Intelligent traffic routing management algorithm for wireless sensor networks.

Intelligent Traffic Routing Management Algorithm for Wireless Sensor Networks

by

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DECLARATION

I, Tshimangadzo Mavin Tshilongamulenzhe, hereby confirm that this research study entitled: Intelligent Traffic Routing Management Algorithm for Wireless Sensor Networks, submitted for the degree Doctor of Computing (D-Computing): Information Technology at the Tshwane University of Technology is my research and has not been submitted to any other institution of higher learning. I further confirm that all articles quoted are indicated and acknowledged by means of a comprehensive list of references.

Signature:…….. Date:……

Dedication

The study is dedicated to my wife, son, and family members who guided, supported, and encouraged me to complete my studies.

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First and foremost, I would like to thank the Almighty God, who gave me the power and guidance to finish this research study. I also wish to express my heartfelt gratitude for the kindness of my supervisors, who contributed much to my completing of this research study (Supervisor: Prof MI Mphahlele; Co-supervisors: Dr. TE Mathonsi and Dr. DP duPlessis). These mentors continued to give me professional advice such as focusing on the research topic; and they provided me with good feedback on my research study.

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4. Tshimangadzo M. Tshilongamulenzhe, Topside E. Mathonsi, Maredi I. Mphahlele and Deon P. Du Plessis “A Priority-Based Congestion Control Algorithm for Wireless Sensor Networks.” Paper Accepted to 2022 Third International Conference on Issues and Challenges in Intelligent Computing Techniques (ICICT-2022), on 11th -12th November 2022 in KIET Group of Institutions, Ghaziabad, India.

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Abstract

Over the past decade, Wireless Sensor Networks (WSNs) have gained attention worldwide for transmitting packets from one location to another. WSNs are formed by sensor nodes (SNs) interconnected with one another through wireless links. SNs in WSNs may be deployed randomly in any location; and they have the potential to move around in the network environment. The deployment areas include the healthcare, military, home, and irrigation environments. In addition, these WSNs are primarily used to monitor temperature, humidity, and pressure, using a variety of SNs. Packet transmission in WSNs allows network users to access information wherever they are, depending on network coverage. However, packet transmission in WSNs comes with various challenges such as packet loss, packet delay, decrement of network throughput, and many others. These challenges are normally caused by head-of-line congestion that occurs in WSNs during packet transmission. Head-of-line congestion occurs when the first packet holds up a line of packets during many-to-one packet routing. The existing algorithms used for packet traffic management have failed to minimize head-of-line congestion in WSNs. This is because the existing algorithms lack proper decision-making based on packet flow to avoid packet congestion in WSNs. Such is the case within the agricultural environment.

As a result, the study designed the intelligent traffic routing management (ITRM) algorithm by integrating machine learning congestion control (MLCC) and load balancing routing mechanism (LBRM). Network Simulator-2 (NS-2) has been used to test the effectiveness of the proposed ITRM algorithm when compared with the MLCC and LBRM. For low-priority packets, the NS-2 simulation results demonstrated that the proposed ITRM algorithm has an average of 0.27% packet loss, 0.4% packet delay, and 98.3% network throughput which is more than MLCC and LBRM when simulation time starts at 30 seconds, with less than 10 bytes of packet size. The NS-2 simulation results for high-priority packets in the agricultural environment demonstrated that the proposed ITRM algorithm has an average of 1.3% packet loss, 1.06% packet delay, and 95.7 % network throughput when packet size is 10 bytes in WSNs.

The simulation results from the NS-2 simulator demonstrated that the proposed ITRM algorithm performs better than the MLCC and LBRM in terms of packet loss and packet delay; and performs much better in terms of the network throughput. As a result, the quality of services (QoS) has been improved in WSNs within the agricultural environment.

Keywords: Wireless Sensor Networks, Sensor Nodes, Intelligent Traffic Routing Management algorithm, Packet transmission, Agricultural environment, Network throughput, Network Simulator-2.

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Glossary

ACA	Automata-based Congestion Avoidance
ACFR	Ambient Crop Field Routing
AIMD	Additive Increase Multiplicative Decrease
AI-SIoT	Artificial Intelligence-based Semantic Internet of Things
ANNA	Artificial Neural Network-based Algorithm
AODV	Ad-hoc On-Demand Vector
AP	Access Point
APs	Access Points
ARA	Agri-based Routing Algorithm
Bps	Bits per second
CAR	Congestion-Aware Routing
CCP	Congestion Control Predictor
CCR	Congestion-aware Clustering and Routing
FFD	First-Fit Decreasing
FTP	File Transfer Protocol
Gbps	Gigabits per second
GloMoSim	Global Mobile Information Systems Simulation Library
GUI	Graphical User Interface
HTAP	Hierarchical Tree Alternative Path
HTTP	Hypertext Transfer Protocol
ICD	Intelligent Congestion Detection
ICN	Implicit Congestion Notification
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol

ISP	Internet Service Provider
ITRM	Intelligence Traffic Routing Management algorithm
ITU-T	International Telecommunication Union-Telecommunication
LAN	Local Area Network
LBRM	Load Balancing Routing Mechanism
LET	Link expiry time
LL	Link Layer
LS	Link stability
MAN	Metropolitan Area Network
MATLAB	MATrix LABoratory
Mbps	Megabits per second
MDM	Multi-criteria Decision-making
ML	Machine Learning
MLCC	Machine Learning Congestion Control
NAM	Network Animator
NS-2	Network Simulator-2
NS-3	Network Simulator-3
OMNeT	Optical Micro-Networks
OSI	Open Systems Interconnection
OTCL	Object Tool Command Language
PA	Precision Agriculture
PAN	Personal Area Network
PCC	Priority-based Congestion Control
PCH	Primary Cluster Head
PRA	Priority-based Rate Adjustment
QoS	Quality of Service
SCH	Secondary Cluster Head

SN	Sensor Node
SNs	Sensor Nodes
TCL	Tool Command Language
TCP	Transmission Control Protocol
TPFC	Traffic Packet-Flow Control algorithm
UDP	User Datagram Protocol
VINT	Virtual InterNetwork Testbed
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WSNs	Wireless Sensor Networks

Chapter 1: Introduction

1.1. Background information to the study

Wireless Sensor Networks (WSNs), which fall under IEEE 802.11 standards, are wireless networks formed by sensor nodes (SNs) that interconnect with one another through wireless links (Huamei et al., 2019; Patel and Patel, 2018; Rojas and Barrett, 2019; Umadevi et al., 2018; Tshilongamulenzhe et al., 2019; Mathonsi and Kogeda, 2016; Buthelezi et al., 2017; Ojha et al., 2015). The SNs are mostly battery-operated and highly constrained regarding energy resources, making them difficult to recharge once depleted (Awoyemi et al., 2019; Biswas et al., 2018; Lakshmi et al., 2019; Nair et al., 2015; Khalid et al., 2017; Elsayed et al., 2017; Baranov et al., 2018; Mukherjee et al., 2019). Furthermore, SNs have the capability of sensing, processing, and communicating over the wireless channel in harsh environments (environments in which it is difficult to implement the traditional networks). SNs transmit data packets through wireless channels from a source node to the destination node (Han et al., 2018; Mathonsi and Kogeda, 2016; Mathonsi et al., 2018; Zhu et al., 2019).

These nodes are inexpensive compared with traditional wired sensors predominantly used for structural health monitoring (Bengherbia et al., 2016; Spencer Jr et al., 2017; Groth and Kulas, 2018; Barkunan and Bhanumathi, 2018; Woods et al., 2019;

Jayapal et al., 2019). Moreover, the data is sensed, measured, and gathered by these SNs (Yick et al., 2008; Umemoto et al., 2018; Grodecki and Nolting, 2019).

In addition, WSNs may be randomly deployed in any place, and the nodes have the potential to move around within the network environment. Deployment areas include the healthcare, military, home, traffic management, and irrigation environments, which allow sensing and monitoring processes to take action in WSNs. Furthermore, the network users in these networks can access information stored in a network as long as there is network coverage. WSNs are observed as a revolutionary information-gathering method, which forms information and communication systems to significantly improve the consistency and efficiency of the system infrastructure (Cisse et al., 2017; Martinez et al., 2019; Álvarez et al., 2019; Parramon et al., 2019).

This research study implements WSNs in the agricultural environment to monitor environmental conditions such as soil moisture, humidity, and soil temperature. Therefore, whether the temperature is high or low, the appropriate environmental parameters required for a high yield of crop production will be implemented. Hence, the remote user and mobile devices will be deployed for communication to notify the agriculturalists of the temperature conditions, as they access information through the internet.

The benefit of WSNs is that SNs can be deployed anywhere a traditional network cannot possibly be implemented (Mathonsi et al., 2018; Ojha et al., 2017; Prabakaran et al., 2011; Shanthi et al., 2019; Al-Turjman, 2018; Krishnan et al., 2019; Kumari et al., 2019; Khamayseh et al., 2018; Chakraborty et al., 2018; Parameswari and Moses, 2019). Furthermore, this will help the agriculturalists to manage the temperature conditions in the agricultural environment using various technologies such as SNs and drones, which will manage and provide signals based on the crop needs, such as soil temperature, sufficient light, warmth, and moisture. Several intelligent traffic management algorithms use prediction-based loading with input parameters, namely: network load, throughput, bandwidth, humidity, radiation, latency, etc., for packet traffic management in WSNs, which have been recommended previously (Tang et al., 2018; Li et al., 2017; de Souza et al., 2016; Sharif et al., 2019; Gutierrez-Estevez et al., 2019). The precision agriculture (PA) decision support system was also implemented as one of the tools which optimize the usage of water fertilizer, and maximize the yield of the crops (Roy et al., 2019; Yost et al., 2019; Zheng et al., 2019; Say et al., 2018; Tamirat et al., 2018; Azevedo, 2019; Lindblom et al., 2017; López-Riquelme et al., 2017; Pallottino et al., 2018). The solutions implemented in farming using wireless sensors include monitoring climate, humidity, pressure, and temperature (Shinghal and Srivastava, 2017; Abouzar et al., 2016; Kiani and Seyyedabbasi, 2018a; Rajput and Kumaravelu,

2019). This research study delineated the traffic congestion that occurs in an agricultural environment, caused by the head-of-line blocking. Such blocking leads to delays, throughput impairment, and packet loss. Therefore, the study will develop an algorithm that will manage traffic and avoid packet congestion to provide proper decision-making using drones in WSNs within the agricultural environment.

Hence, this research study proposed an intelligent traffic routing management (ITRM) algorithm in order to manage the flow of packets. This would avoid congestion in the network while improving the quality of service (QoS) in an agricultural environment. The ITRM algorithm designed by integrating two methods, namely, the machine learning congestion control (MLCC) proposed by (Kamble et al., 2020), and the load balancing routing mechanism (LBRM) proposed by (Cui et al., 2019) in order to manage traffic and avoid packet congestion in WSNs. Such will lessen the packet loss and packet delay during packet transmission, and improve the network throughput within an agricultural environment.

When designing the proposed ITRM algorithm, the study used the following multiple input parameters: network load, throughput, bandwidth, latency, radiation, humidity, intermediate hops, delays, and packet loss for traffic management in WSNs implemented into the agricultural environment.

1.2. Motivation of the study

In conducting this research, researchers are able to direct their attention to learning and gaining more knowledge on implementing WSNs into the agricultural environment. Researchers can then help in solving various problems such as farming resources optimization, decision-making support, traffic congestion, and land monitoring. WSNs are defined as a group of devices known as SNs that work together to form a wireless network. WSNs have challenges of traffic congestion caused by several factors such as low bandwidth allocation, a many-to-one traffic scenario, and head-of-line blocking which leads to delays, throughput impairment, and packet loss. This research study has developed an ITRM algorithm that manages the traffic packets in an agricultural environment, thus avoiding packet congestion caused by head-of-line blocking.

1.3. Problem Statement

A review of the literature based on WSNs in the agricultural environment emphasizing crop production has indicated that wireless networks comprise a large number of SNs. Such are growing every day to collect information within the agricultural environment for monitoring purposes. These networks often experience congestion problems during packet transmission in an agricultural environment. Such is normally caused by a high number of packets being transmitted in wireless

routing nodes in the form of a many-to-one traffic scenario (sensor nodes forwarding packets to a single destination node). This further leads to delays, throughput impairment, and packet loss (Huamei et al., 2019; Liazid et al., 2019; Patel and Patel, 2018; Rahman et al., 2017; Yang et al., 2018; Mathonsi et al., 2019). Packet congestion in WSNs happens when there is low bandwidth allocation for routing packets, low latency (packet speed in a channel), and too many packets transmitted through a network simultaneously (Kaur and Singhai, 2019; Patel and Patel, 2018). The use of adaptive control packet frequency and a data-rate method was proposed by (Kaur and Singhai, 2019) to overcome packet congestion during packet transmission in a network. This was accomplished by selecting the channel condition, depending on the transmission nodes and mobility. Furthermore, the authors stated that this method enables the nodes to adjust their data rate, depending on the current packet transmission speed from different nodes within the network.

This research study focuses on head-of-line blocking which is caused by a many-to-one packet routing that occurs in an agricultural setting when the first packet holds up a line of packets during transmission. This type of congestion is noted when multiple packets are waiting to be transmitted to their destination node, which further leads to high packet loss and packet delay. As a result, WSNs in an agricultural environment continue to experience poor network throughput and QoS. This

research study noted that there are exiting traffic management algorithms such as the artificial neural network-based algorithm (ANNA), the priority-based congestion control (PCC), and the traffic packet-flow control (TPFC) implemented into WSNs to overcome the packet congestion problem (Chen et al., 2017; Yang et al., 2018; Esguerra et al., 2017). Hence, the ITRM algorithm is proposed to minimize the packet loss and packet delay; and to improve network throughput in WSNs within an agricultural environment.

