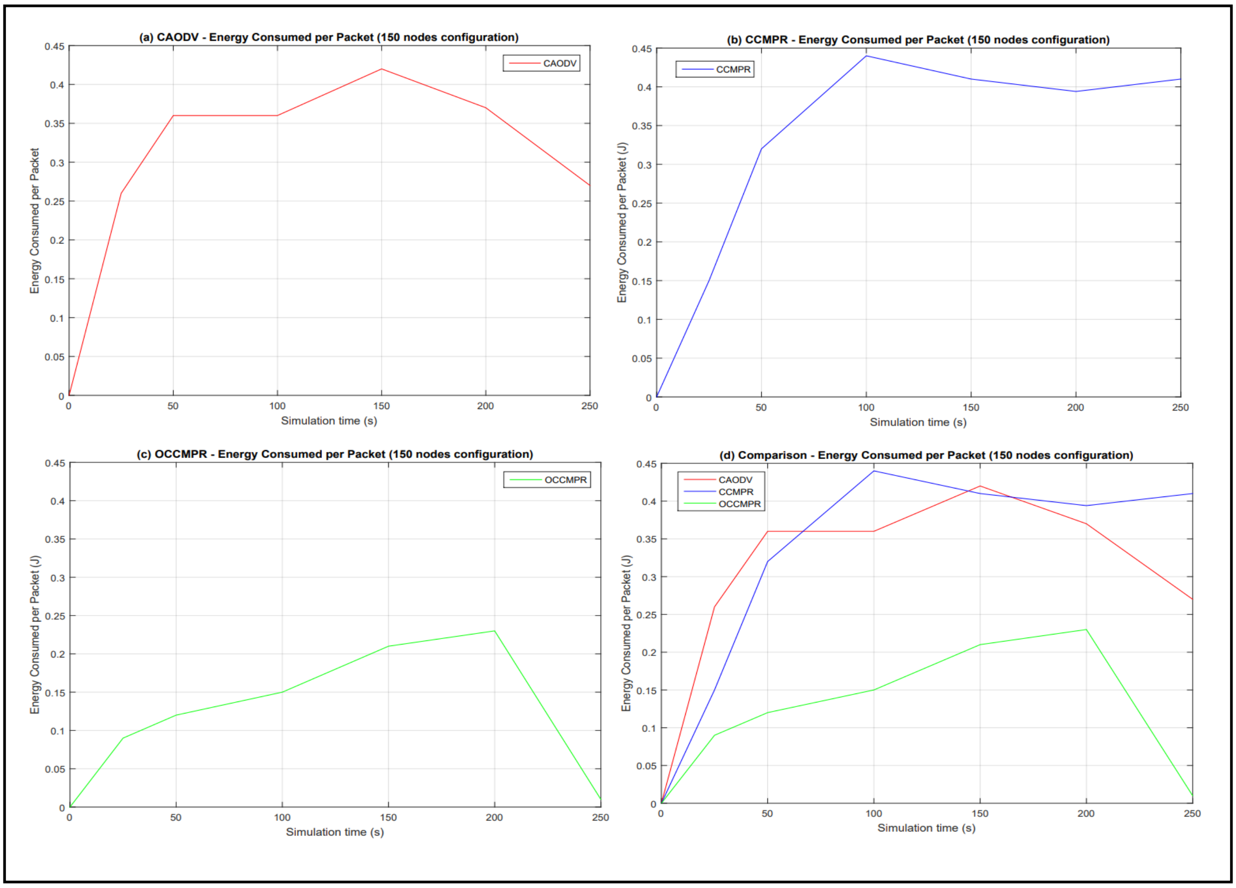


Figure 6-3: Energy Consumed per Packet results (150 nodes configuration)

6.1.6. Overall Energy Consumed per Packet results

Figure 6-4 indicates the overall Energy Consumed per Packet results under five (5) scenarios; one (1), two (2), three (3), four (4), and five (5). We observed that in all the given scenarios, OCCMPR consumed lower energy per packet. In all the protocols under the different given scenarios, we depict that energy consumed per packet increases when the nodes' number increases. Therefore, we conclude that the energy consumed per packet is directly proportional to the network hubs.

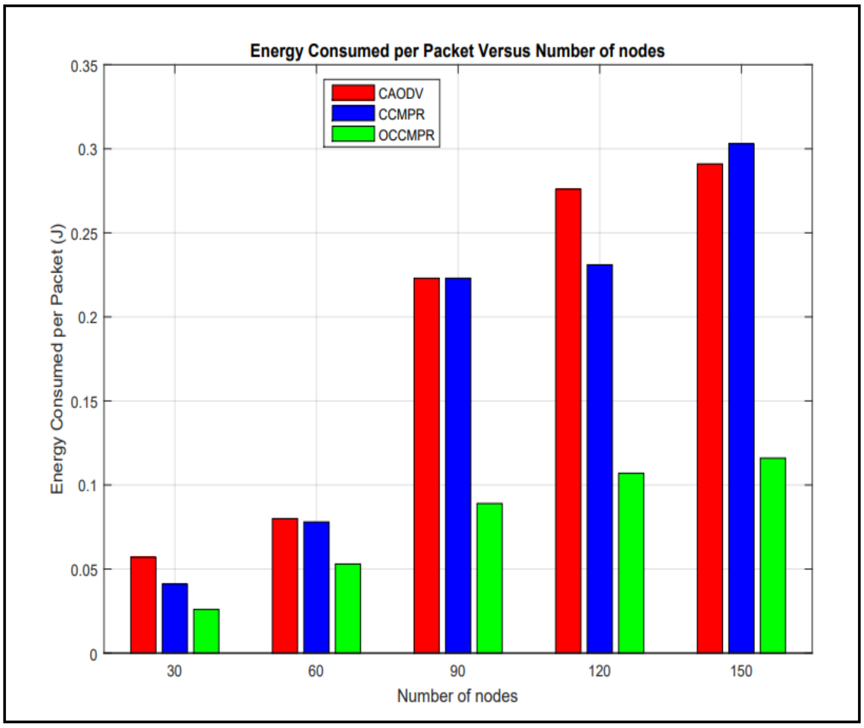


Figure 6-4: Overall Energy Consumed per Packet results

6.2. Throughput

6.2.1. Scenario 1 – 30 nodes configuration

The first scenario consist of thirty (30) nodes and all the simulations setup parameters are as represented in chapter 4. This scenario's results are presented in Figure 6-5 and Figure 6-8, showing that OCCMPR has obtained higher achievable throughput than the other protocols.

The results for scenario one (1) show inconsistent movement for all the three (3) protocols and downward trend movement for the CAODV after 150 seconds of the simulation time, justified by the fact that more packets may have been dropped due to collisions amongst the nodes.

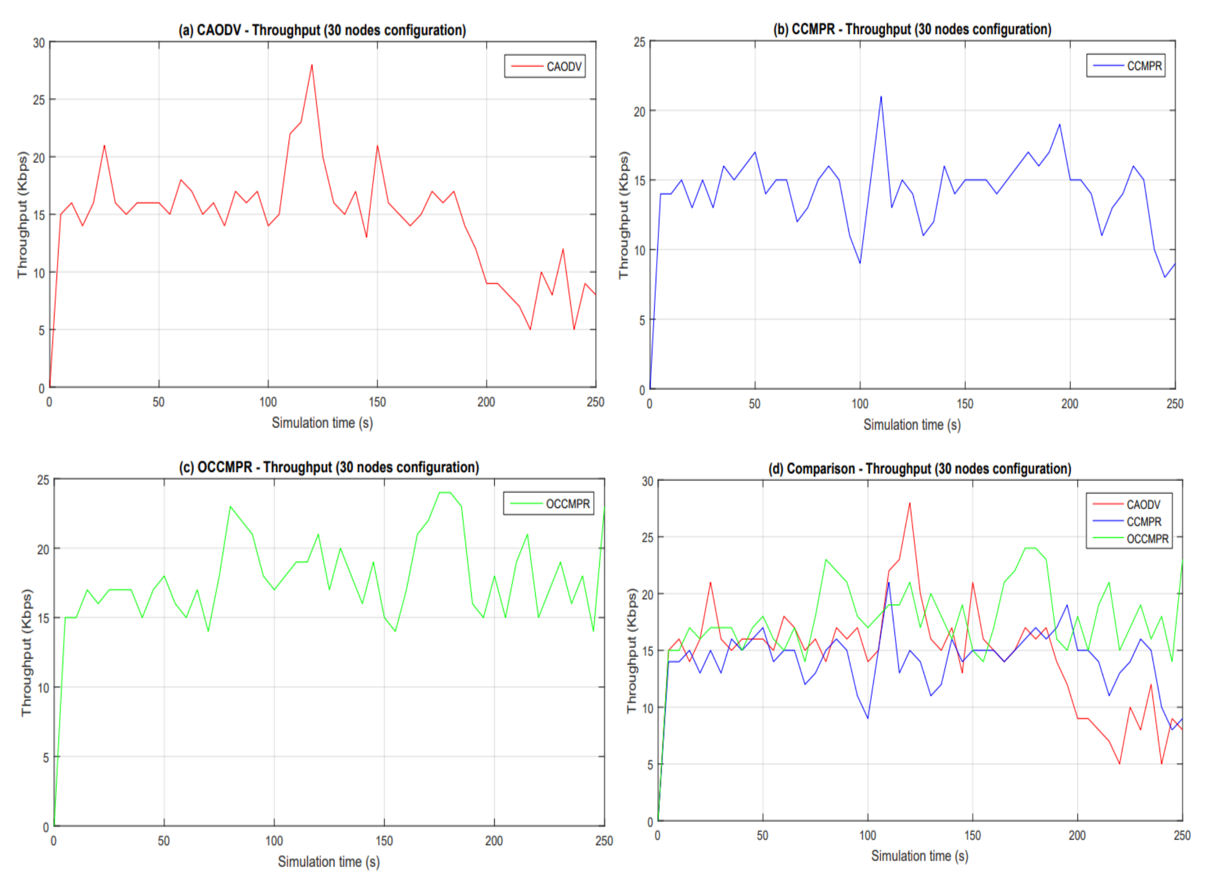


Figure 6-5: Throughput results (30 nodes configuration)

6.2.2. Scenario 2 – 60 nodes configuration

In scenario two (2), we increased the number of nodes to sixty (60) and all the simulations setup parameters were not changed. This scenario's results are presented in Figure B-1 of the Appendix and Figure 6-8, showing that OCCMPR achieved the highest throughput than the other protocols.

6.2.3. Scenario 3 – 90 nodes configuration

In scenario three (3), we increased the number of nodes to ninety (90), and all the simulations setup parameters were not changed. This scenario results are in Figure 6-6 and Figure 6-8, showing that OCCMPR obtained the highest throughput.

Scenario three (3) results show the unsteady movement of all the three (3) protocols. OCCMPR protocol in Figure 6-6 (d) achieved the highest throughput compared to the other protocols. The high throughput of the OCCMPR protocol is justified because this protocol can utilise the network resources dynamically and more accurately; thus, more packets will successfully reach their destinations packet.