1.4. Research Questions

The main question reads as follows: How could one develop an algorithm that will reduce packet congestion caused by head-of-line blocking, thus managing network traffic in WSNs within an agricultural environment?

In order to answer the above main research question and provide a solution to the identified problem, the study adequately answered the following sub-questions:

Sub-Questions

1. What are the current algorithms used for traffic management in WSNs within an agricultural environment?
2. How can the proposed ITRM algorithm be designed to reduce traffic congestion in WSNs within an agricultural environment?

3. How will the proposed ITRM algorithm be implemented to achieve the reduction of traffic congestion in WSNs within an agricultural environment?

4. What is the effectiveness of the proposed ITRM algorithm compared with the current algorithms?

1.5. Aim and Objectives of the study.

The main aim was to develop an ITRM algorithm in order to avoid packet congestion caused by head-of-line blocking, thus managing traffic in WSNs within an agricultural environment.

The research study accomplished this by implementing the following technical objectives:

1. To identify the current algorithms used for traffic management in WSNs within an agricultural environment.

2. To design an ITRM algorithm that reduces traffic congestion in WSNs within an agricultural environment.

3. To implement the proposed ITRM algorithm in order to reduce traffic congestion in WSNs within an agricultural environment.

4. To evaluate the efficiency of the proposed ITRM algorithm by comparing it with current algorithms.

1.6. Research Statement

This research study postulates that the adaptivity of an ITRM algorithm to changes in network conditions such as congestion and user preferences, based on packet transmission, will lead to reduced ranking abnormality, minimizing erroneous network selection, packet loss, and packet delays. Consequently, there must be assurance of optimal network selection, while balancing the trade-offs between network conditions, packet traffic, and QoS requirements.

1.7. Research Methodology

In order to achieve the main objective of this research, this research study adopted an experimental methodology. The methods used are given below:

1.7.1. Literature Review

A comprehensive literature study of related works was conducted in order to help this research study to understand the opinions and views of various other scholars, academics, and authors in the field of WSNs. Journals, books, conference proceedings, and other internet sources were used to gain a better understanding of other researchers. Information collected from the source was analysed, and thereafter, findings were discussed.

1.7.2. Modelling

The ITRM algorithm was designed and developed using mathematical models for the strategy on implementing the proposed algorithm. Besides that, mathematical models are sets of equations that take into account many factors which represent a phenomenon. The design algorithm was achieved by effectively assimilating (MLCC and LBRM) in order to manage traffic and avoid congestion while reducing packet delay, and packet loss; and improving network throughput and QoS during packet transmission in WSNs. Input parameters that were used during the design and development of the proposed ITRM algorithm are the humidity sensor, bandwidth, temperature sensor, network load, latency, delay, and throughput.

1.7.3. Implementation

After designing and developing the proposed ITRM algorithm using mathematical models, a code of the ITRM algorithm was written; thus the effectiveness of the proposed algorithm could be evaluated using a network simulator.

1.7.4. Simulation

A code of the proposed ITRM algorithm was evaluated using Network Simulator-2 (NS-2). An NS-2 simulation was used in this research study

because it presents a widespread simulation environment for network applications, traffic models, protocols, and various network types. NS-2 is an open source code and is freely obtainable on the internet. NS-2 is considered helpful in studying and examining the dynamic nature of WSNs, because it is a simple, event-driven simulation tool. Furthermore, NS-2 allows for add-ons, modification of protocols, and implementation of multiple interfaces on a mobile node. This research study presents the alignment of research questions, technical objectives, and research methodology using Table I.

Table 1.1: Research Questions, Technical Objectives, and Research Methods

Research Questions	Technical Objectives	Research Methods
What are the current algorithms used for traffic management in WSNs within the agricultural environment?	To identify the current algorithms used for traffic management in WSNs within the agricultural environment.	Literature Review
How can the proposed ITRM algorithm be designed in order to reduce traffic congestion in the agricultural environment?	To design an ITRM algorithm that reduces traffic congestion in the agricultural environment.	Modelling
How can the proposed ITRM algorithm be implemented in order to achieve the reduction of traffic congestion in the	To implement the proposed ITRM algorithm in order to reduce traffic congestion in the agricultural environment.	Implementation

agricultural environment?		
What is the effectiveness of the proposed ITRM algorithm compared with the current algorithms?	To evaluate the efficiency of the proposed ITRM algorithm compared with the current algorithm.	Simulation

1.8. Significance of the study

This research study is based on the research International Telecommunications Union – Telecommunication (ITU-T), the IEEE 802.11 standard, and the international organization for standardization (ISO) 9001 model. ITU-T was used because it defines how telecommunication networks operate and interwork. The IEEE 802 standard was used when designing network architectures and developing communication models. The ISO 9001 employed to ensure quality during the algorithm design phase, the implementation phase, the testing phase, and the inspection phase. The ISO 9001 guidelines require that all phases are planned, controlled, and verified.

1.9. Contributions of the Thesis

The contributions of this research study compared with other related algorithms are structured as follows:

1. An ITRM algorithm that managed the traffic packets and avoided congestion while improving QoS in WSNs within an agricultural environment.
2. The ITRM algorithm that selected the most cost-effective path whenever packets were to be transmitted from one sensor node (SN) to another.
3. The proposed ITRM algorithm that gave different priorities for traffic flow in WSNs within an agricultural environment.

1.10. Ethical Considerations

No ethical clearance was required for this research study. This is because the data used in the study did not involve either directly or indirectly, any human and animal information; data comprised purely a computer algorithm and simulations.

1.11. Structure of this Dissertation

The remainder of this research study is structured as follows:

Chapter 2 presents the literature review which includes: WSNs overview, the design of WSNs, classification of WSNs, application of WSNs, routing and traffic modelling protocols in WSNs, congestion in WSNs, mechanisms used in WSNs congestion,

related work, together with the overview of wireless network simulators, NS-2 environment, and the chapter summary. Chapter 3 presents the methodology, which includes the system design and architecture of the proposed algorithm.

Chapter 4 presents the system implementation of the proposed ITRM algorithm. The computer simulation set-up and technologies used to implement the proposed IRTM algorithm are also presented in Chapter 4. In Chapter 5, this research study presents the tested and analysed computer simulation results with respect to three performance metrics considered in our study: packet loss, end-to-end delay, and network throughput. Chapter 6 presents the research study conclusion. The chapter summarizes the contributions of the research, and provides direction for future work.

1.12. Summary

In this chapter the background of WSNs, the motivation, and the mechanism that outlines the importance of implementing WSNs into an agricultural environment, were discussed. Furthermore, the challenges of packet congestion during packet transmission in WSNs from various source nodes to a destination node were also debated. However, these networks experience an increase in packet volume, which results in network congestion. Therefore, proposes the ITRM algorithm to curb the above-mentioned challenges, and improve the network performance of WSNs.

This research study has defined a set of research questions, which were answered by implementing some technical objectives. The experimental methodology adopted and used the following methods: literature review, modelling, implementation, and simulation to address the identified research problem. Furthermore, the research study discussed the contributions of this thesis. In the next chapter, the research study presents a comprehensive literature review and related work.

Chapter 2: Literature Review

2.1. Introduction

WSNs are self-configured, which allows nodes to communicate together through radio signals (Ranganathan et al., 2019; Komguem et al., 2017; Ashraf et al., 2016; Sadouq et al., 2018; Verma et al., 2020; Queiroz et al., 2017; Deborah et al., 2018; Rampatel and Baskar, 2018). WSNs continue to experience volume increase of various sensing devices competing for the available services and resources within the network environmental field. Furthermore, WSNs consist of several sensors positioned together to provide better communication when transmitting sensed data from one node to another. This research study contains a comprehensive literature review. The remainder of Chapter 2 is organized as follows: In Section 2.2, the WSNs overview is presented. In Section 2.3, the design of WSNs is provided. The classification of WSNs is discussed in Section 2.4. In Section 2.5, the application of WSNs is confirmed. In Section 2.6, the routing and traffic modelling protocols in WSNs is discussed. In Section 2.7, congestion in WSNs is presented. The mechanism used in WSNs congestion is considered in Section 2.8. In Section 2.9, related work is outlined. In addition, this research study provides an overview of wireless network simulators in Section 2.10; the NS-2 environment in Section 2.11 is discussed. Lastly, in Section 2.12, the chapter summary is presented.

2.2. Overview of Wireless Sensor Networks

WSNs are defined as a group of devices known as SNs (wireless sensors) that work together to form a wireless network (Darabkh et al., 2019; Hassan et al., 2017a; Krishnan et al., 2018; Midi et al., 2017; Irish et al., 2019; Mathonsi et al., 2019; Tshilongamulenzhe et al., 2019). These sensors transfer information from the SN (node that gathers information from the agricultural environment) to the sink node (node that receives information from SN) using the transmission channel provided (see Figure 2.1 below).

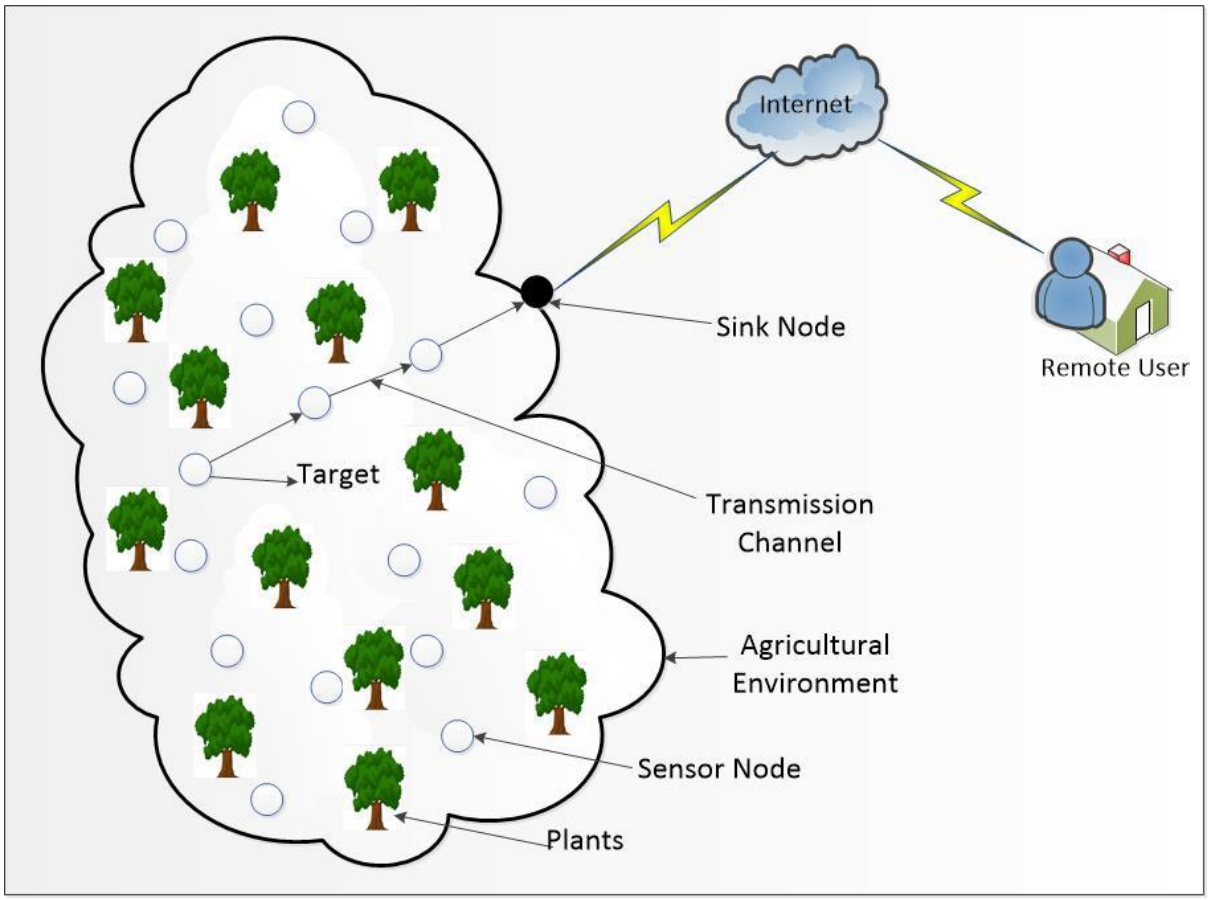

Figure 2.1: Wireless sensor network structure (Irish et al., 2019)

Figure 2.1 shows that SNs can be either mobile or static (Lamaazi et al., 2018; Xie et al., 2017; Irish et al., 2019). These SNs have the capability of sensing and transmitting information. Furthermore, all SNs share a single communication channel (transmission channel) through multiple access protocols, for example, random access protocols (protocols used for a transmitting node, to transmit always at the full rate of the channel); and a media access control protocol (protocol used for coordinating the access from active nodes).

2.3. Design of Wireless Sensor Networks

WSNs are designed using a set of nodes (wireless nodes) equipped with sensors, such as environmental nodes, source and sink nodes, and a transmission channel. When these nodes are connected so as to transmit packets, they can face the challenge of traffic congestion within the environment. Therefore, this research study outlines under 2.3.1 the most fundamental factors that influence the design of WSNs implemented into an agricultural environment.

2.3.1. The fundamentals that influence the design of WSNs within an agricultural environment.

Certain fundamentals influence the design of WSNs in an agricultural environment. These are listed below (Nascimento, 2019).

a) Scalability – is the ability of network nodes implemented into an agricultural environment to change the number of the nodes in order to meet a farmer's needs (Elsmany et al., 2019; Lattanzi et al., 2018; Volnes et al., 2019). Hence, the new design structure should be able to work and operate with high density (shown by the number of nodes in the area) of WSNs in the agricultural environment. Such a density can range from some SNs to several hundred within the network environment.

b) Topology − the arrangement of high numbers of nodes needs high care of topology maintenance in the network. This is because the nodes are susceptible to numerous failures, which makes the maintenance a challenging task (Farhat et al., 2019; Morais and Mateus, 2019).

c) Fault tolerance – is the ability to retain the sensor network operating without any interruption when some nodes in a network fail (Shyama and Pillai, 2019; Kaiwartya et al., 2017; Mohapatra and Rath, 2019). The fault-tolerance level required by sensor networks depends on the request, e.g., whether the SNs are organized in an agricultural environment to monitor the humidity and temperature levels; or whether the condition (level) of the fault tolerance is low and flexible, the SNs organised in this environment not being easily susceptible to damage or noise interference.

d) Production cost − the rate of the node should be minimized, since sensor networks can consist of up to thousands of nodes; so a small extra charge for each node will be a large cost for the network which is implemented into agriculture (Sun and Halgamuge, 2019; Lara-Nino et al., 2018).

2.3.2. WSNs topologies within an agricultural environment

WSNs communicate in different ways depending on the environmental deployment (Watt et al., 2019; Khasawneh et al., 2018; Ndiaye et al., 2017). There are different types of topology that are implemented into an agricultural environment. Some examples are outlined and presented below:

i) Star topology – nodes (remote nodes) are connected to a centralized device (base station) to communicate with one another (see Figure 2.2).

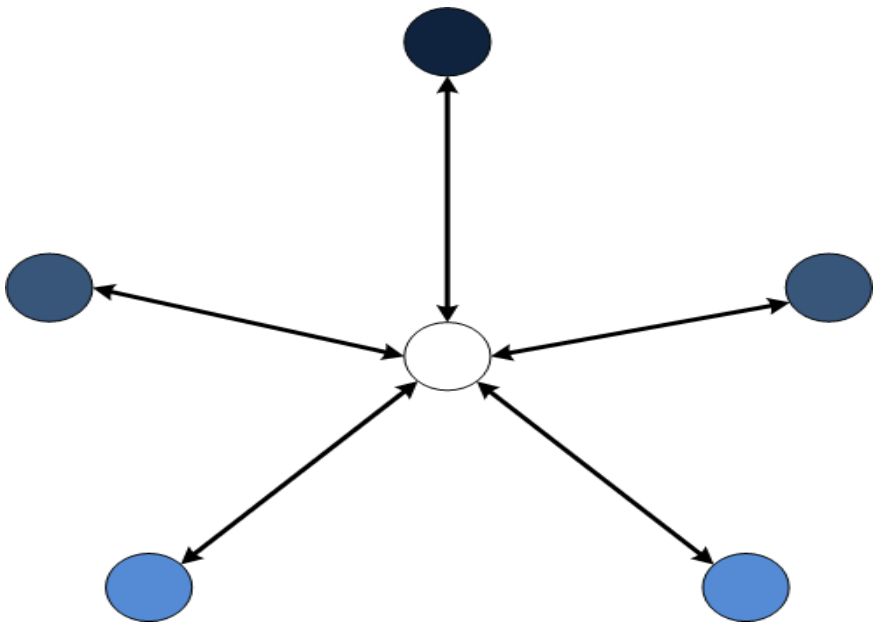

Figure 2.2: Star topology of WSNs

Packets are sent through the base station from the remote node before reaching the destination or other nodes as implemented into the WSNs (Lipowski and Efe, 2019; Balabanov et al., 2016; Gnad et al., 2017; Ma et al., 2018; Servajean and Misson, 2019). Communication between the remote nodes is not permitted. Hence, Star topology is very simple. It can minimize power consumption at the remote nodes, resulting in low latency communications between base station and remote nodes. The drawback of this topology in an agricultural environment is that it has a limited maximum transmission range between the devices and gateways.

ii) Mesh topology – is the topology that gives growth to the network connectivity and load-balancing traffic within the agricultural environment. Therefore, the node in mesh topology within the agricultural environment transmits packets to other nodes. Based on the communication range the node chooses the most cost-effective path (see Figure 2.3) (Kikinzon et al., 2018; Zainuri et al., 2019).

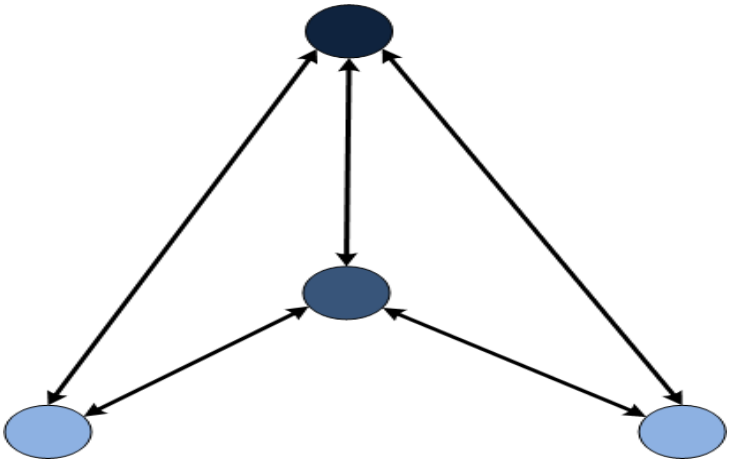

Figure 2.3: Mesh topology of WSNs

This is known as multi-hop communication, which helps to forward packets from one node to a node out of its range, per an intermediate node. The advantage of this topology is that when there is node failure, the remote node can still transmit its packets. The node can use another node in its range to forward the packets to the destination node. The drawback of this topology in the agricultural environment is that the node uses a high-power consumption.

iii) Hybrid topology – is a combination of various types of topology, which include star and mesh to provide a robust and versatile communication network within an agricultural environment (see Figure 2.4) (Sun et al., 2018; Huber, 2019). It is easy to increase the topology size within the agricultural environment to more effective and reliable topology. The drawback is that the cost of the infrastructure is very high.

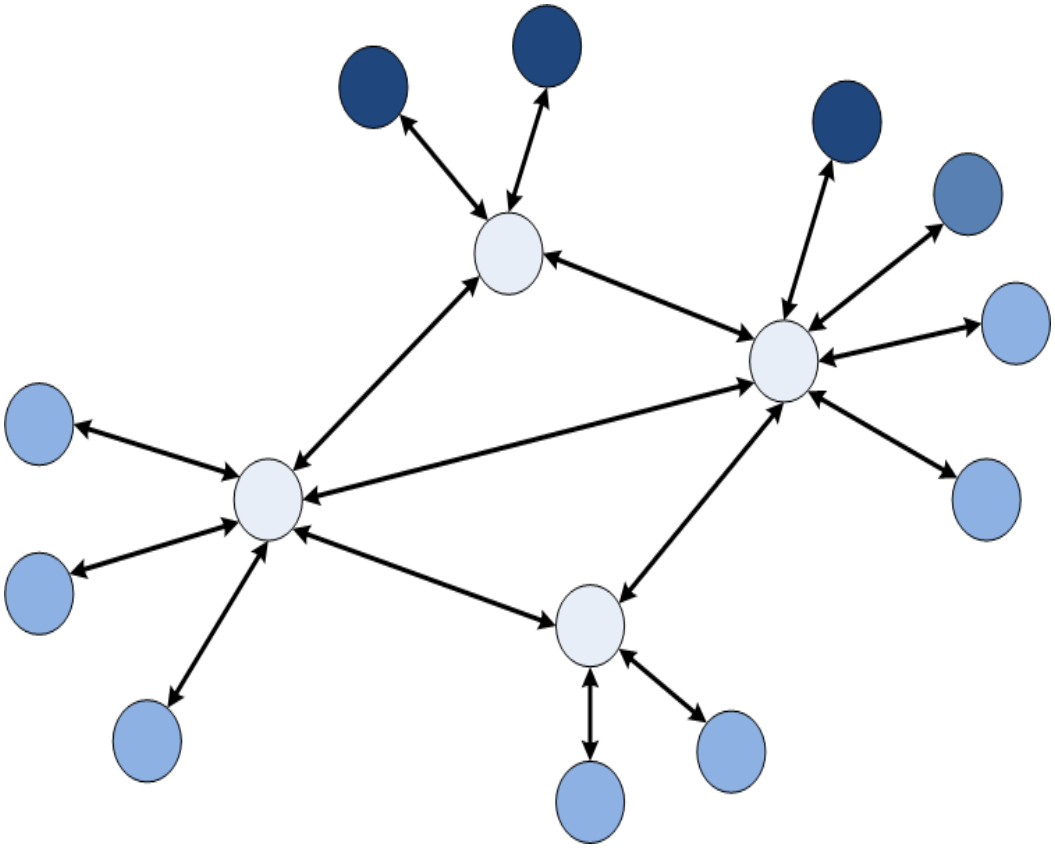

Figure 2.4: Hybrid Star-Mesh topology of WSNs

2.3.3. IEEE standards used in agricultural environment for WSNs

The Institute of Electrical and Electronics Engineers (IEEE) 802 standards are the most important standards for wireless networks; these are used in an agricultural environment (Fahmi et al., 2017; Sharma et al., 2019; Inzillo et al., 2018). In this research study, the IEEE standards will assist in monitoring various environmental parameters within the agricultural area, mentioned in Chapter 1. This standard also assists in the execution of packets within the WSNs. Such allows the packets to be distributed amongst each node within the agricultural environment. IEEE standards provide a common wireless structure in the form of technology usage,

implementation, and interaction within an agricultural environment. This includes various standards, for instance, the 802.11 standard in local area networks, the 802.16 standard in metropolitan networks, and the 802.11 standard in wide area networks. These IEEE standards further provide the network scalability and transactions within an agricultural environment (Devi et al., 2019; Lin et al., 2020; Yusuf et al., 2019). The IEEE standards allow networks to carry variable-size packets within WSNs (Buruganahalli and Vissamsetty, 2017; Assasa et al., 2018). The committee of IEEE802 has developed many related standards ranging from IEEE.802.1 to IEEE802.25 (see Figure 2.5).

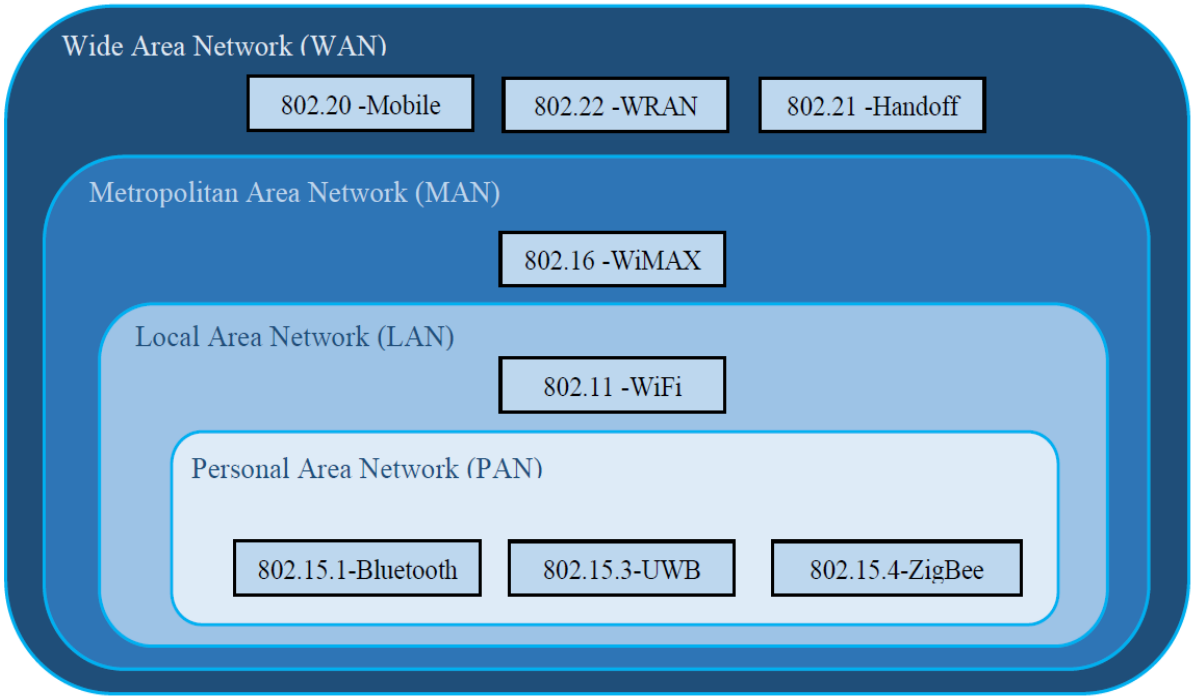

Figure 2.5: Different wireless network technologies IEEE802 standards (Inzillo et al., 2018)

Figure 2.5 shows that wireless networks have multiple standards based on IEEE 802. The Wireless Fidelity (Wi-Fi) 802.11 standard is a technology that uses 2.4GHz and 5.8GHz for radio bands in a local area network (LAN) which allows nodes to communicate together within an agricultural environment (Kumar et al., 2017; Bouhafs et al., 2019; Perwej, 2017; Mustofa et al., 2018; López-Pérez et al., 2019; Maksutov et al., 2019). Furthermore, any device which is compatible with this standard in an agricultural environment can exchange and transfer data wirelessly over the network, giving rise to high-speed internet connections.

The personal area network (PAN) is a network for devices (computer, telephone, and personal digital assistants) which are implemented close to one person (within a range of metres) (Redding, 2017; Gonzalez, 2016; Parmar and Desai, 2016; Hassan et al., 2017b; Naqvi et al., 2019; Baker and Lathrop, 2018; Diwane et al., 2019). In this research study, this network is used in the monitoring room. Examples of technologies for this topology are IEEE802.15.1 (Bluetooth), IEEE802.15.3a (Ultra-Wideband), and IEEE802.15.4 such as ZigBee: refer to Figure 1.4. These standards are used in WSNs for communication which is further implemented into an agricultural environment.