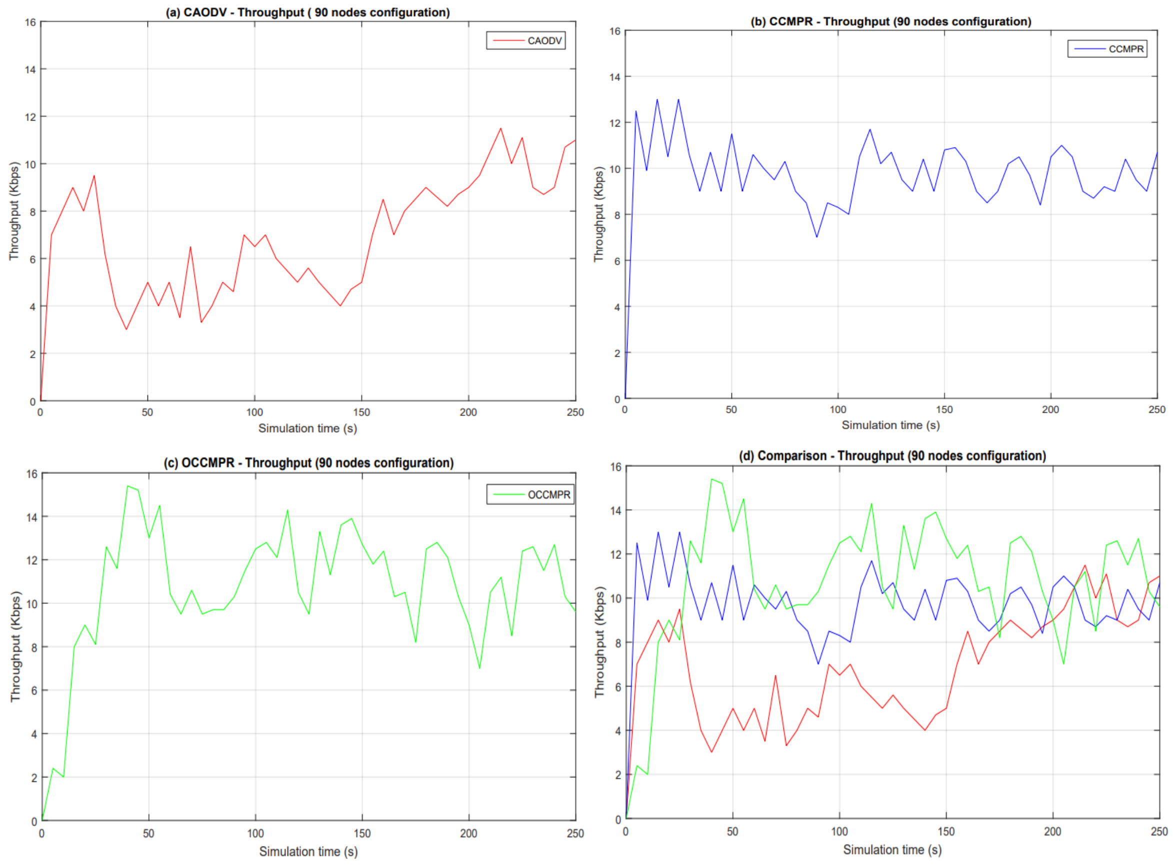


Figure 6-6: Throughput results (90 nodes configuration)

6.2.4. Scenario 4 – 120 nodes configuration

In scenario four (4), we increased the network nodes to a hundred and twenty (120), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure B-2 of the Appendix and Figure 6-8, showing that OCCMPR attained the highest throughput.

6.2.5. Scenario 5 – 150 nodes configuration

In scenario five (5), we have increased the network nodes to a hundred and fifty (150), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-7 and Figure 6-8, which illustrated that OCCMPR accomplished high throughput than the other protocols.

The results of scenario five (5) demonstrate the inconsistent movement of all the protocols, uptrend movement for the CAODV protocol after about 75 seconds of the simulation time, the downward trend for CCMPR protocol after 50 seconds of the simulation time and uptrend for OCCMPR protocol after 100 seconds of the simulation time. Figure 6-7 (d) clearly shows that OCCMPR outperformed the CAODV and CCMPR protocols. This is because the OCCMPR chooses many paths to the destination node as it uses multi-route routing when each route to destination fails OCCMPR has another alternative to choose amongst the available routes for delivering the packets.

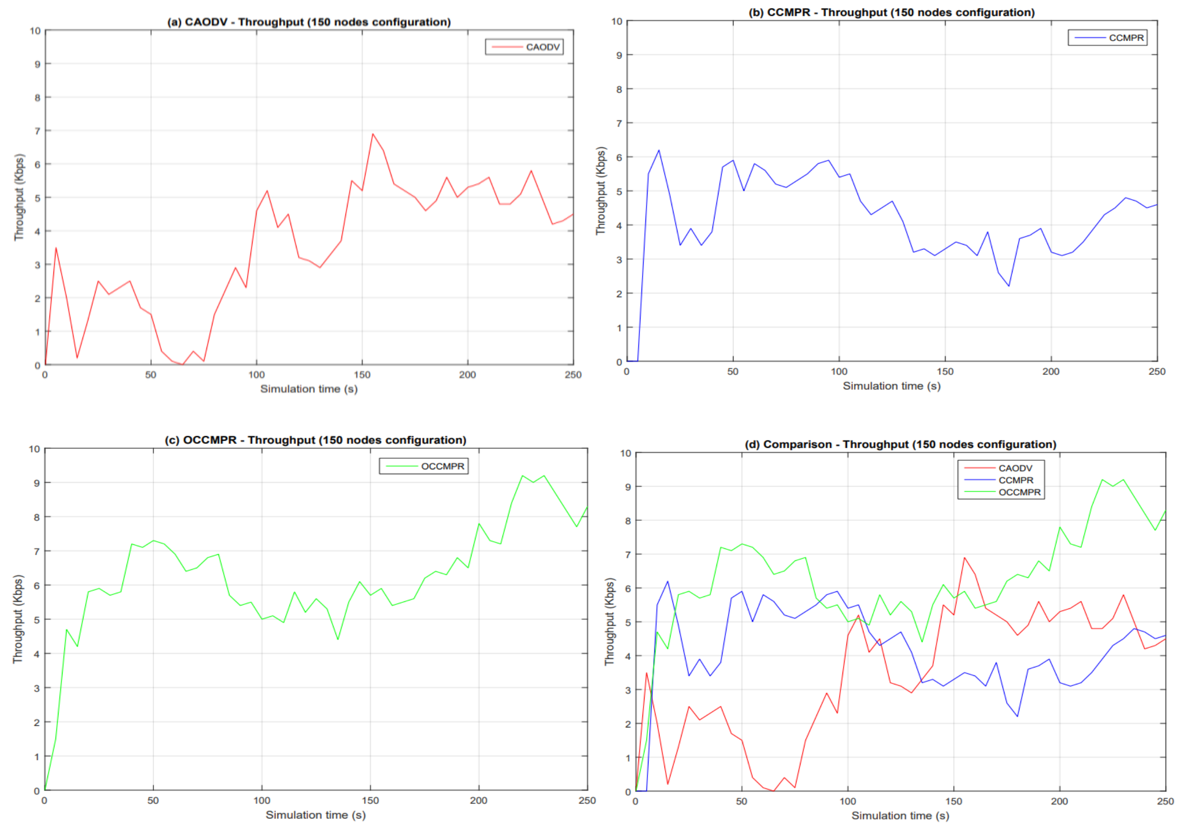


Figure 6-7: Throughput results (150 nodes configuration)

6.2.6. Overall Throughput results

Figure 6-8 illustrates the overall throughput results for all the five (5) scenarios. We see that in all the given scenarios, OCCMPR achieved the highest throughput compared to CAODV and CCMPR. In all the protocols under the different given scenarios, we depict that the throughput decreases when we increase the network nodes. We can therefore conclude that throughput is inversely proportional to the number of the network nodes.

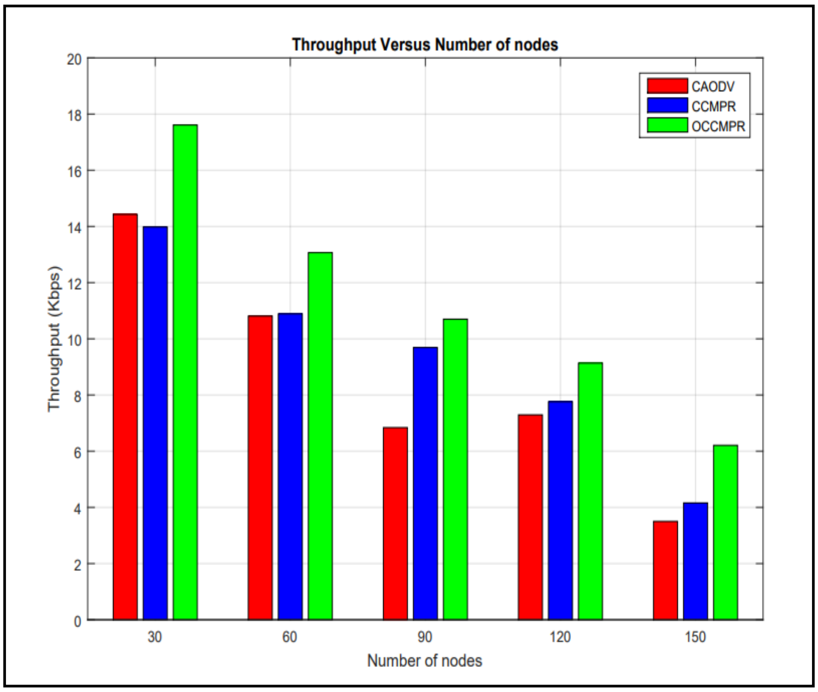


Figure 6-8: Overall Throughput results

6.3. Average delay

6.3.1. Scenario 1 – 30 nodes configuration

In the first scenario, we had thirty (30), and all the simulations setup parameters are as illustrated in chapter 4. This scenario's results are presented in Figure 6-9 and figure 6-12, which shows that OCCMPR did not incur a delay.

The average delay results for scenario one (1) shows inconsistent movement for the two (2) protocols, CAODV and CCMPR. OCCMPR did not record any average delay under this scenario. This may be the case since the OCCMPR protocol incorporates TDMA where PU nodes are allocated scheduled time slots. This makes every PU node aware of their time slot to access the spectrum on the shared medium, and this will result in transmissions with no collisions between the nodes and the minimisation of the queuing delay. We also realise that CAODV shows high average delay compared to CCMPR. The CCMPR protocol favours routes with higher transmission capacity (bandwidth) hence its reasonable performance. Additionally, accessibility to elective routes if there should arise link failures, removes route discovery, adding to the delay.

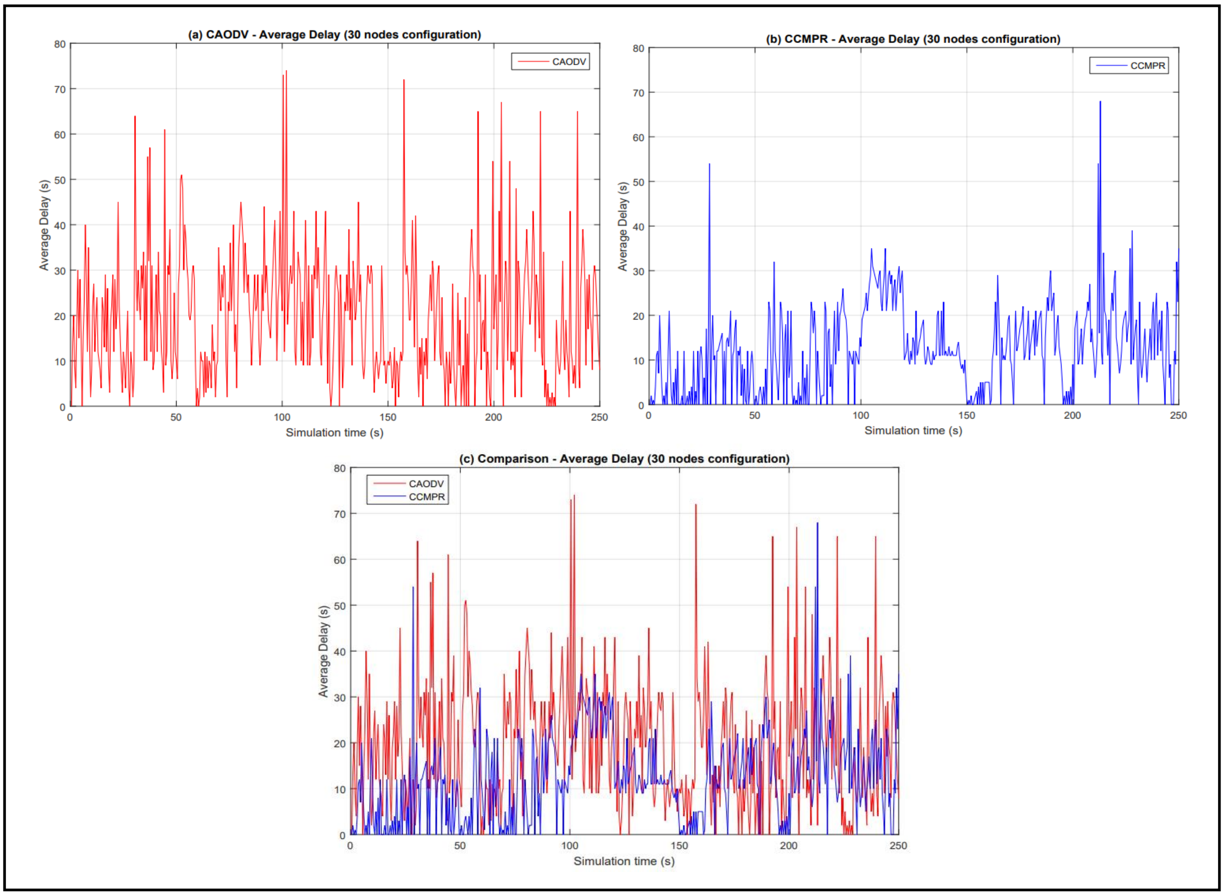


Figure 6-9: Average Delay results (30 nodes configuration)