The proposed standard for WSNs within an agricultural environment is IEEE 802.15.4, which further focuses on low cost of deployment, low complexity, and low power consumption. The IEEE802.15.4 defines the characteristics of the two lower

OSI layers (physical layer and MAC layer) (Bhaskar and Mallick, 2015; Postolache, 2017; Jiang and Liu, 2018, Kim and Tran-Dang, 2019; Kalla et al., 2020; Elappila et al., 2020;Rasouli et al., 2019). The IEEE802.15.4 physical layer supports various frequency bands for communication: 2.4GHz (worldwide), 915MHz (USA), and 868MHz (Europe) (Al-Sarawi et al., 2017; Saadeh et al., 2017; Dong et al., 2016; Muñoz et al., 2018; Mohammadmoradi et al., 2018; Soni et al., 2019; Daiya et al., 2020; Bhushan and Agrawal, 2020; Lattanzi et al., 2020; Augustin et al., 2016). The characteristics of the physical layer in IEEE802.15.4 are outlined in Table II. The TX (means transmit) power is the required power for router transmission in WSNs. Therefore, the smallest signal power that the node is able to detect is sensitivity, and channels refer to the number of channels available.

Table 2.1: Characteristics of IEEE802.15.4 Physical layer (Rasouli et al., 2019)

Frequency band	TX Power (mW)	Sensitivity (dBm)	Channels
902.0 – 928.0 MHz	50	-100	10
868.0 – 868.6 MHz	315	-112	1
2.4 – 2.4835GHz (IEEE802.15.4)	63.1	-100	16
2.40 – 2.70GHz	50	-102	14

(ZigBee)			

The ZigBee standard is constructed on IEEE802.15.4, and defines the higher layer protocols implemented into an agricultural environment (Femmam and Benakila, 2016; Seyedolhosseini et al., 2017; Shyama and Pillai, 2019; Zainuri et al., 2019). The ZigBee standard is implemented into mesh topology to form networks using thousands of nodes. Moreover, there are three types of node in the ZigBee standard used in an agricultural environment. There is the ZigBee coordinator, a device that initiates the network, stores information, and can bridge networks. The ZigBee router is used to link groups of nodes together and to provide multi-hop communication. The end device consists of sensors which communicate with the router to transmit information to the coordinator.

2.4. Classification of Wireless Sensor Networks

WSNs have been categorized in different forms based on their function when implemented within the environment, such as in either an agricultural environment, the military, at home, or in the health-care environment (Umar et al., 2018).

a) Static or mobile network: SNs are static in an agricultural environment; and some applications need mobile nodes (Xie et al., 2019; Umar et al., 2018). Therefore, mobile nodes in an agricultural environment can be positioned in any situation

and can manage any rapid changes that may happen in network topology (Memon et al., 2019). Furthermore, the wireless performance can be improved by using a mobile sink rather than a static sink. The selection of a convenient radius for the mobile sink, and choosing a proper duty cycle for nodes, will achieve higher energy efficiency within the environment.

b) Single-sink and multi-sink networks: based on the single-sink network in an agricultural environment, the SNs transmit their sensed information to one sink which is nearly inside the sensed environment (Chauhdary et al., 2019; Umar et al., 2018). The multi-sink network SNs in an agricultural environment transmit their information to the closest sink. This can make the traffic more reliable and balanced, since it can reduce the number of hops (see Figure 2.6) (Guercin, 2019).

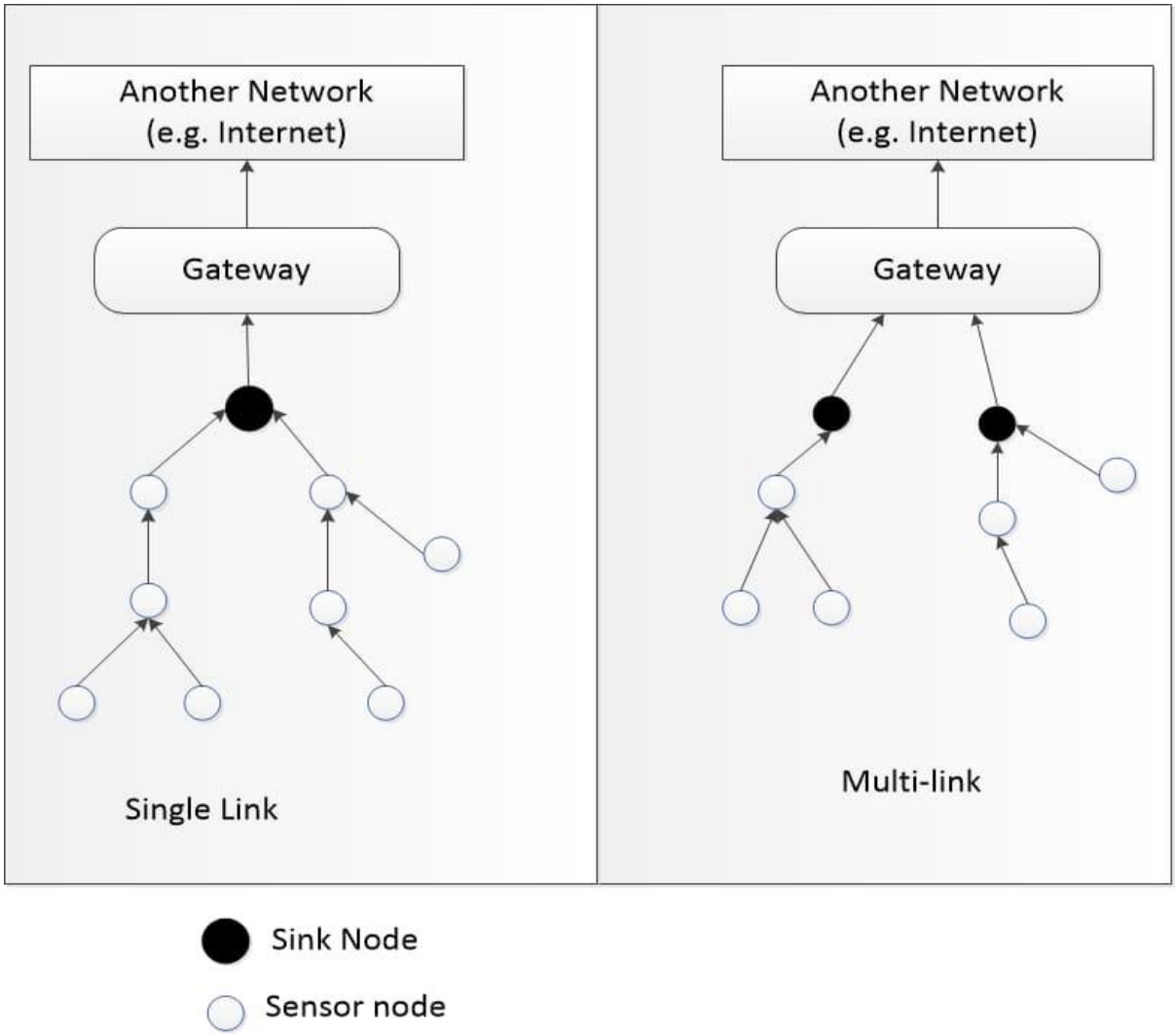

Figure 2.6: Single-sink and multi-sink networks (Chauhdary et al., 2019)

c) Single-hop and multi-hop networks in an agricultural environment: the single-hop network comprises nodes which transmit in one hop their sensed information directly to the sink node within an agricultural environment (Tripathi et al., 2019). Hence, this network is easy to design and may consume a great deal of energy because of its radio range which is large (Mitra and Sharma, 2018). Such may increase packet collision at the sink within the environment: all nodes which are connected may try to send information simultaneously. A multi-hop network within

an agricultural environment consists of nodes which transmit information to the sink through many different intermediate nodes (Tripathi et al., 2019). These intermediate nodes route the data to the sink and may perform data processing to eliminate redundant data, hence reducing the quantity of the data traffic. The power efficiency of the network is thus improved (See Figure 2.7 below).

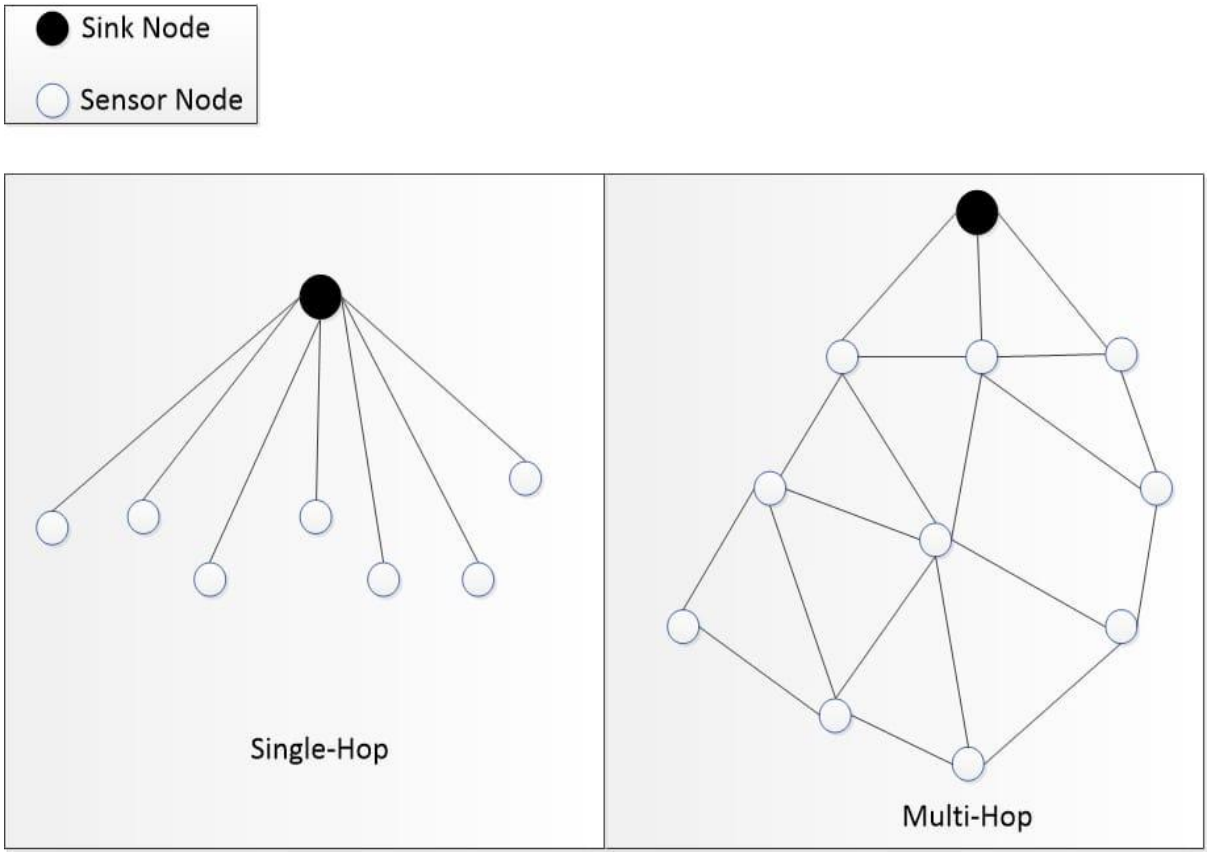

Figure 2.7: Single-hop and multi-hop networks (Konorski and Szott, 2019)

The above figure shows that the single-hop network is more suitable for applications in small sensing areas with a small number of nodes. Conversely, the multi-hop network can be used for a wide range of applications in which the number of nodes is large.

d) Deterministic or non-deterministic network: These network types depend on the deployment of the SNs within the agricultural environment. In the deterministic networks, nodes positions are pre-planned within the agricultural environment (Boukerche and Sun, 2018). In the non-deterministic networks, the deployment is not pre-planned because of the hostile environment (Yao, 2019). Moreover, a non-deterministic network is more scalable and flexible. It does not need planning work, but leads to increased complexity because the nodes require the ability to organize themselves within the agricultural environment (See Figure 2.8 below).

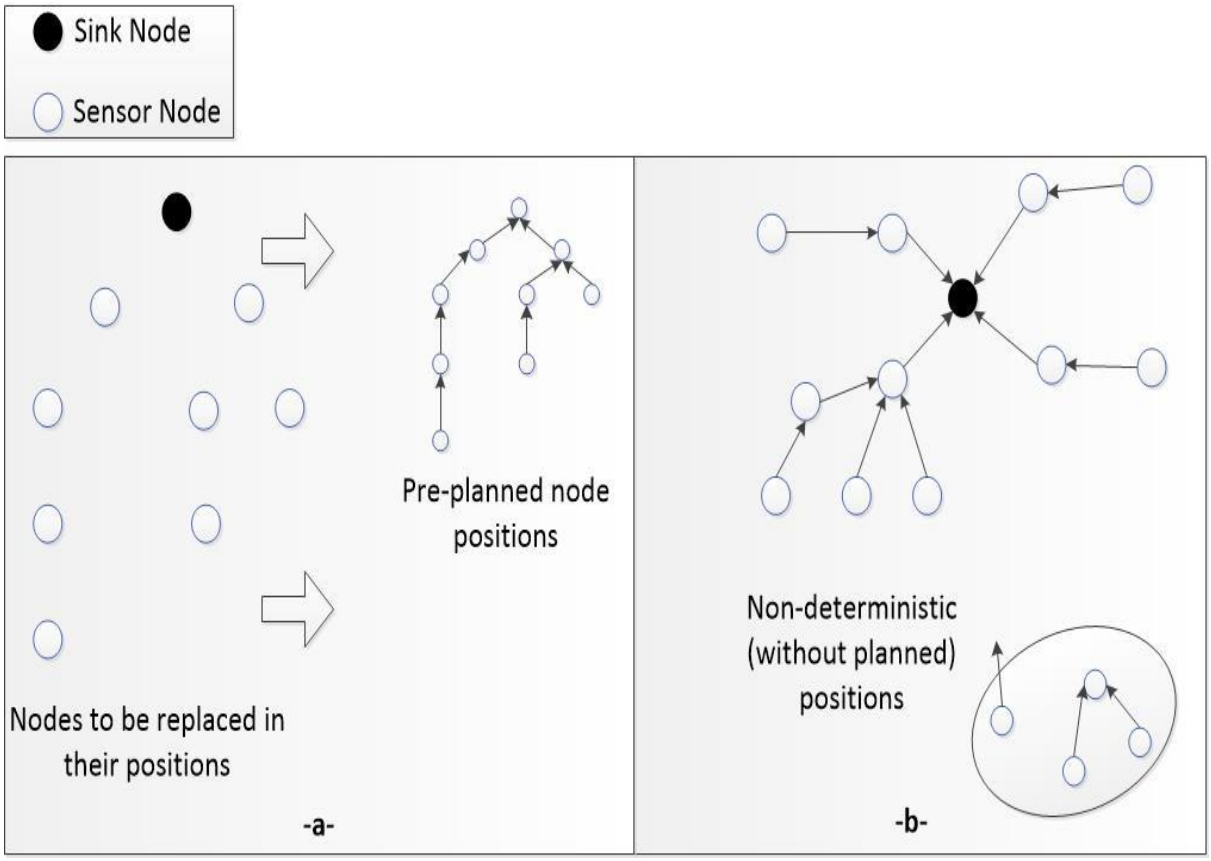

Figure 2.8: Deterministic and non-deterministic networks (Schütze et al., 2018)

2.5. Routing and Traffic Modelling Protocols in WSNs

There are various applications of WSNs which use routing protocols to improve their performance demand within a network environment (Singh et al., 2018b; Elappila et al., 2018; Wang et al., 2019; Hamzah et al., 2019). In addition, in this research study, the concentration is on mitigating WSN congestion by implementing another method in the event of congestion within the environment field; therefore, a review of important WSN routing protocols is a good starting point. In this section, details of some of the important traffic modelling protocols existing in WSNs are discussed.

2.5.1. Routing protocols

Routing protocols specify how routers communicate with one another by sharing information from source to destination within a reliable and efficient energy routine in order to increase the lifetime and improve the overall performance of the network. There are various types of routing protocols which include both static and dynamic routing protocols. Dynamic routing protocols are used in large networks environment so that routers can share information about the network with other routers. This allows them to select the best path for reaching a destination. Figure 2.9 illustrates the various characteristics of dynamic routing protocols.

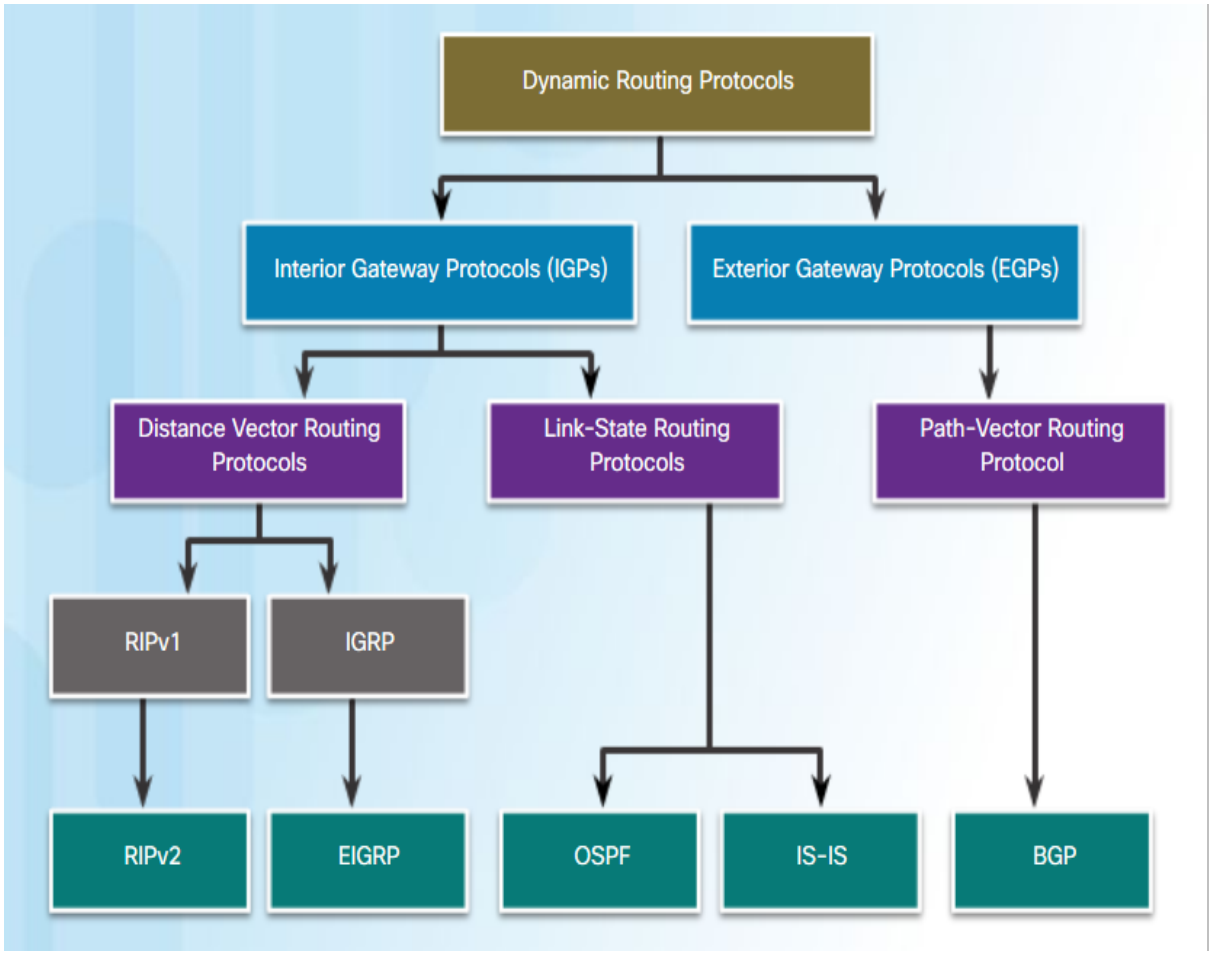

Figure 2.9: Characteristics of dynamic routing protocols (Balasas et al., 2019)

The routing protocols on WSNs have the following features (Bhushan and Sahoo, 2019; Al-Turjman, 2019b,; Agarkhed et al., 2017; Yan et al., 2016; Guleria and Verma, 2019; Onthachi and Jayabal, 2018; Elhoseny and Hassanien, 2019):

- SNs do not have internet protocol (IP) addresses as in the traditional networks (Froiz-Míguez et al., 2018; Rahmani et al., 2018; Mermoud et al., 2019; Heđi et al., 2017). Therefore, IP-based routing protocols cannot be applied to WSNs.
- The design of protocols must be scalable.

- Protocols should manage the communication among many nodes and forward the data to the destination.
- The protocol should meet the resource constraints of the node (limit power, low-bandwidth, low storage) (Araújo et al., 2018; Farhan and Kharel, 2019; Thubert et al., 2019; Alhaidari and Alqahtani, 2020; Bello et al., 2017; Dizdarević et al., 2019).
- Issues such as efficiency, fault tolerance, fairness, and security, should be achieved under the design of the network protocols.

Static routing protocols demand manual configuration and selection of a network route, usually managed by the network controller (Verma and Bhardwaj, 2016; Al-Humidi and Chowdhary, 2017; Hossain and Akter, 2019; Baveja et al., 2018; Manzoor et al., 2020; Alouache et al., 2019). Hence, static routing protocols are implemented in situations in which the network parameters and environment are expected to remain constant. The static routing is only optimal in a few situations within a network environment.

2.5.2. Traffic modelling protocols

Traffic modelling is a method that manages the network bandwidth, which delays some or all packets in bringing them into compliance with the desired traffic profile (Rubin et al., 2019).

The traffic modelling method is used to:

- Optimize or guarantee performance such as the design (Rubin et al., 2019).
- Improve latency, e.g., by giving the accurate measure or amount of time that it takes to send a request for resources (Rubin et al., 2019).
- Increase usable bandwidth for some kinds of packets by delaying other kinds, e.g., network capacity (Stockman and Coomans, 2019).

2.6. Congestion in Wireless Sensor Networks

The Wireless Sensor Network (WSN) is defined as a group of devices called SNs that work together to form a wireless network (Modieginyane et al., 2018; González-Briones et al., 2018; Anadiotis et al., 2019; Jeong and Lee, 2018; Gbadouissa et al., 2020; Hammoodi et al., 2020; Laouid et al., 2019; Tayyaba et al., 2017; de Oliveira et al., 2018; Thiagarajan, 2020; Tsvetanov et al., 2020). These nodes transmit environmental information from the monitored area to the sink node in one or multiple hops through wireless links communication.

However, due to the resource constraints of WSNs, there are a number of deployed nodes that are an event-driven nature of WSNs (Yogarajan and Revathi, 2018; Erdelj et al., 2017; Al-Turjman et al., 2017; Malavolta et al., 2019; Al-Turjman, 2019a; Mathonsi et al., 2019; Tshilongamulenzhe et al., 2019; Elhabyan et al., 2019; Priyadarshi et al., Tabassum et al., 2020; Saraswathi et al., 2020). Hence, there is

many-to-one communication, and a high traffic of SNs. WSNs in some applications like event-driven applications face significant challenges due to a huge amount of transmitted data from the nodes in the event place. This large amount of data might lead to traffic congestion (Aravamudhan et al., 2019; Kurabayashi et al., 2018; Barmpounakis and Geroliminis, 2020; Nikokheslat and Ghaffari, 2017; Serrano et al., 2019; Mamaghani and Jamali, 2019; Mansouri et al., 2019).

Furthermore, this can cause a breakdown such as a decrease in the network throughput and energy efficiency, packet loss, increased delays, and reduction of network lifetime. The dropped packets must be retransmitted, which, in turn, means that more energy will be consumed; these mentioned problems will impact the QoS (Mothku and Rout, 2019; Holakouei and Venkatasubramanian, 2019; Mirzaeinia et al., 2020; Shpiner et al., 2019; Smirnov, 2018; Rajapakse, 2017; Sharma and Murthy, 2016; Patwardhan and Kulkarni, 2016; Al-Roubaiey et al., 2019; González-Briones et al., 2018).

There are various types of WSN congestion: two categories are constructed on the environment (Al-Kashoash et al., 2019; Krishnamoorthy and Vijayarajan, 2020):

- First category: this is based on how packets are lost, which is divided into 2 types, namely: node-level congestion (buffer overflow), and link-level

congestion (see Figure 2.10) (Ouyang et al., 2019; Mehranzadeh et al., 2019; Al-Kashoash, 2020a; Praghash and Ravi, 2019).

i) Node-level congestion refers to the packets that cause the buffer overflow on a specific node within a network. Therefore, the overflow that causes the congestion in a network occurs when the packet arrival rate is higher than packet service time (Maatouk et al., 2019b; Rezaei et al., 2019; Coyac-Torres et al., 2020; Vuletić et al., 2020). This type of congestion causes packet loss and increasing queuing delay. The packet loss must be retransmitted, which decreases the network lifetime (Farhan et al., 2018; Ayati et al., 2018; Peng et al., 2020; Zhang et al., 2019).

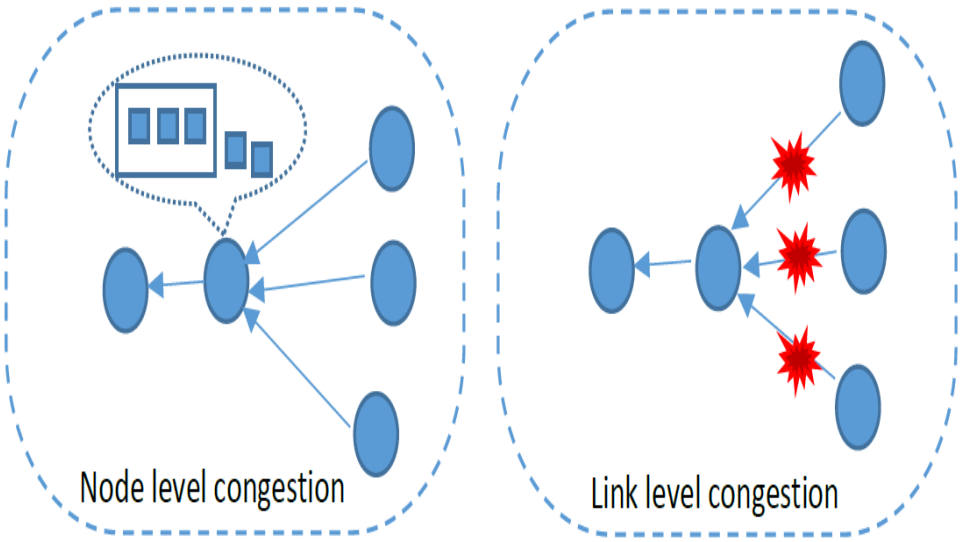

Figure 2.10: Common Congestion in WSNs (Chydzinski and Samociuk, 2019)

ii) Link-level congestion: This type of congestion occurs when multiple active SNs share the same wireless channel; each one tries to send

packets in the same transmission medium. A collision might occur, and the transmitted packets may fail to reach the destination node because of the collision between the packets. This type of packet collision increases the packet service time, and decreases the link utilization (Nasrallah et al., 2019; Ikegawa, 2019; Nguyen et al., 2018; Qureshi et al., 2020; Tajiki et al., 2018; Alqahtani, 2019; Pushpan and Velusamy, 2019).