6.3.2. Scenario 2 – 60 nodes configuration

In scenario two (2), we increased the number of nodes to sixty (60) and all the simulations setup parameters were not changed. This scenario's results are presented in figure C-1 of the Appendix and Figure 6-12, which shows that OCCMPR incurred the least average delay than the other protocols.

6.3.3. Scenario 3 – 90 nodes configuration

In scenario three (3), we increased the network nodes to ninety (90), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-10 and Figure 6-12, which illustrated that OCCMPR incurred the least average delay.

The average delay results for scenario three (3) shows the unsteady movement for the protocols. We depict that OCCMPR recorded less average delay in comparison to the CAODV and CCMPR protocols. This is justifiable by the integration of TDMA and CSMA/CA algorithms. With TDMA the PU is assigned slots to access the medium channel, and SU incorporates the CSMA/CA algorithm. The CSMA/CA enables the SU to listen to the channel if any PU is accessing the channel before utilising it. When SU finds that the channel is not vacant, it waits until the present transmission of the PU ends, and therefore contention starts. The two algorithms minimise the average delay, given that there would be less congestion incurred in the network.

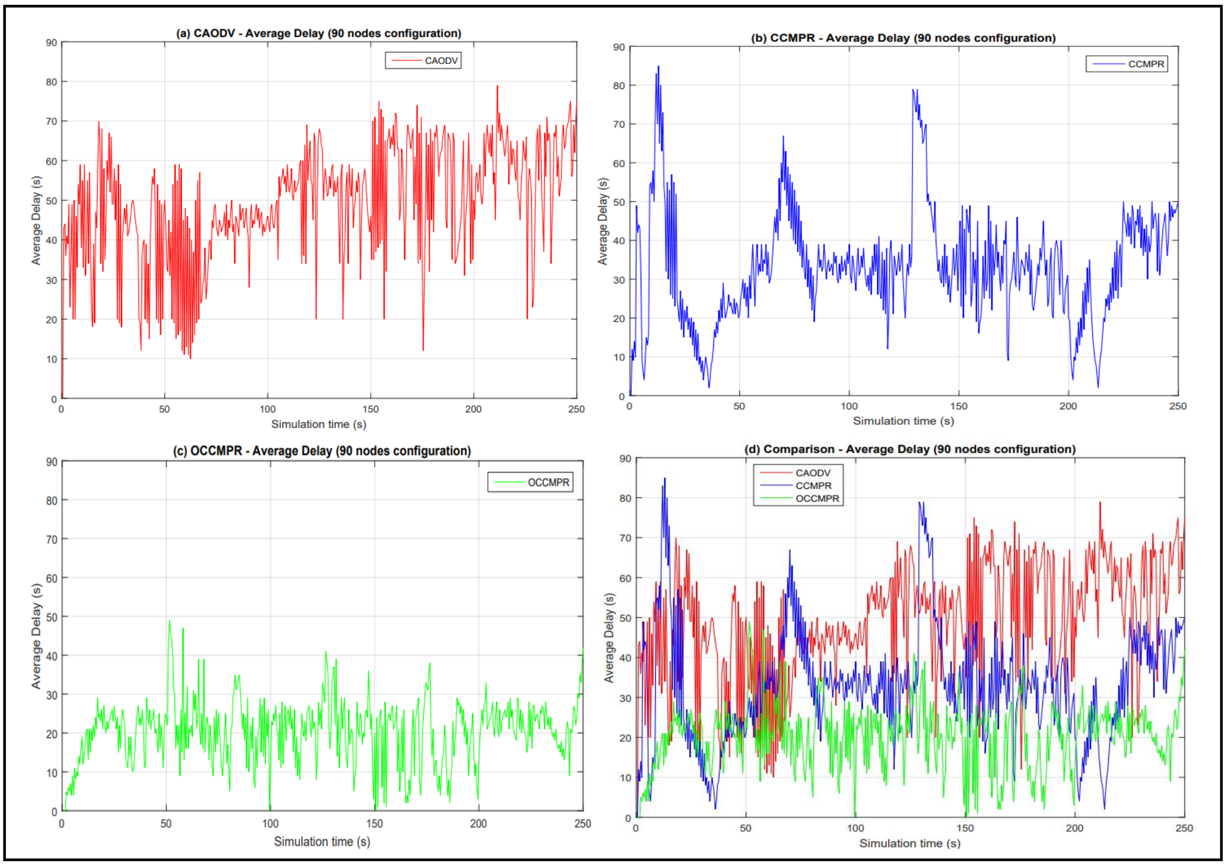


Figure 6-10: Average Delay results (90 nodes configuration)

6.3.4. Scenario 4 – 120 nodes configuration

In scenario four (4), we increased the network nodes to a hundred and twenty (120), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure C-2 of the Appendix and Figure 6-12, which depict that OCCMPR obtained the least delay compared to the previous scenario 3, and the other protocols.

6.3.5. Scenario 5 – 150 nodes configuration

In scenario five (5), we have increased the network nodes to a hundred and fifty (150), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-11 and Figure 6-12, which again showed that OCCMPR obtained the least average delay.

Scenario five (5) average delay results show inconsistent movement for all the protocols and the uptrend movement for the CAODV protocol. CCMPR attained lesser average delay than CAODV and CCMPR protocols because it SU access the channel opportunistically and effectively, therefore, collisions and congestion are avoided.

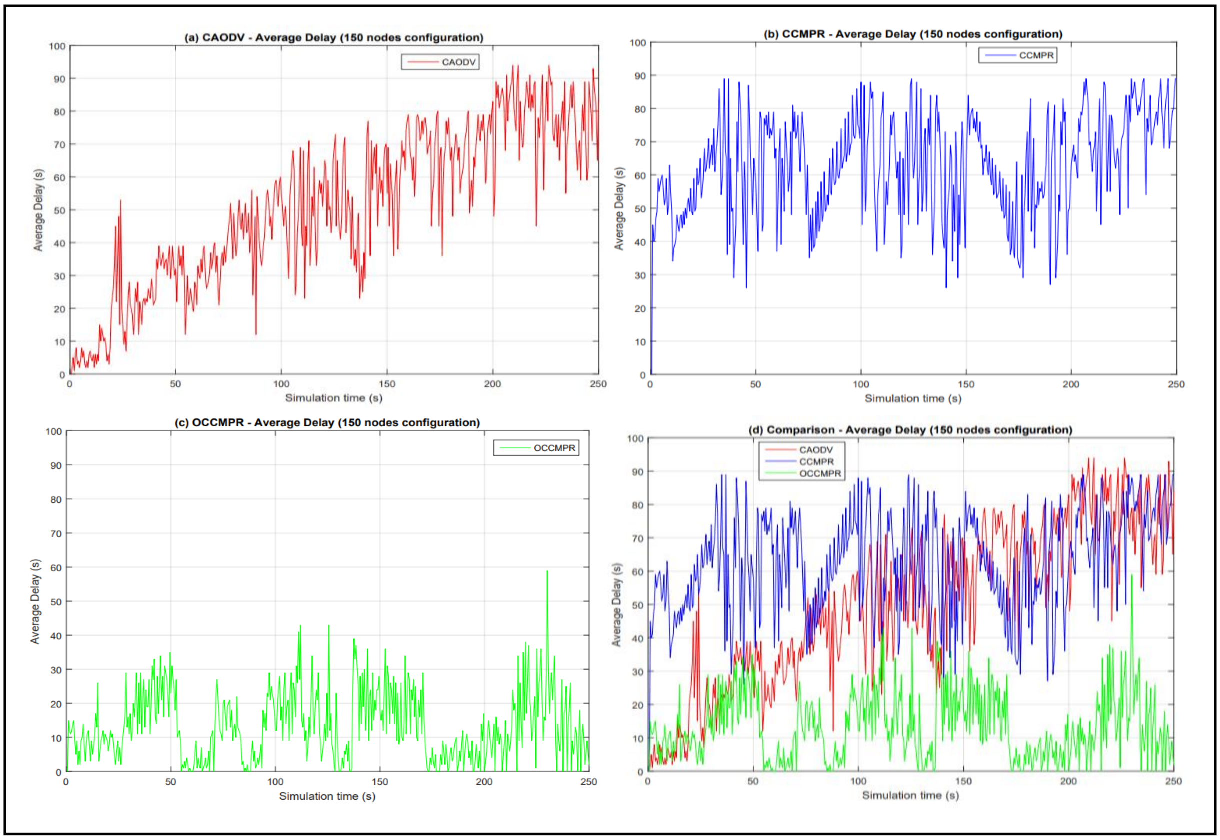


Figure 6-11: Average Delay results (150 nodes configuration)

6.3.6. Overall Average Delay results

Figure 6-12 demonstrates the overall average delay results under five (5) scenarios; one (1), two (2), three (3), four (4) and five (5). We observe that OCCMPR achieved very low average delay in all the given scenarios than CAODV and CCMPR. The results for all the given scenarios are inconsistent for all the schemes, and in all the scenarios, OCCMPR obtained less delay.

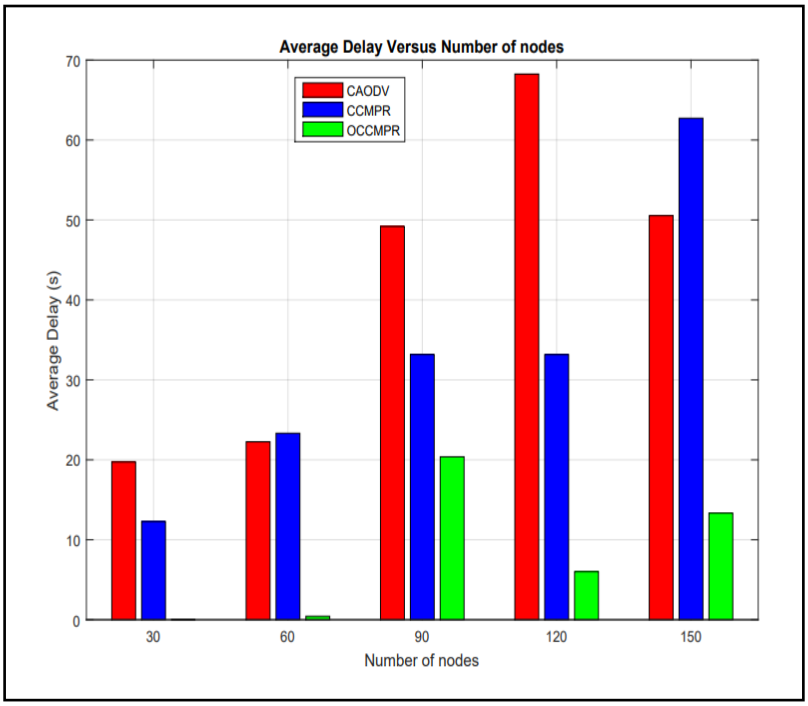


Figure 6-12: Overall Average Delay results

6.4. Packet delivery ratio (PDR)

6.4.1. Scenario 1 – 30 nodes configuration

Initially, in scenario one (1), we set the number of nodes to thirty (30) and all the simulations setup parameters as presented in chapter 4. This scenario's results are presented in Figure 6-13 and Figure 6-16, which illustrate that OCCMPR obtained high PDR compared to CAODV protocol.

Under scenario one (1), the PDR results in Figure 6-13 show steady uptrend movement for all the protocols.

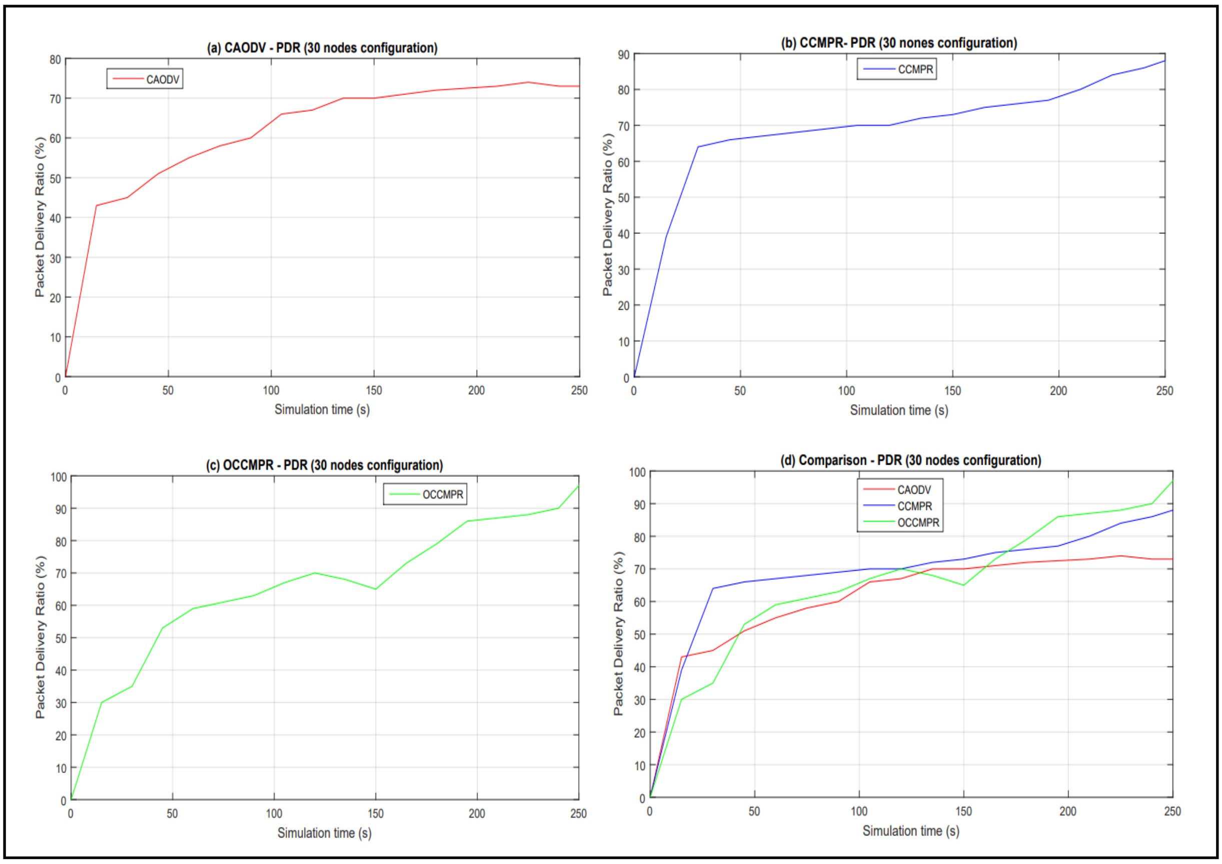


Figure 6-13: PDR results (30 nodes configuration)

6.4.2. Scenario 2 – 60 nodes configuration

In scenario two (2), we increased the network nodes to sixty (60) and all the simulations setup parameters were not changed. This scenario's results are presented in Figure D-1 of the Appendix and Figure 6-16, which depict that OCCMPR attained the highest PDR compared to the other protocols.

6.4.3. Scenario 3 – 90 nodes configuration

In scenario three (3), we have increased the network nodes to ninety (90), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-13 and Figure 6-16, which showed that OCCMPR achieved high PDR compared to the CAODV and CCMPR protocols.

Scenario three (3) PDR results recorded a varying movement for all the protocols and the uptrend movement for the CAODV protocol. We can slightly see that the OCCMPR demonstrate slightly higher PDR compared to CAODV and CCMPR protocols. This can be justified because OCCMPR incorporates remaining hub energy for cost function, which lessens the connection failures by averting hub with low energies. This decrease in link failures expands the PDR.

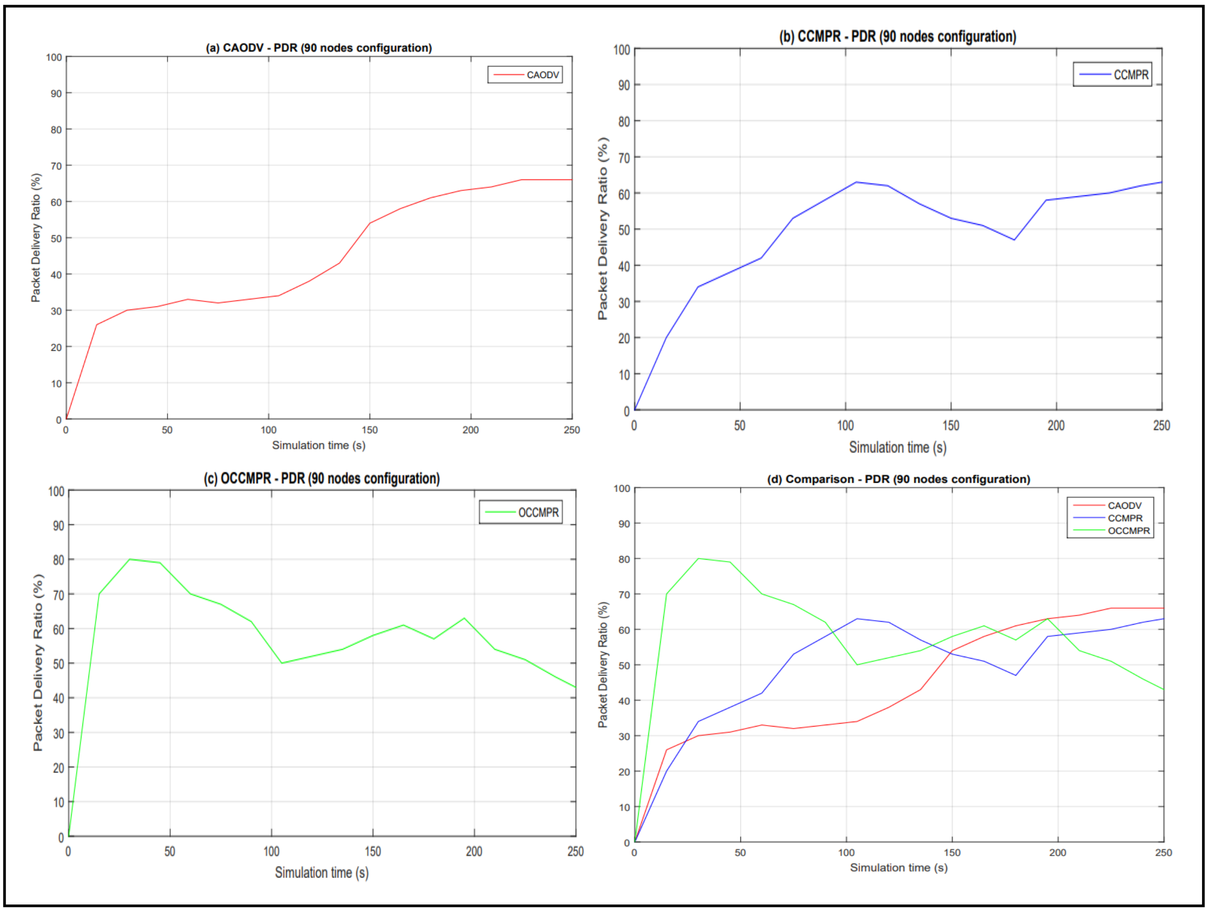


Figure 6-14: PDR results (90 nodes configuration)

6.4.4. Scenario 4 – 120 nodes configuration

In scenario four (4), we increased the network nodes to a hundred and twenty (120), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure D-2 of the Appendix and Figure 6-16, showing that OCCMPR achieved the highest PDR.

6.4.5. Scenario 5 – 150 nodes configuration

In scenario five (5), we have increased the network nodes to a hundred and fifty (150), and all the simulations setup parameters were not changed. This scenario's results are presented in Figure 6-15 and Figure 6-16, which shows that OCCMPR achieved the highest PDR.

Figure 6-15 presents the PDR results for scenario five (5). The results recorded a changing movement for the CAODV and OCCMPR protocols and the uptrend movement for the CCMPR protocol. OCCMPR accomplished higher achievable PDR than CAODV and CCMPR protocols because OCCMPR favours routes with higher transfer speed or bandwidth, decreasing the packet drops, increasing the PDR.

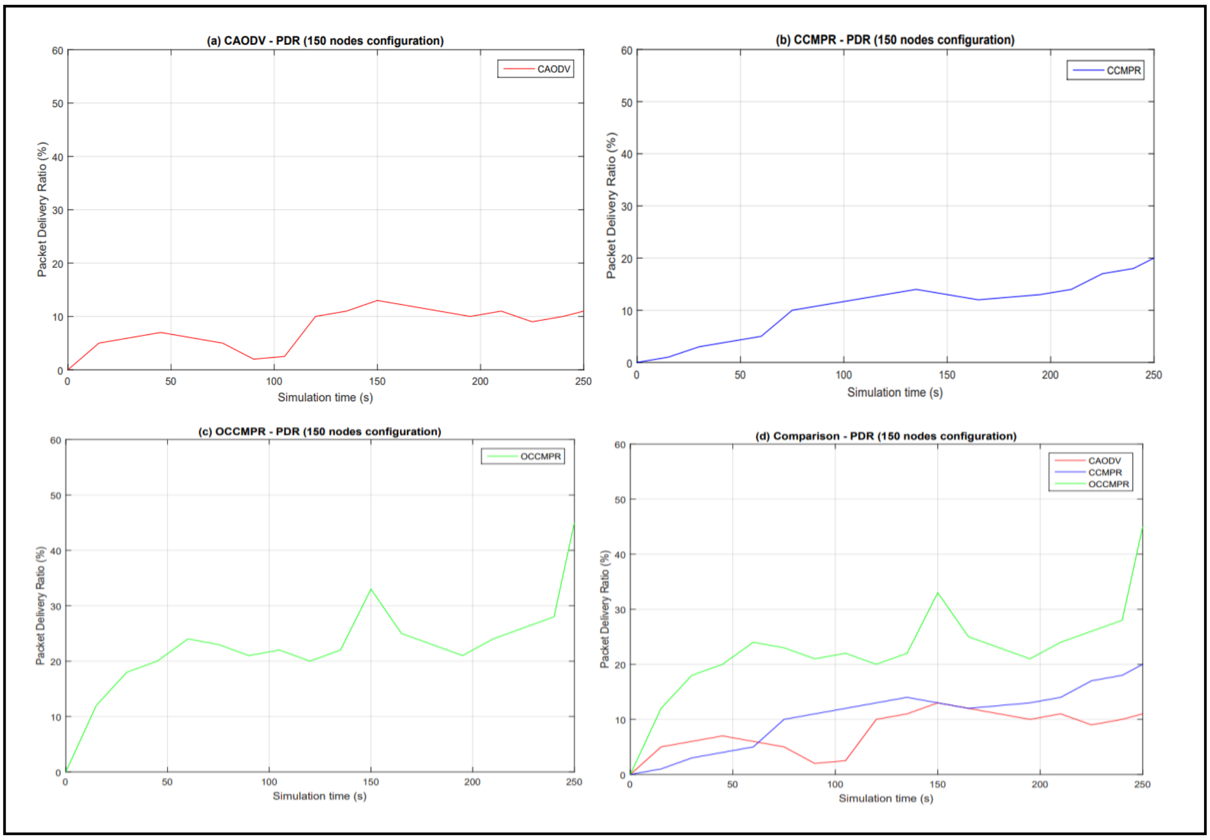


Figure 6-15: PDR results (150 nodes configuration)

6.4.6. Overall PDR results

Figure 6-12 depicts the overall PDR results under five (5) scenarios; one (1), two (2), three (3), four (4) and five (5). We observe that from scenario two (2) – five (5), the OCCMPR protocol outperformed the CAODV and CCMPR protocols. In the results, we observe that as we increase the nodes, the PDR decreases and, therefore, concludes that the PDR is inversely proportional to the number of nodes.