- Second category: this is based on the congestion place (hotspot) within the network. There are three typical hotspot situations, as listed below (Caliskan and Sokullu, 2019; Praghash and Ravi, 2019; Bhattacharjee et al., 2018; Shafiei and Sattari-Naeini, 2018).

  i) Source hotspot: this type of hotspot is created around the occurred event when packets are transferred from source nodes to sink nodes whose sensing range cover the event spot; see Figure 2.11 below.

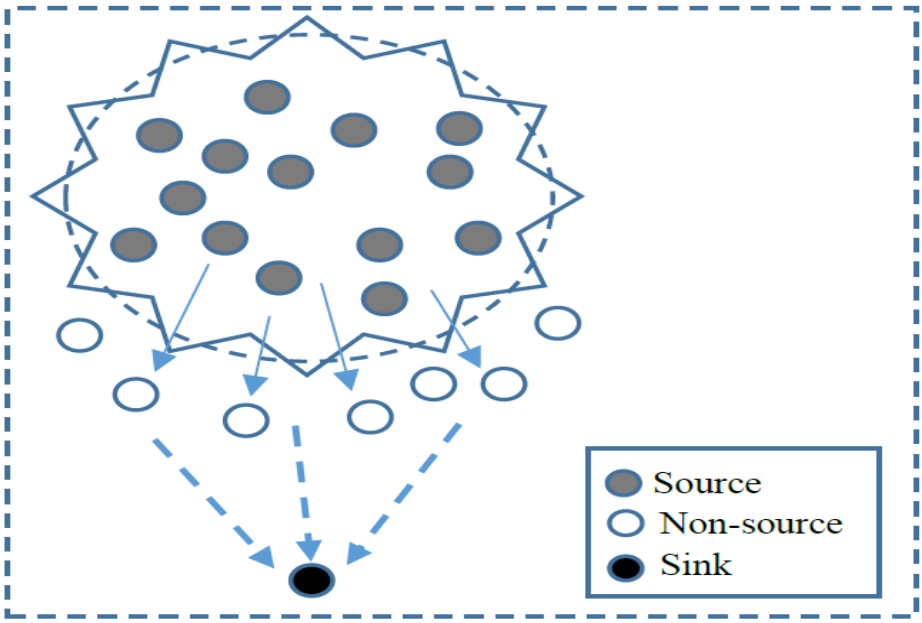

Figure 2.11: Source hotspot event (Guerriero et al., 2019)

Figure 2.11 shows the different nodes sending control messages from congested nodes to source nodes, which will be effective in controlling the traffic rate, and in changing the sending route.

ii) Intersection hotspot: the traffic intersection can arise in the network because of the presence of numerous sinks, see Figure 2.12 below (Zhang and El Kamel, 2018; Mohebifard and Hajbabaie, 2019). The intersection nodes can become congested hotspots due to overflow of the cumulative traffic load.

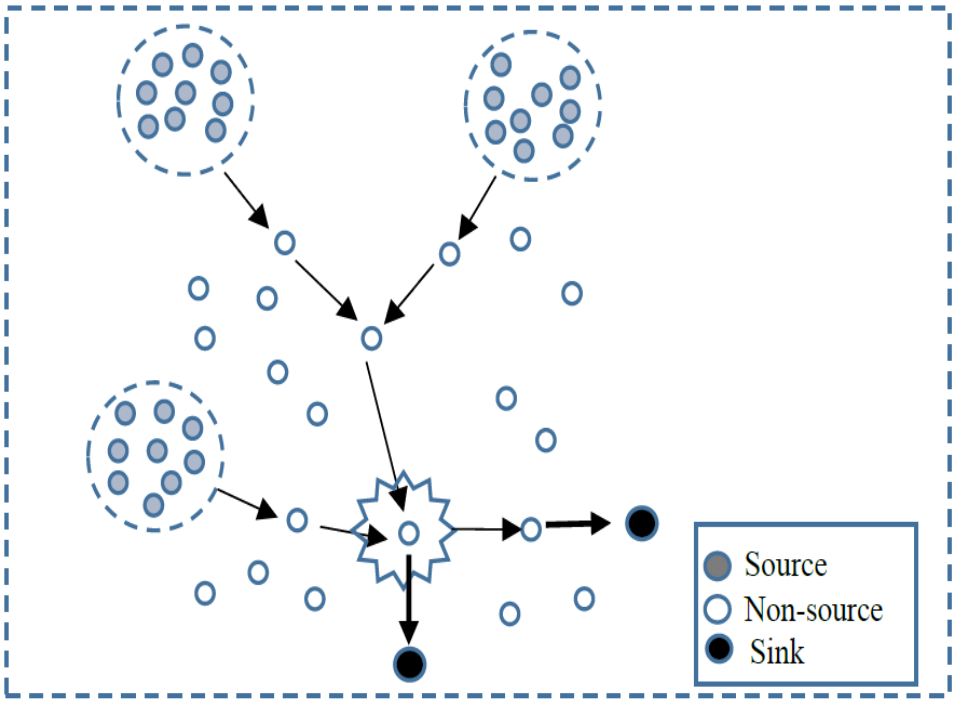

Figure 2.12: Intersection hotspot with numerous sinks (Guerriero et al., 2019)

Figures 2.11 and 2.12 show the types of congestion that have a negative effect on network performance, such as network throughput that can decrease; time delay that can also increase throughput and energy consumption. Therefore, to enhance the network performance and manage the traffic properly, an appropriate algorithm should be developed to control the congestion which arises, such as packet congestion and packet loss. Hence, the ITRM algorithm is developed to manage packet traffic and to avoid congestion in a network.

2.7. Mechanism used in WSNs Congestion

There are various mechanisms used for traffic management in WSNs congestion; these are divided into three phases: congestion detection, congestion notification,

and congestion mitigation (Avatefipour and Sadry, 2018; Doibale and Kurundkar, 2019).

2.7.1. Congestion detection

The presence and place of congestion in WSNs are detected through the process of congestion detection. The detecting of WSN congestion uses various parameters for traffic management protocols, such as buffer occupancy, packet service time and channel load (Singh et al., 2018a; Rukmani and Nagarajan, 2019; Speight, 2019; Al-Kashoash, 2020b; Masdari and Naghiloo, 2017; Kandris et al., 2017; Tonnemacher et al., 2018).

- Buffer occupancy: this is also identified as queue length, because the incoming packets are frequently stored in SN buffers (Gambhir and Kathuria, 2018; Gelenbe and Abdelrahman, 2018; Babayo et al., 2017; Paranjape et al., 2016; Rohit and Eswarathevar, 2019; Maatouk et al., 2019a), hence, the congestion in WSNs indicated through the occupancy of the buffer. In many algorithms implemented, congestion is identified when buffer occupancy of the SN exceeds a constant edge for queue length (Sunitha et al., 2018; Showail et al., 2016; Gobinath and Tamilarasi, 2019; Sanchez-Iborra and Cano, 2017; Srivastava et al., 2019; Benyahia et al., 2018; Ma et al., 2019; Doibale, 2018; Kotian et al., 2017).

- Packet service time/packet inter-arrival time: Either time method or a combination of the two is used by some protocols to detect congestion in WSNs (Osanaiye et al., 2016; Harkat and Amrouche, 2018; Sciancalepore et al., 2019).
- Channel load: this is one of the parameters used by some protocols when the time for transmission of a packet in the wireless channel exceeds a predefined edge; congestion is then detected (Kaur et al., 2019; Kaur and Malik, 2018; Rajpoot and Dwivedi, 2018; Ahmed and Paulus, 2017).

2.7.2. Congestion notification

On the congestion notification, the upstream nodes (nodes that transfer packets to the congested node) will be informed of the detected congestion; the congested node will notify them either explicitly or implicitly. The notification may be as small as a single bit in the packet header, which is known as congestion notification (Sup et al., 2017; Bahr et al., 2018; Sumathi and Venkatesan, 2016; Bergamasco et al., 2019; Figuera et al., 2019).

- Explicit notification: A notification type occurring explicitly comes about when the control packets are transmitted from the congested node to upstream nodes, informing of the congestion and performing the required action (Nicolaou et al., 2019; Siddiqui et al., 2019; Shah et al., 2017; Parsavand and

Ghaffari, 2018; Prakash et al., 2017; Gholipour et al., 2018; Kumar et al., 2016; Thibaud et al., 2019). While the transmission channel is already congested, sending control packets as notification messages will add more pressure to the congested wireless transmission channel. Therefore, based on these elements, the explicit notification has not been implemented by many congestion algorithms in WSNs.

- Implicit notification: in this notification, there are no extra packets added to the congested network (Benko, 2019; Hinkel et al., 2019; Emesowum et al., 2018; Felici-Castell et al., 2018; Megyesi et al., 2016; Charif et al., 2017). Furthermore, the congested node is freeloading the notification bit in the packet header to inform other neighbouring nodes of its congestion status.

2.7.3. Congestion mitigation

There are various traffic-management protocols used in WSNs. These protocols work differently from one another in detecting, notifying, and mitigating the congestion (Jain et al., 2018; Nikokheslat and Ghaffari, 2017; Sakya and Sharma, 2019).

Some categories classified for traffic-management protocols are listed below:

- Traffic control: In traffic control, when the loaded packet in the network is nearby or exceeds the network capacity, then congestion has occurred

(Vedam et al., 2019; Parvanak et al., 2019; Rangisetti and Tamma, 2017; Høiland-Jørgensen et al., 2018; Ghorbani et al., 2017; Feng et al., 2018; Sonchack et al., 2016). Therefore, the mechanism of traffic control will be used to alleviate network congestion.

- Queue-assisted technique: in the queue-assisted technique, the length of the queue within the network node is used to alleviate the congestion (Rezaee and Pasandideh, 2018; Vedam et al., 2019; Høiland-Jørgensen et al., 2018; Nikokheslat and Ghaffari, 2017; Al-Kashoash, 2020c; Abdullah et al., 2019; Yaqoob et al., 2019). The protocols implemented in this technique observe the length of the queue in network nodes, and then reduce the packet rate to decrease the length of the queue to the shortest possible length.

2.8. Related Work

Recent related works have proposed numerous traffic-management algorithms, which consider diverse aspects of avoiding packet congestion in a network. This section discusses the existing related works used for traffic management within an agricultural environment. Thereafter the research gap is outlined.

2.8.1. Artificial intelligence-based algorithms

Guo at al. (2018) proposed an artificial intelligence-based semantic Internet of Things (AI-SIoT) algorithm to integrate heterogeneous IoT devices to support and

manage the intelligent services within agricultural fields. This algorithm provides the flow function of each packet within high-priority traffic. Packets move through the network environment in a series of hops with various parameters within the agricultural environment. The authors outlined that the proposed algorithm is empowered by semantic and AI technologies, which enable flexible connections among heterogeneous devices implemented into agricultural fields for high-priority traffic packets. The algorithm proposed by the authors used the following input parameters, namely, bandwidth, latency, mobile speed, and throughput, in order to lessen packet delay within a network. MATLAB was deployed to implement the authors' AI-SIoT algorithm. The simulation results showed that their algorithm minimized the packet delay which was caused by packets with high-priority within a network. The high-priority packets are regarded as unusual packets gathered by sensor nodes. Those packets are above a given traffic threshold within the agricultural environment. However, the algorithm proposed by (Guo at al. 2018) does not consider the packet delay with low-priority within a network. This remains a problem for network performance. Their algorithm focuses more on packets with high-priority. This research study proposed the use of the AI-SIoT algorithm in order to prioritize the high-priority and low-priority packets within an agricultural environment during packet transmission. In this research study, the high-priority packets are regarded as packets gathered by sensor nodes within the agricultural

environment, carrying critical information that needs to be transmitted immediately; and packets with low-priority are regarded as packets that do not have any critical information which needs to be transmitted immediately. Moreover, the low-priority packets regarded as packets that are marked according to the threshold, and can cope with the utilization of channels in the agricultural environment.

Yang et al. (2018) proposed a congestion-aware clustering and routing (CCR) algorithm to reduce packet-congestion issues in agricultural yields, as this affects the bandwidth usage and QoS downgrades in farming. The authors indicated that the proposed algorithm achieved this issue by decreasing the end-to-end delay, through choosing the appropriate primary cluster head (PCH) and the secondary cluster head (SCH) within the environment. Furthermore, authors illustrated that when sensor nodes want to send packets to the destination node within the agricultural environment, they first check the availability of the PCH before the SCH. If the PCH is available to receive packets, the sensor node will forward the packets; and if not, the available sensor node will forward packets to the SCH. The authors used NS-2.35 as their experimental method in order to demonstrate the effectiveness of the proposed CCR algorithm. Their experimental results indicated that the proposed CCR algorithm managed to decrease the overflow of packets. Bandwidth usage was also reduced in comparison to the state-of-the-art techniques in farming.

An ambient crop field routing (ACFR) algorithm was proposed and implemented by (Sodhro et al., 2019), in order to decrease the number of packet drops. Such manages the hop-count based on every packet forwarded from sensor node to destination node within agricultural fields. The authors indicated that the proposed algorithm had achieved its goal by integrating two operations, namely: multiple path identification and congestion mitigated routing. The multiple path identification was used for unknown coordinates of sensors within the agricultural fields. This assisted in forming more packet transmission paths within the existing paths. The congestion mitigated routing used routing packets from source to the destination node by considering the forwarded packets per second and the bandwidth size. The authors used MATLAB to test the effectiveness of their proposed algorithm. Their simulation results showed that the proposed ACFR algorithm decreases the packet drops by 4.7%. The hop-count also improved by 2.1% when compared with the congestion-aware routing (CAR) mechanism and agri-based routing algorithm (ARA).