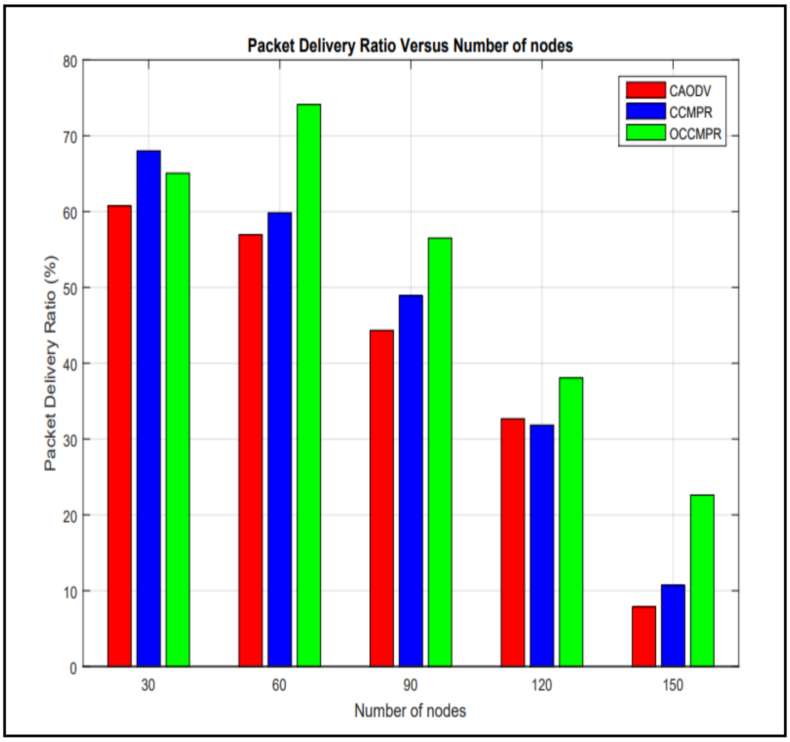


Figure 6-16: Overall PDR results

6.5. Summary

This chapter presented results and discussions. We demonstrated the comparisons simulation results between three protocols, the CAODV, CCMPR and OCCMPR. The comparisons of these results were concluded using the energy consumed per packet, throughput, average delay, and PDR metrics. The OCCMPR has proven to be mostly performing better under given different scenarios; hence, we can say we have achieved our aim for this study.

CHAPTER 7 – CONCLUSION

7. Conclusion and recommendations

7.1 Introduction

CRN gained so much attention due to spectrum scarcity and underutilisation of the spectrum bands. CRN allows the utilization of spectrum holes when the PU does not access the spectrum, using the DSA technique. Unlike previously the FSA was not advantageous since only the PU could access the spectrum which led to underutilisation of the spectrum. CLD in CRN also came as a solution to the traditional strict layering approach, where sharing from a certain layer was restricted to other layers. The problems faced with the traditional approach are that it was non-optimal and did not permit sharing of data between the distinctive layers and the traditional layered structure does not guarantee execution enhancement for the whole system. Another problem is that it was not flexible therefore difficult to work with as it cannot adjust to the sudden changes of the system condition and environment, and lastly, it could not deal with congestion related matters. The goals for CDL are security, QoS and mobility.

7.2 Research summary

This study presented current work in CLD. We showed the different CLD methodologies, and for this study, we used the merging of adjacent layers incorporated with direct communication between the network and the data-link layers. We also demonstrated the advantages of using CLD and the shortcomings of the traditional layered approach.

This study aimed to develop a CLD multi-routing protocol that maximises spectrum opportunities incorporated with channel selection. With the analysis of the simulation results, it showed that our scheme, OCCMPR mostly outperformed the CAODV and CCMPR protocols given different scenarios using the average delay, throughput, energy consumed per packet and PDR metrics.

7.3. Recommendations

With the current CLD, some shortcomings need to be looked at, such as the unintended cross-layer interaction, stability, long-term sustainability, and security issues. The formation of new communications between layers can prompt unexpected dependencies which are not anticipated by simulations. Architectures do their best to vet framework performance through simulation and testing; real-world employment is frequently subjected to unexpected situations. A given CLD may improve at one-layer dependent on feedback from another layer due to joint optimisation. As a result, this makes a closed-loop feedback framework with most of the related configuration challenges. Execution of any CLD must be precisely symbolised against this framework variety, and it is difficult to capture, simulate, and characterised. Because of the ordinary rule, strict models with completely defined sub-framework accountabilities and associations prompt strong, modular frameworks. This is one of the best advantages of the OSI model. Each layer can be freely outlined, changed, or redesigned with no required activity for alternate layers in the framework. A change made at some random layer could influence some other layer's performance. Furthermore, it is not clear which CLD recommendations could be joined to additionally enhance execution.

7.4. Final conclusion

In this study, we designed and optimised a cross-layer routing and MAC protocol that uses time slots with the TDMA approach for the PU and the CSMA/CA for the SU. These two algorithms were advantageous to our OCCMPR scheme as our simulation comparative results witness that under different given scenarios. Our simulation metrics were energy consumed per packet, throughput, average delay, and PDR. Our scheme achieved high throughput and PDR, lesser energy consumed per packet and average delay.

References

[1] D. Singhal, "Cross Layer Protocols in Cognitive Networks," ResearchGate, India, 2015.

[2] S. Mim, "Cross-layer Design in Cognitive Radio Networks: Issues and Possible Solutions," in *ResearchGate*, Carleton University, Canada, 2016.

[3] Y. Saleem, F. Salim and M. H. Rehmani, "Routing and channel selection from cognitive radio network’s perspective: A survey," *Computers and Electrical Engineering,* vol. 42, pp. 117-134, 2015.

[4] C. Matteo , C. Francesca and E. Eylem , "Routing in cognitive radio networks: Challenges and solutions," *Elsevier,* vol. 9, pp. 228-248, 2011.

[5] S. Zhihui, Q. Yi , Y. Yaoqing and S. Hamid , "A cross-layer study for application-aware multi-hop cognitive radio networks," *Wireless communications and mobile computing,* vol. 16, no. 10, pp. 607- 619, 2014.

[6] P. Himanshu and S. K. Awadhesh , "Fault Tolerant Spectrum Assignment in Cognitive Radio Networks," *Procedia Computer Science,* vol. 46, pp. 1188 - 1195, 2015.

[7] S. M. Tarek, A. E.-k. Sherine, R. M. Salah and A.-M. Zaki, "Opportunistic Spectrum Access in Cognitive Radio Ad Hoc Networks," *IJCSI International Journal of Computer Science Issues,* vol. 11, no. 1, pp. 1694 - 0784, 2014.

[8] X. Cui, "A Survey of Cross-Layer Design for Cognitive Radio Networks," in *ResearchGate*, University of Ottawa, Canada, 2017.

[9] H. Mohammed , B. Shrief and A. A. Mahmoud , "A tree routing protocol for cognitive radio network," *Egyptian Informatics Journal,* vol. 18, pp. 95 - 103, 2017.

[10] A. I. Adebayo, M. A. Linoh and D. Karim , "Spectrum selection techniques to reduce the number of channel switching for dynamic spectrum access in Cognitive Radio Networks," in *Proceedings of the IASTED International Conference Modelling and Simulation*, Gaborone, Botswana, 2014.

[11] M. Nafees , I. Muzahidul , Z. Mahdi and B. Sabariah , "Cognitive Radio Ad-Hoc Network Architectures: A Survey," in *ResearchGate*, Malaysia, 2014.

[12] John Andrew Msumba, "Cross-Layer Design For Multimedia," University of Kwa-Zulu Natal, Durban, 2015.

[13] S. Yasir , S. Farrukh and R. H. Mubashir , "Routing and channel selection from cognitive radio networks," *Elsevier,* vol. 42, pp. 117-134, 2015.

[14] Y. Moustafa, I. Mohamed , A. Mohamed , C. Lin and V. V. Athanasios , "Routing Metrics of Cognitive Radio Networks: A Survey," *IEEE communications surveys & totorials,* vol. 16, no. 1, pp. 92-109, 2014.

[15] K. Rahul and V. P. Om , "An effective collaborative movie recommender system with cuckoo," *Egyptian Informatics Journal,* vol. 18, pp. 105-112, 2017.

[16] K. A. Athar , R. H. Mubashir and R. Martin , "Requirements, Design Challenges, and Review of Routing and MAC Protocols for CR-Based Smart Grid Systems," in *IEEE communication Magazine in ResearchGate*, 2017.

[17] P. Garg, "A survey of Cross-Layer Design in Cognitive Radio Networks: Issues and proposed solutions," in *ResearchGate*, Carleton University, Canada, 2017.

[18] T. Vahid and S.-B. Mohammad , "Cross-layer Design in Cognitive Radio Standards," in *Centre for Telecommunications Research*, King’s College London, UK, 2017.

[19] A. S. Ahmed, T. S. Kumaran, S. S. Abdul and S. Subburam, "Cross-Layer Design Approach for Power Control in Mobile Ad Hoc Network," *Egyptian Informatics Journal,* pp. 1-7, 2015.

[20] S. Subburam, T. Senthilkumaran, S. Revathi and M. Mathivanan, "An Innovative Design Approach to control over Ad Hoc Networks," *Circuits and Systems,* vol. 7, pp. 971-982, 2016.

[21] D. Kliazovich and F. Granelli, "WHY CROSS-LAYER? ITS ADVANTAGES AND DISADVANTAGES," in *CROSS LAYER DESIGNS IN WLAN SYSTEMS*.

[22] S. Thota, "cross layer design at network layer: issues and solutions," in *Research gate*, Carleton University, Canada, 2016.

[23] Y. K. Pala, "Cross-layer design in Software Defined Networks (SDNs): issues and possible solutions," in *Research gate*, University of Ottawa, Canada, 2017.

[24] M. Ogunfeibo, "Cross Layer Design in Internet of Things: Issues and Possible Solutions," in *Research gate*, Carleton University, Canada, 2018.

[25] J. Changpeng , N. Xiaoqiu and Y. Yujie , "A Cross-layer Scheduling Algorithm Based on Cognitive Radio Network," *Applied Mathematics & Information Sciences. An International Journal,* vol. 7, no. 2, pp. 611 - 617, 2013.

[26] V. Mathi and T. Senthilkumaran, "An Innovative Design Approach to Control over Ad Hoc Networks," in *ResearchGate*, Bangalore, 2016.

[27] K. Adrian , . T. Dionysia, D. N. Luca, H. Oliver , G. Liljana and B. Aimilia , "Cross-Layer analysis in Cognitive Radio—context identification and decision making aspects," *IEEE transactions on cognitive communications and networking,* vol. 1, no. 4, pp. 450 - 463, 2015.

[28] A. A. kannampilly, "State of the art and future directions of Cross-layer design in Cognitive radio networks," in *ResearchGate*, Carleton University, Canada, 2017.

[29] H. Zara and H. B. Faisal , "QoS inWirelessMultimedia Sensor Networks: A Layered and Cross-Layered Approach," in *Wireless Pers Commun*, New York, 2014.

[30] Y. Xiao, "A Survey of Cross-Layer Designs in Wireless Networks," in *ResearchGate*, University of Alabama, United States, 2014.

[31] M. Anandteerth and S. Mrinal , "Cross Layer Design Approaches, Schemes and Optimization Methodologies for Cognitive Radio Networks: a Survey," *Journal of Electronics and Communication Engineering Research,* vol. 1, no. 4, pp. 15 - 21, 2013.

[32] R. Santhosha and S. Kumara , "Cross layer protocols for multimedia transmission in wireless networks.," *International Journal of Computer Science & Engineering Survey (IJCSES),* vol. 3, no. 3, pp. 15 - 28, 2012.

[33] R. Mahajan, "Cognitive Radio Networks Issues and Solutions," in *ResearchGate*, Carleton University, Canada, 2016.

[34] S. L. Yadav and M. Phogat, "A survey on Cross-layer Design implementations in Wireless Sensor Networks," *International Journal of Science, Engineering & Computer Technology,* vol. 7, no. 1, pp. 17 - 19, 2017.

[35] P. Charan, R. Paulus, M. Kumar and A. K. Jaiswal, "A Cross Layer approach for Performance Optimization in Wireless Sensor Networks using Cooperative Diversity," *IJCST,* vol. 3, no. 2, pp. 158 - 163, 2012.

[36] P. Singh, A. Kumar, V. Kumar and A. Kumar, "A Comprehensive Study on Cross Layer Design and its Future," *International Journal of Advanced Research in Computer Science,* vol. 3, no. 3, pp. 669 - 674, 2012.

[37] R. Saifan, A. E. Kamal and Y. Guan, "A Cross-Layer Routing Protocol (CLRP) for Cognitive Radio Network," Jordan.

[38] N. P. Gogulwar and A. R. Manusmare, "An Attack Aware Cross Layer Routing Protocol for Multi-hop Cognitive Radio Network," *International Journal of Computer Applications,* vol. 148, no. 1, pp. 0975-8887, 2016.

[39] A. P. Westerhagen, "Cognitive Radio NetwORKS: elements and architectures," Blekinge Institute of Technology, Karlskrona, Sweden, 2014.

[40] Pratibha, S. S. Khare and S. Gupta, "Performance Comparison of AODV and CAODV Routing Protocol using Cognitive Radios," *Internal Journal of Future Generation Communication and Networking,* vol. 7, no. 3, pp. 129-140, 2014.

[41] A. S. Cacciapuoti, M. Caleffi and L. Paura, "Reaction routing for mobile Cognitive Radio ad Hoc Networks," *ACM Digital library,* vol. 10, no. 5, pp. 803 - 815, 2012.

[42] H. K. Cheng, "Design and Development of MAC and Routing Protocols for Cognitive Radio Based Wireless Mesh Networks," India, 2014.

[43] Z. Shu, "ON APPLICATION-AWARE DESIGN OF MULTI-HOP COGNITIVE RADIO NETWORKS - CHANNEL ALLOCATION AND ROUTING," Lincoln, Nebraska, 2014.

[44] S. B. Sunita and K. Parag , "A Performance based Routing Classification in Cognitive Radio Networks," *International Journal of Computer Applications,* vol. 44, no. 19, p. 0975 – 8887, 2012.

[45] L. Ding, T. Melodia, S. N. Batalama, J. D. Matyjas and M. J. Medley, "Cross-Layer Routing and Dynamic Spectrum Allocation in Cognitive Radio Ad Hoc Networks," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 59, no. 4, 2010.

[46] D. Singhal and R. M. Garimella, "Cognitive cross-layer multipath probabilistic routing for cognitive networks," *International Institute of Information Technology,* vol. 21, no. 4, pp. 1181 - 1192, 2014.

[47] F. Ye, . X. Zhang, Y. Li and H. Huang, "Primary User Localization Algorithm Based on Compressive Sensing in Cognitive Radio Networks," *MDPI,* vol. 9, no. 25, pp. 1-11, 2016.

[48] M. S. Madiba, M. Velempini and R. L. Moila, "Spectrum handoff management strategies in cognitive radio routing protocols for mobile adhoc networks," in *SATNAC*, Durban, Zimbali, 2019.

[49] A. E. Gouda, S. I. Rabia, A. Y. Zakariya and M. A. Omar, "Reactive spectrum handoff combined with random target channel selection in cognitive radio networks with prioritized secondary users," *Alexandria Engineering Journal,* vol. 57, pp. 3219 - 3225, 2018.

[50] M. E. Bayrakdar and A. Çalhan, "Improving spectrum handoff utilization for prioritized cognitive radio users by exploiting channel bonding with starvation mitigation," *International Journal of Electronics and Communications (AEÜ),* vol. 71, pp. 181 - 191, 2017.

[51] L. C. Wang, C. W. Wang and K. T. Feng, "A queueing-theoretical framework for QoS-enhanced spectrum management in cognitive radio networks," *IEEE Wirel. Commun.,* vol. 18, no. 6, pp. 18 - 26, 2011.

[52] I. Christian, S. Moh, I. Chung and J. Lee, "Spectrum Mobility in Cognitive Radio Networks," IEEE Communications Magazine, Chosun University, 2012.

[53] S. Atmaca, "Improving TDMA Channel Utilization in Random Access Cognitive Radio Networks by Exploiting Slotted CSMA," in *Wireless Pers Commun*, New York, 2013.

[54] M. S. Madiba and V. Mthulisi, "The design and optimisation of cross-layer scheme - routing and medium access control protocols for throughput in cognitive radio networks," in *ICONIC*, Mauritius, Plaine Magnien, 2020.

[55] A. N. Akhtar, F. Arif and A. M. Siddique, "Spectrum Decision Framework to Support Cognitive Radio Based IoT in 5G," in *Cognitive Radio in 4G/5G Wireless Communication Systems*, Islamabad, Pakistan, IntechOpen, 2018.

[56] S. Adebayo, A. O. Akinwunmi and E. O. Ogunti, "A Survey of Medium Access Control Protocols in Wireless Sensor Network," *International Journal of Computer Applications,* vol. 116, no. 22, p. 0975 – 8887, 2015.

[57] H. K. Cheng and M. Maode, "Design and Development of MAC and Routing Protocols for Cognitive Radio Based Wireless Mesh Networks," School of Electrical and Electronic Engineering, Nanyang Technological University (NTU) Singapore, 2014.

[58] D. Dudeja, "Cross Layer Design in Software Defined Networks: Problems and solutions," in *ResearchGate*, University of Ottawa, Canada, 2017.

[59] A. s. George, "Cross Layer Design in Software Defined Networks (SDNs): Issues and Solutions," in *ResearchGate*, Carleton University, Canada, 2017.

[60] Y. Bastawisy, "Cross-Layer Design in Software-Defined Networks (SDNs)," in *ResearchGate*, University of Ottawa, Canada, 2017.

[61] M.D.Nikose, "A REVIEW OF CROSS LAYER DESIGN," *International Journal of Emerging Trends in Engineering & Technology (IJETET),* vol. 2, no. 1, pp. 2248 - 9592, 2013.

[62] J. Geraghty, "Genetic Algorithm performance with defferent selection strategies in solving TSP," in *World Congress on Engineering*, London, U.K., 2011.

[63] S. H. Bukhari, S. Siraj and M. H. Rehmani, "NS-2 Based Simulation Framework for Cognitive Radio," in *Springer Science+Business Media*, New York, 2016.

APPENDIX

A. Energy Consumed per Packet

1.1. Scenario 2 – 60 nodes configuration

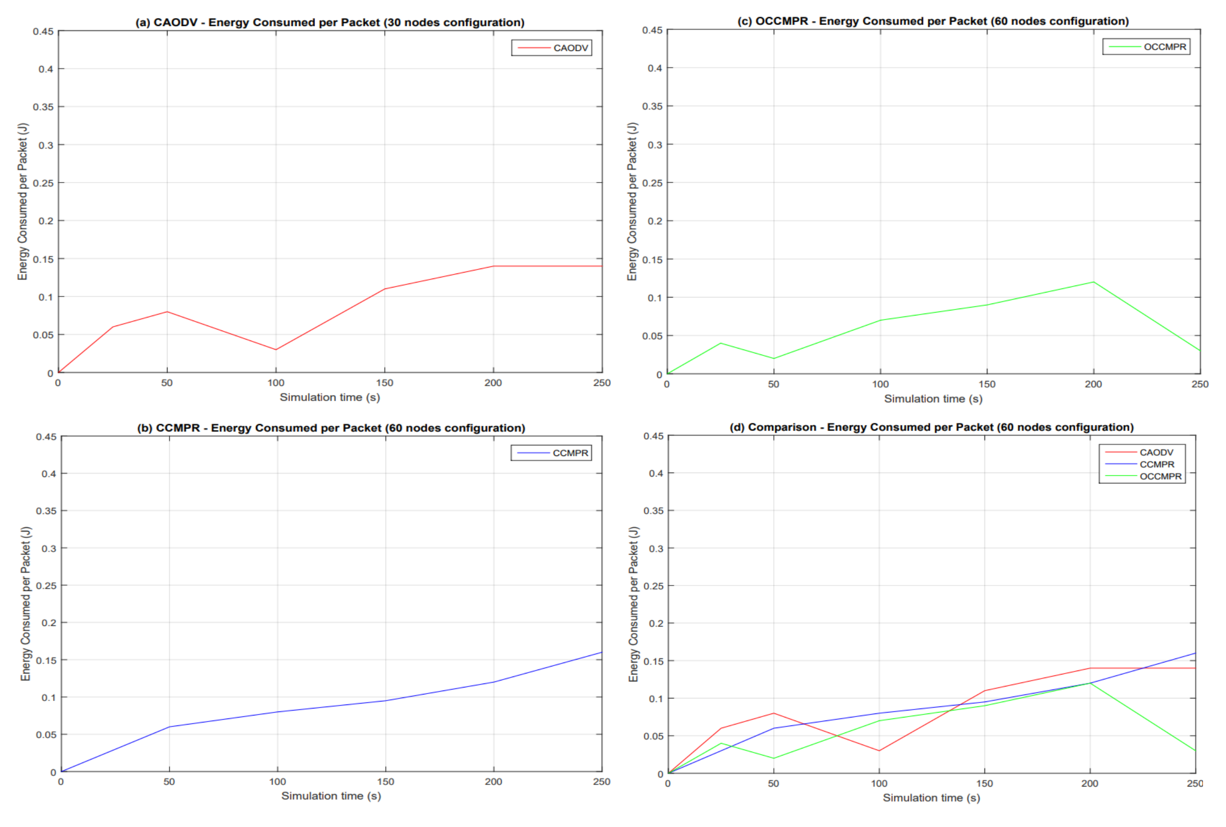


Figure A-1: Energy Consumed per Packet results (60 nodes configuration)