However, the algorithms presented by (Yang et al., 2018) and (Sodhro et al., 2019) did not consider the buffer overflow: this happens when the number of packets generated by a node exceeds its transmission throughput. This is because the above algorithms failed to minimize packet delay when many packets were transmitted simultaneously. As a result, their algorithms experienced poor network throughput within the agricultural fields. This research study implemented the proposed ITRM

algorithm alongside the AI-SIoT in order to lessen the packet delay and improve the network throughput process by establishing the traffic source which will identify traffic routes within the agricultural environment.

2.8.2. Traffic-control management-based algorithms

A low-overhead congestion management distribution mechanism known as the traffic packet-flow control (TPFC) algorithm was proposed by (Esguerra et al., 2017) with the use of a distributed rate adaptation technique for each node that converges on a fair and efficient packet flow in an agricultural environment. The authors shows that, to achieve fairness and efficiency of packet flow within an agricultural environment, the node shares the congestion information with the potential interferers (a node is a potential interferer if a flow originating from the first node uses a link that interferes with the link between the second node and its parent). Therefore, the authors use three interrelated components which combined the TPFC. These were measuring the node level congestion, sharing congestion information with potential interferers, and using additive increase multiplicative decrease (AIMD) control to adapt the transmission rate. Then, when the queue size of a node exceeds an upper threshold within the agricultural environment, the congestion takes place immediately. The node is considered congested, and the rate is reduced according to the AIMD rate-adaptation scheme. Each outgoing packet is attached to its packet header showing the average queue size and the current transmission rate. The authors used the

MATLAB simulator to acquire their results. Moreover, the simulation results reflected that the proposed algorithm performed very well, showing a % improvement of packet distribution from source node to destination node.

Panah et al. (2017) proposed a congestion control predictor (CCP) algorithm based on an agricultural environment which managed the packet flows during the packet transportation within a network. During the development of the CCP, the authors considered some parameters such as network energy consumption, packet delay, and percentage of the delivered high- and medium-priority packets to their destination. The authors outlined that their proposed algorithm consisted of congestion prevention, congestion control, and energy control plans, using the shortest path-selection algorithm. In the congestion prevention plan, congestion is prevented by investigating the queue length. In the congestion control plan, the congestion is controlled by reducing the transmission rate. Lastly, the energy control is used to balance the energy nodes which avoid network failures due to energy outage on the node within an agricultural environment. The authors used NS-2 to implement their proposed CCP algorithm. The simulation results indicated that their proposed CCP algorithm has a higher efficiency in the aforementioned parameters.

Srivastava et al. (2019) proposed the priority-based congestion control (PCC) algorithm. This algorithm consists of three mechanisms: intelligent congestion detection (ICD), implicit congestion notification (ICN), and priority-based rate

adjustment (PRA). The authors indicated that the proposed algorithm was for implementation in agricultural fields based on crops, soils, and by mitigating flood risks through the farming practices. The ICD uses the ratio of packet inter-arrival time (time of received packet at the node) over packet service time (needed time for processing packets at the node) to detect the congestion. This ratio is also named congestion degree. In ICN, the congestion notification is given through setting the header of data packets. Each SN might have a different priority depending on their function or location. A node priority index (assigned depending on the node traffic) is introduced in this proposed algorithm to reflect the importance of each SN.

However, the algorithms proposed by Esquerra et al., 2017; Panah et al., 2017; and Srivastava et al., 2019, did not prevent packets dropped during packet distribution caused by the signal degradation over the transmission channel due to multi-path fading. This is because their algorithms focus more on packet flows, delays, and notification for each packet distributed in the WSNs. This research study uses multiple links in the agricultural environment for packet transportation in order to avoid any packet drop. Furthermore, this research study proposed the use of the TPFC algorithm in order to manage the packet flows during packet transportation within the agricultural environment.

2.8.3. Artificial neural networks-based algorithms

Chen et al. (2017) proposed a multilayer feedforward artificial neural network-based algorithm (ANNA) for traffic management within an agricultural environment in order to reduce packet delay which decreases the network performance in the environment. Their artificial neural network-based algorithm used data rate, humidity, bandwidth, and velocity within the sensor node as input parameters when reducing packet delay in an agricultural environment. Their simulation results showed that their proposed algorithm minimized packet delay compared with the two algorithms − the hierarchical tree alternative path (HTAP) algorithm, and the priority-based congestion control (PCC) algorithm. However, their proposed algorithm does not consider the packets dropped due to buffer overflow (when the sink node exceeds its transmission throughput) within their network environment. As a result, their algorithm experienced packet drops which led to poor network throughput. This research study utilizes the AI-SIoT in order to lessen the packet delay while improving network throughput. Moreover, multiple links and sink nodes are implemented into this research study in order to avoid packet drop in an agricultural environment.

Wu et al. (2018) proposed an automata-based congestion avoidance (ACA) algorithm to prevent the traffic congestion in WSNs which results in packet loss and bandwidth reduction. The authors demonstrated that the proposed ACA algorithm

was instigated into the agricultural field to monitor the soil temperature and moisture for crop production. The proposed algorithm uses packet inter-arrival time to check the distributions for each packet sent to the destination node from the source node. It further imposes the hop-by-hop count for bandwidth usage within the agricultural fields. The authors simulated their proposed algorithm using the MATLAB simulator. Their simulation results showed that the proposed algorithm managed to reduce packet loss and to stabilize the bandwidth usage within the agricultural field. However, the proposed algorithm does not consider the delays within the environment. As a result, their proposed algorithm during packet transmission produced poor network throughput within the agricultural field in the WSNs.

2.8.4. First-fit decreasing heuristic-based approach

Natesha et al. (2018) proposed the designing of the first-fit decreasing (FFD) heuristic-based approach for processing the packets near to the edge of the network, where processing is achieved by distributed network nodes. The authors outlined that the proposed approach utilizes the Internet of Things (IoT) in an agricultural environment for monitoring crop production. Furthermore, the authors expressed that the ideal of designing the FFD approach is to minimize the packet congestion caused by the packet delay which affects the network performance using the IoT in agricultural environments. Their simulation results demonstrated that the proposed

approach significantly decreases (by 3%) packet congestion caused by the delay of packets compared with the other method.

The FFD approach proposed by (Natesha et al., 2018) managed to decrease packet congestion caused by packet delay; however, the packet drop remains as a problem in their proposed approach. The proposed ITRM algorithm utilizes the FFD approach in order to monitor and manage packet traffic in WSNs within an agricultural environment.

2.8.5. Multi-criteria decision-making algorithm

Algahtani et al. (2019) proposed a multi-criteria decision-making (MDM) algorithm with an optimal probability prediction to achieve good network performance based on the network's traffic capacity and data rate in WSNs within an agricultural environment. The authors outlined that the proposed algorithm is based on multiplatform networks and load balancing. The authors further explain that all nodes initially perform a cluster head selection process before sending their packets with statuses to the base station on whether or not there is a candidate cluster head, node IDs, and geographical positions, to avoid packet congestion. As the base station receives the packets from all nodes, it searches for an optimal probability of nodes being cluster heads via a genetic algorithm, by minimizing the total energy consumption required for completing one round in the sensor field. Thereafter, the

base station broadcasts an advertisement of packets with the optimal value for all nodes. Algahtani et al. (2019)'s simulation results show that the proposed algorithm effectively produces better network traffic and load balancing in WSNs, which also minimizes packet congestion within an agricultural environment. The authors further outlined that they used input parameters such as throughput, bandwidth, latency, radiation, intermediate hops, and delays in order to produce better load balancing and network traffic in the agricultural environment.

The proposed MDM algorithm effectively produces better network traffic in WSNs within an agricultural environment. However, the proposed algorithm does not count the number of packets which are distributed by the nodes within the network environment. This process has led to packets being lost in a network because packets that did not reach the destination were not noticed. The proposed ITRM algorithm utilizes the MDM algorithm for managing the network traffic in an agricultural environment.

2.8.6. Summary of related work

The literature review showed that several researchers have designed and implemented various algorithms based on managing traffic packets in WSNs in order to reduce the packet delay, managing the packet drop, network throughput, and bandwidth utilizations in the agricultural environment. However, more research is still

required in this area of agricultural environment because the existing algorithms based on traffic management within agriculture result in unfavourable situations such as unnecessary buffer overflow, and end-to-end delay. This research study focuses on managing packets in an agricultural environment to avoid traffic congestion caused by head-of-line blocking. As a result, the ITRM algorithm was proposed in order to manage packet flow in an agricultural environment to avoid traffic congestion caused by head-of-line blocking. In this thesis, an ITRM algorithm was designed by integrating the MLCC and the LBRM in order to reduce the packet loss and delays, and to improve network throughput within an agricultural environment during packet transmission in WSNs. Furthermore, the proposed ITRM algorithm used multiple input parameters mentioned in Section 1.1 of Chapter 1. To the best of this research study knowledge, this thesis is the first attempt at incorporating the MLCC and the LBRM in order to challenge the head-of-line blocking which causes packet loss, delays, and poor network throughput in an agricultural environment.

2.9. Overview of Wireless Network Simulators

Over the years, many researchers have used network simulators to evaluate protocols and applications under fluctuating network configurations. This is because setting up a real network is expensive as well as time-consuming. Network simulators allow researchers to implement and monitor the performance of the existing and newly designed models in a controlled manner.

In this section, this research study provides an overview of the most-used network simulators, presenting a comparison of these network simulators. Researchers have applied varying network simulators to simulate communication within WSNs. These network simulators are used to assess the peformance of various methods or algorithms implemented in the study. This research study chose to use Network Simulator-2 (NS-2) because it allows add-ons, modification of protocols, and implementation of multiple interfaces on wireless networks. In addition, this research study provides the key characteristics of some network simulators that have the capability of simulating the traffic-management model in WSNs.

2.9.1. Network simulators

The research community chooses the network simulators because of their widespread usage. Most researchers use them to validate their proposed solutions (Pearlin and Rekha, 2016; Chernyshev et al., 2017; Sudhakar et al., 2019; Saluja et al., 2017; Qaqos et al., 2018; Lee et al., 2019). In this research study, we only discuss the open source network simulators. This research study further discusses the reasons for NS-2 being preferred over other network simulators.

1. Network Simulator-2 (NS-2) is a discrete event network simulator built by the Virtual Internetwork Testbed (VINT) project research group from the University of California (Pearlin and Rekha, 2016; Chernyshev et al., 2017;

Borboruah and Nandi, 2014; Narayanan, 2015; Wirawan et al., 2018). NS-2 simulates network protocols with varying network architectures; and it can simulate both wired and wireless networks, as exemplified in Figure 2.13. NS-2 provides support for the simulation of protocols, namely, transmission control protocol (TCP), user datagram protocol (UDP), file transfer protocol (FTP), hypertext transfer protocol (HTTP), etc., over wired and wireless (local and satellite) networks. NS-2 makes use of C++ to carry out core communication functions. NS-2 applies an object tool command language (OTCL/OTcl) to create a simulation interface (Pearlin and Rekha, 2016; Chernyshev et al., 2017; Borboruah and Nandi, 2014; Narayanan, 2015; Wirawan et al., 2018).

The benefits of NS-2 include the network animator (NAM) whose interface consists of control features that allow users to play, forward, pause, and stop the simulation at any time. In addition, NS-2 allows for add-ons, modification of protocols, and implementation of multiple interfaces on a wireless network. Presently, NS-2 is one of the most popularly used network simulators. This is because there is an online support group by which users assist each other with their projects.