1.2. Scenario 4 – 120 nodes configuration

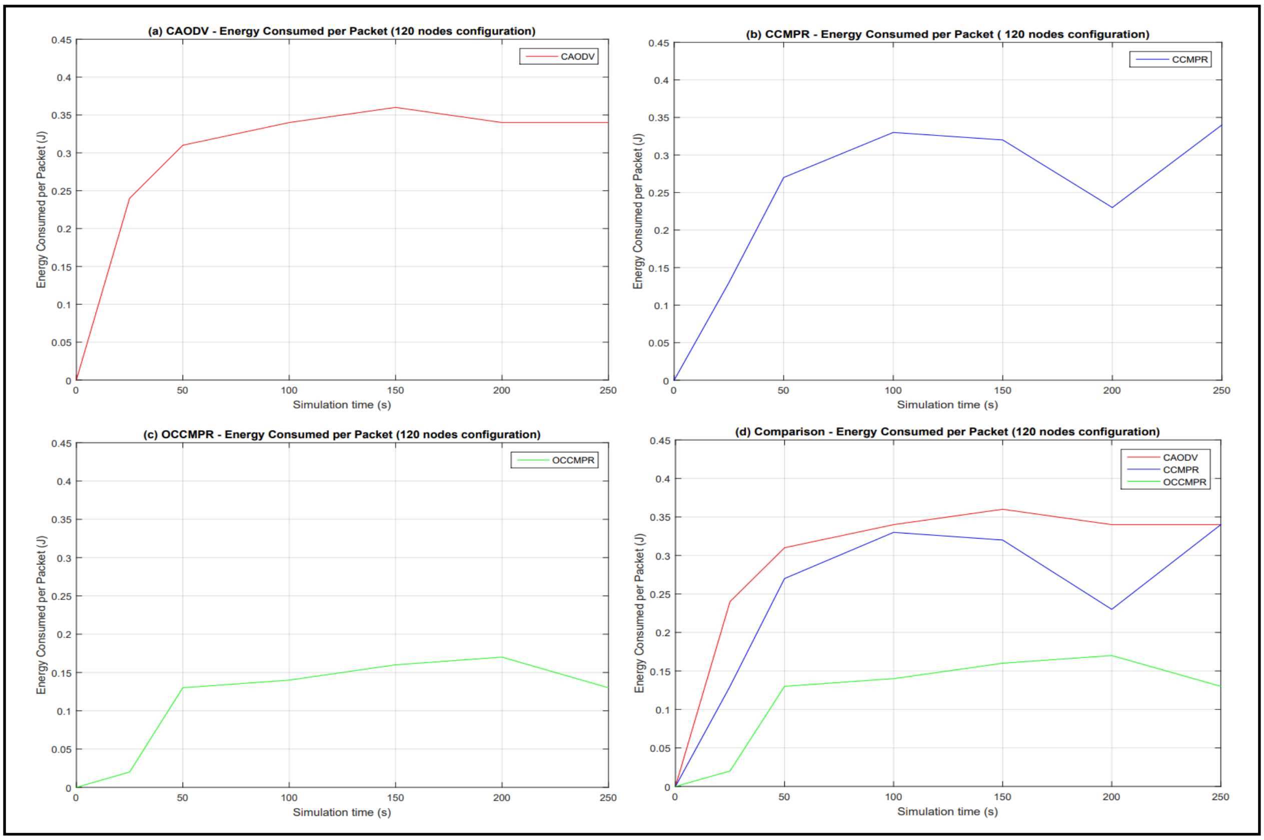


Figure A-2: Energy Consumed per Packet results (120 nodes configuration)

B. Throughput

2.1. Scenario 2 – 60 nodes configuration

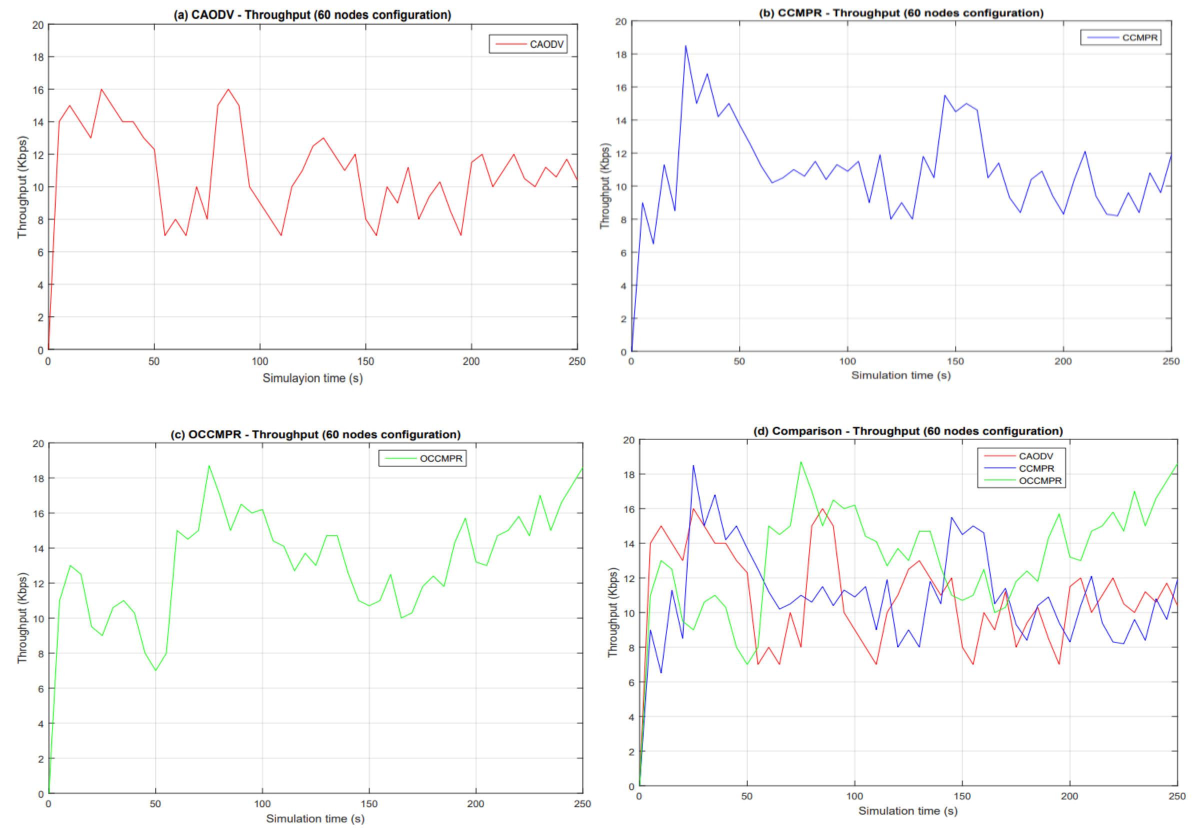


Figure B-1: Throughput results (60 nodes configuration)

2.2. Scenario 4 – 120 nodes configuration

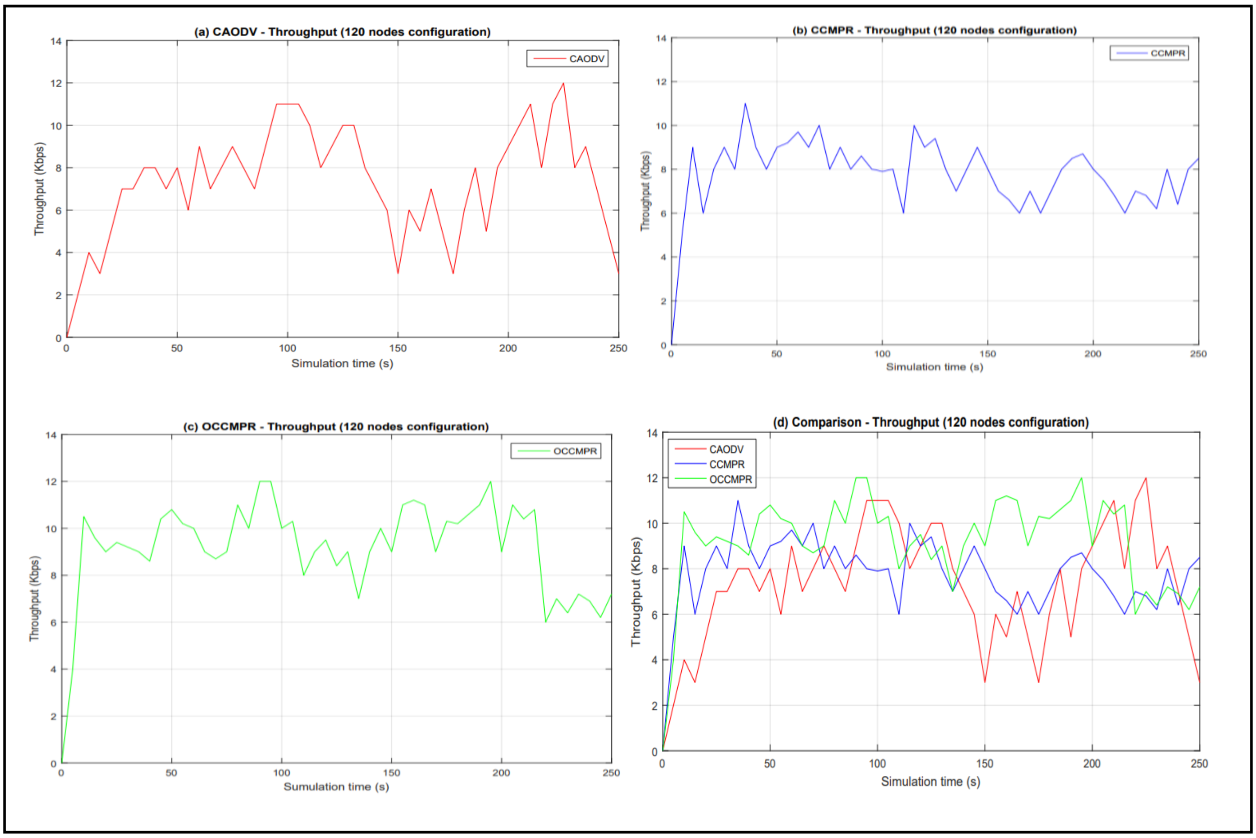


Figure B-2: Throughput results (120 nodes configuration)

C. Average delay

3.1. Scenario 2 – 60 nodes configuration

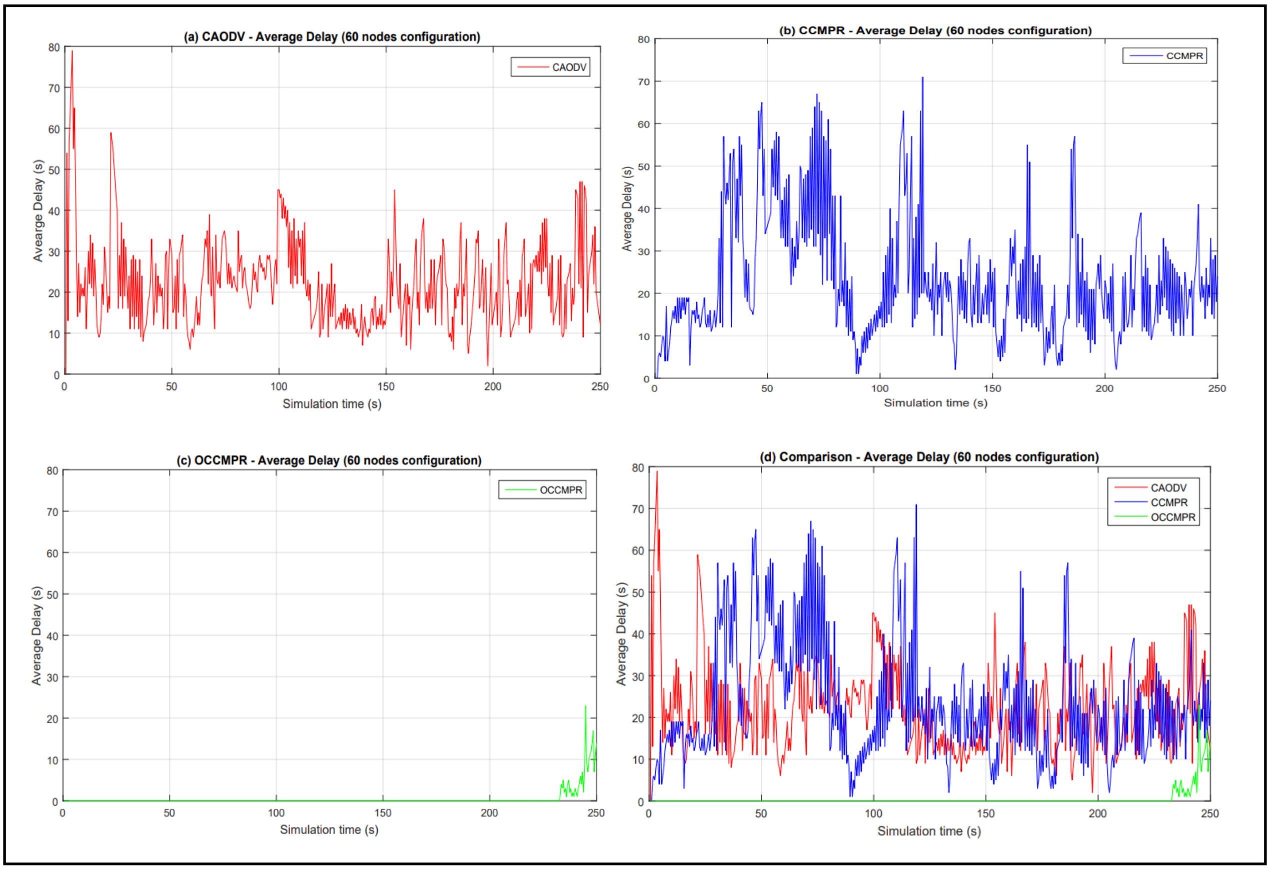


Figure C-1: Average Delay results (60 nodes configuration)

3.2. Scenario 4 – 120 nodes configuration

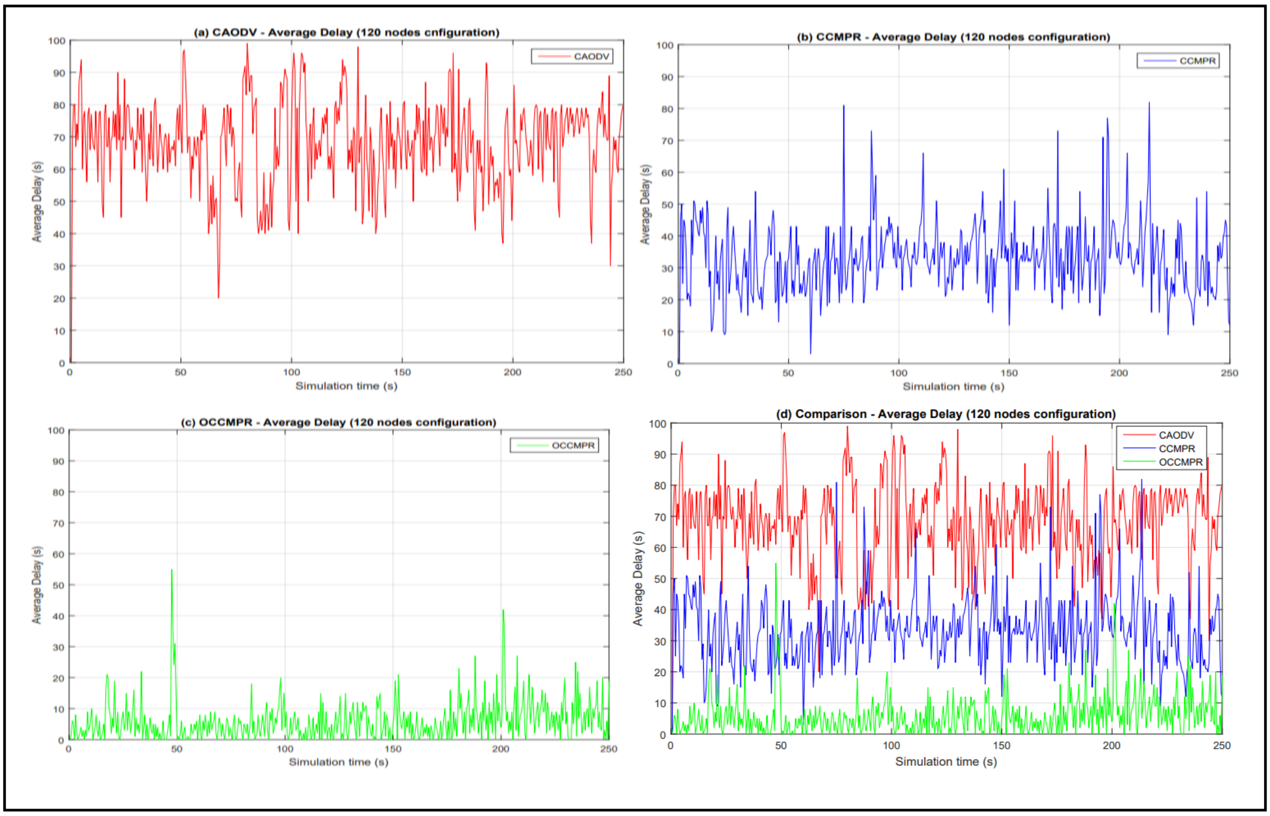


Figure C-2: Average Delay results (120 nodes configuration)

D. PDR

4.1. Scenario 2 – 60 nodes configuration

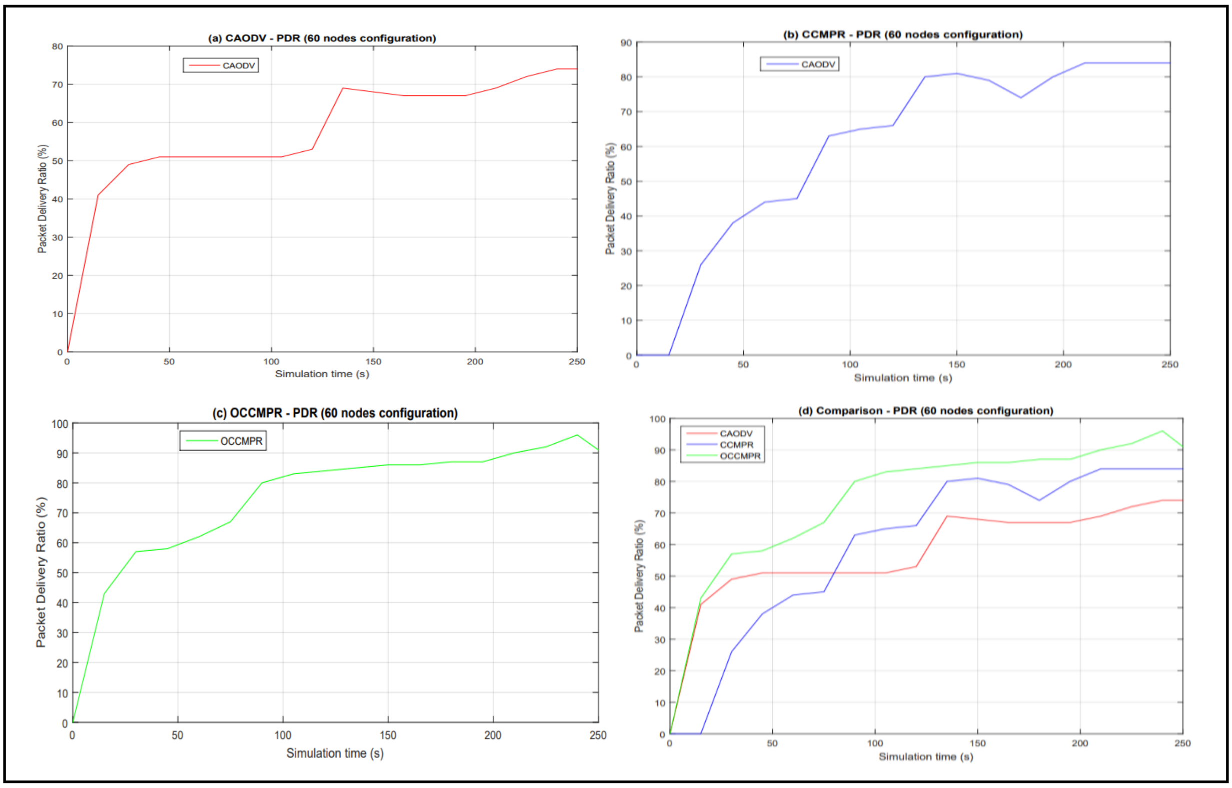


Figure D-1: PDR results (60 nodes configuration)

4.2. Scenario 4 – 120 nodes configuration

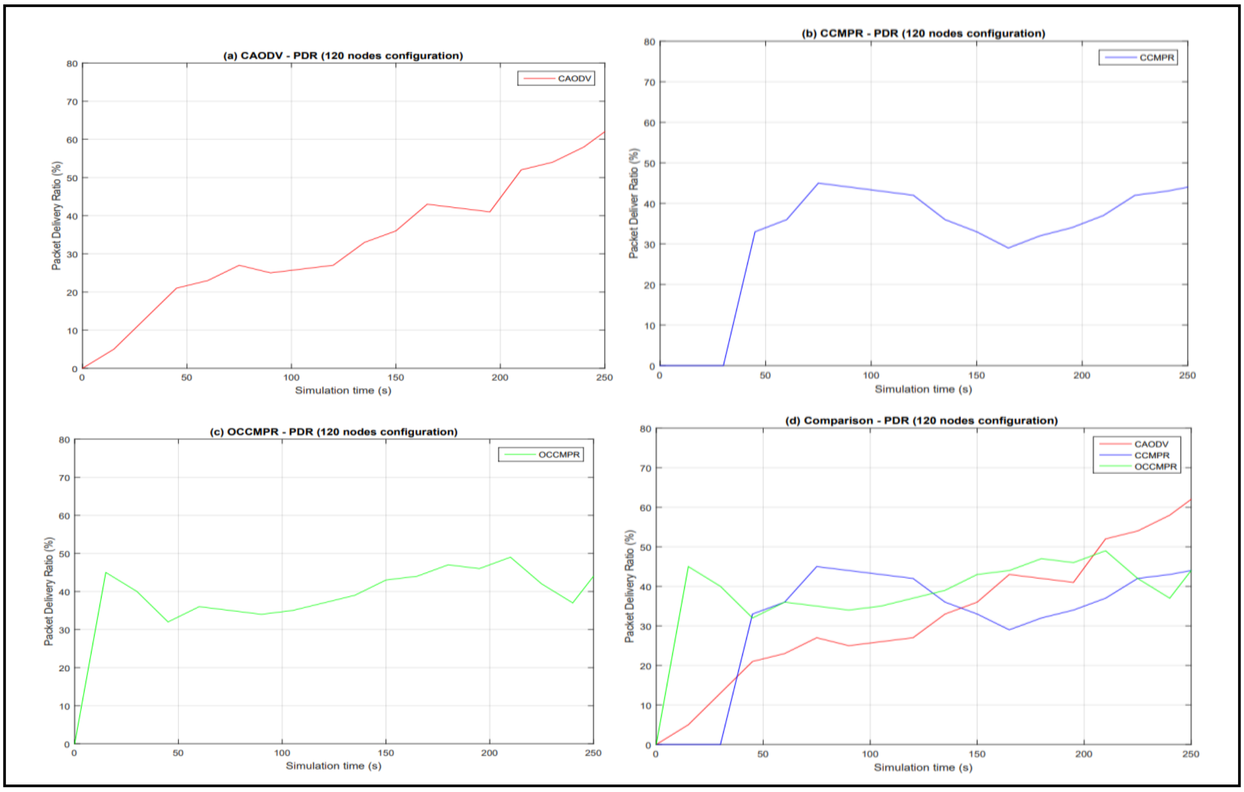


Figure D-2: PDR results (120 nodes configuration)