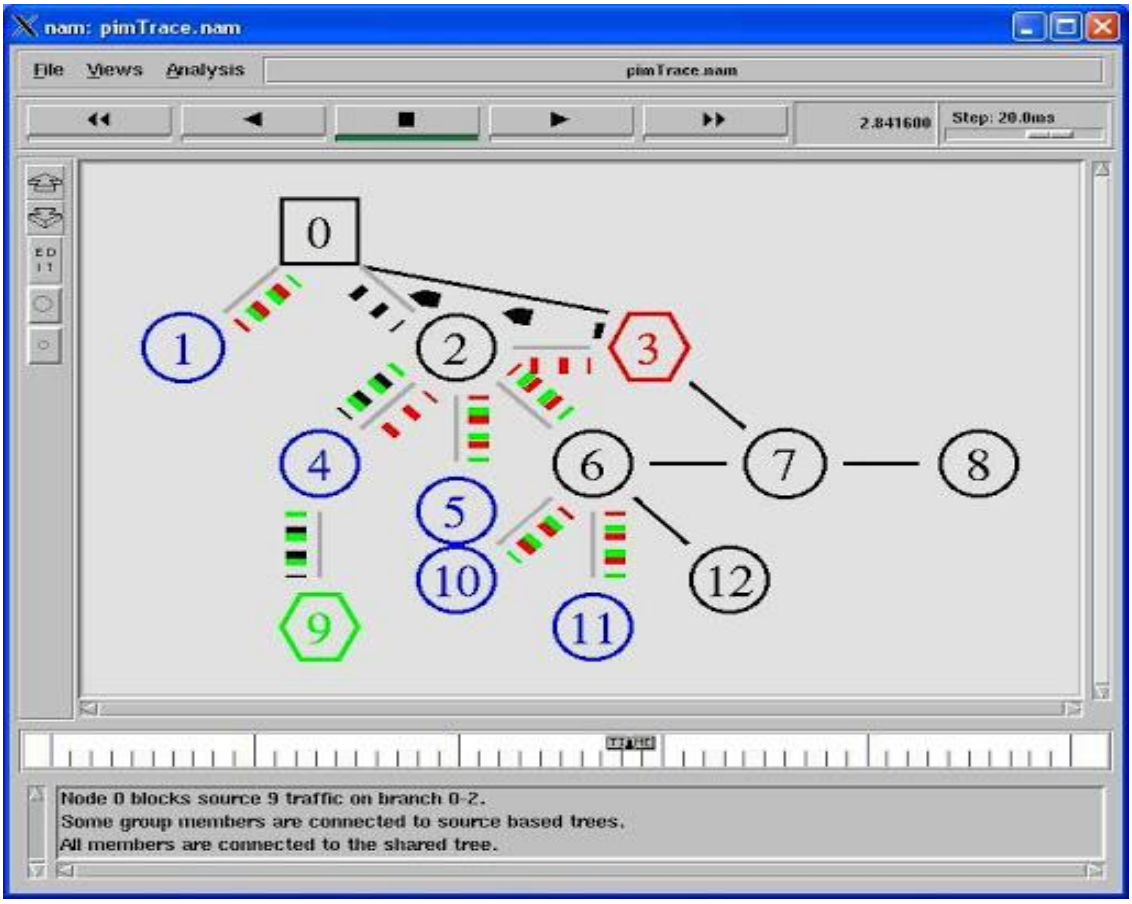

Figure 2.13: NS-2 simulation interface

2. Network Simulator-3 (NS-3) is also a discrete-event network simulator developed for the simulation of internet systems. NS-3 is an upgrade of NS-2; however, NS-3 is fairly complex and time-consuming to learn and use compared with the NS-2. In addition, NS-3 uses C++ only to implement the models and network topologies (Pearlin and Rekha, 2016; Chernyshev et al., 2017; Borboruah and Nandi, 2014; Sakamoto et al., 2016; Bojovic et al., 2018). As a result, designing and implementing a network topology using NS-3 is very difficult (Bojovic et al., 2018; Borboruah and Nandi, 2014; Sakamoto et al., 2016).

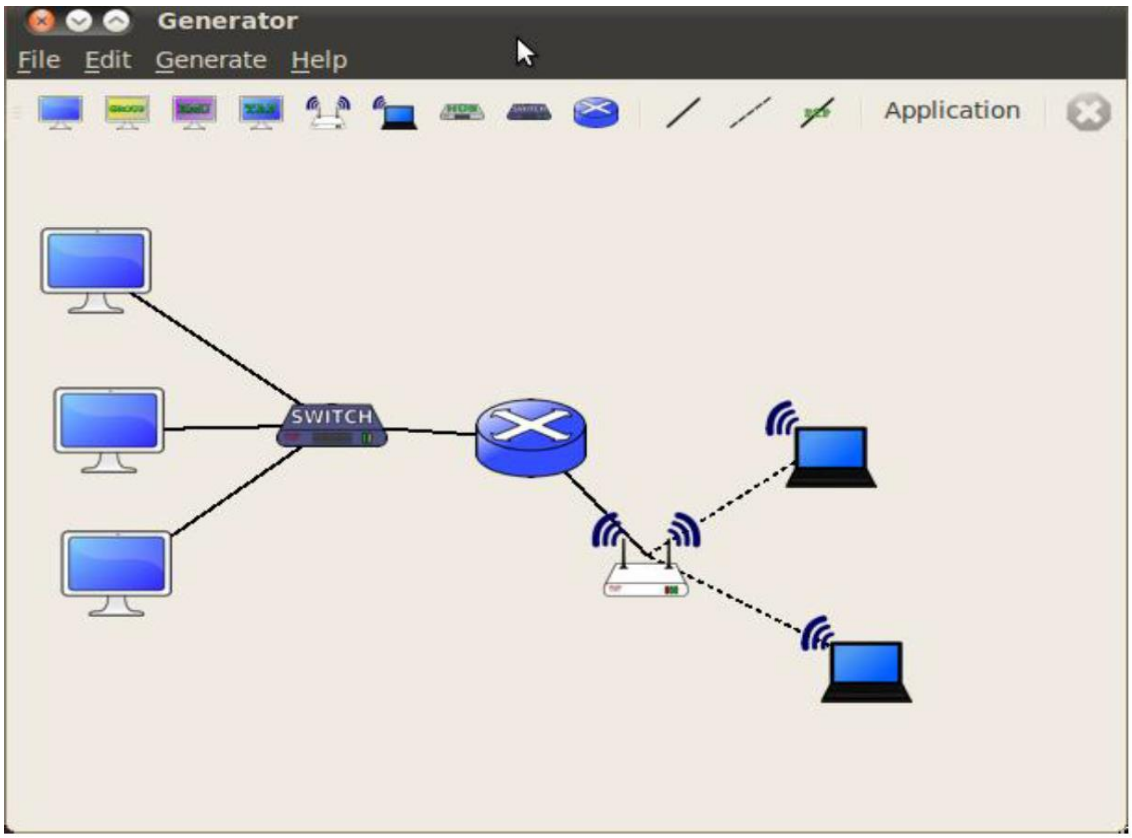

Figure 2.14: NS-3 simulation interface

3. Global Mobile information systems Simulation Library (GloMoSim) – is a simulation tool designed to implement large-scale wireless and wired networks (Chengetanai and O'Reilly, 2015; Ahmed et al., 2017). GloMoSim design follows a layered approach similar to the open systems interconnection (OSI) seven-layer model; and provides support to varying protocols at each layer. GloMoSim supports asymmetric and multicast path configurations. The QualNet simulator is the most widely used commercial version of GloMoSim (Chengetanai and O'Reilly, 2015; Ahmed et al., 2017). QualNet can simulate a large-scale network with multiple nodes of heterogeneous communication paths, including satellite and multi-hop wireless communication, as illustrated

in Figure 2.15. However, setting up of QualNet on the Linux operating system is very difficult.

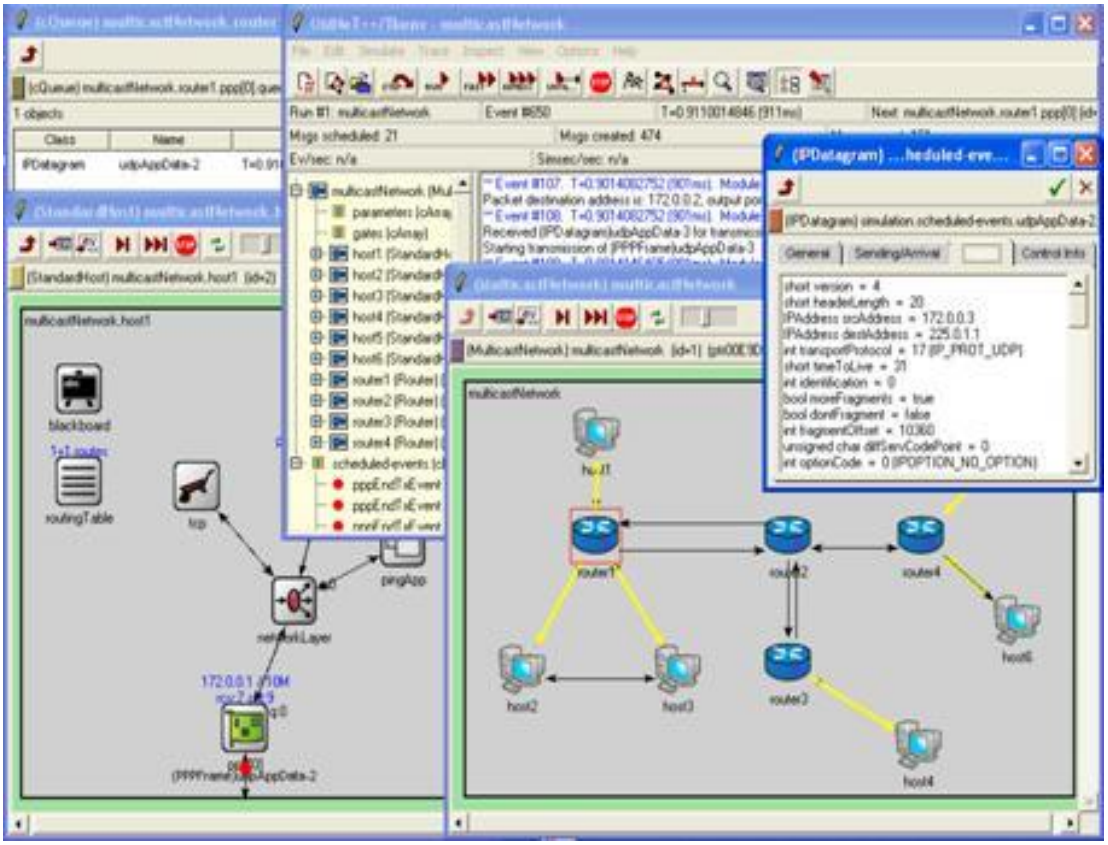

Figure 2.15: QualNet simulation interface

4. Optical Micro-Networks (OMNeT) ++ – is an expendable, modular, component-based C++ simulation library and framework, mostly used for building a larger-scale network with multiple nodes, as exhibited in Figure 2.16. OMNeT uses C++ to programme the components (modules) before assembling them into larger components and models using a high-level language (Tessinari et al., 2016; Udugama et al., 2017; Jiang et al., 2018). However, OMNeT does not support a variety of protocols; and as a result, it

requires more effort to create the simulations in OMNeT++ than in other simulators.

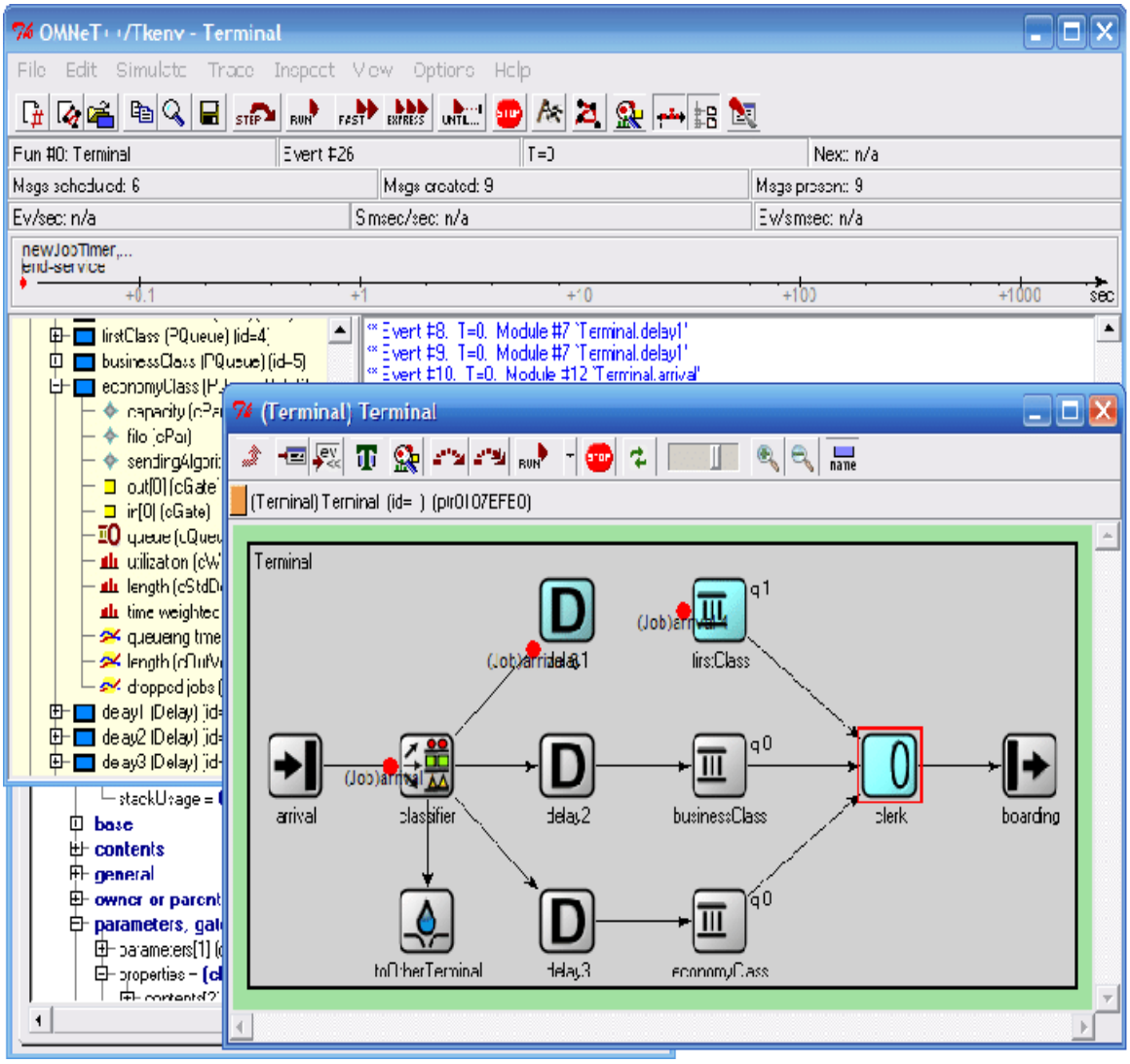

Figure 2.16: OMNeT++ simulation interface

5. MATrix LABoratory (MATLAB) is a multi-paradigm numerical computing environment and fourth-generation programming language developed in the 1970s by Cleve Moler, the chairperson of the computer science department at the University of New Mexico. MathWorks developed MATLAB to allow matrix

manipulations, the creation of user interfaces, implementation of new and existing algorithms, and enhancement of existing algorithms; and plotting of data results, as reflected in Figure 2.17.

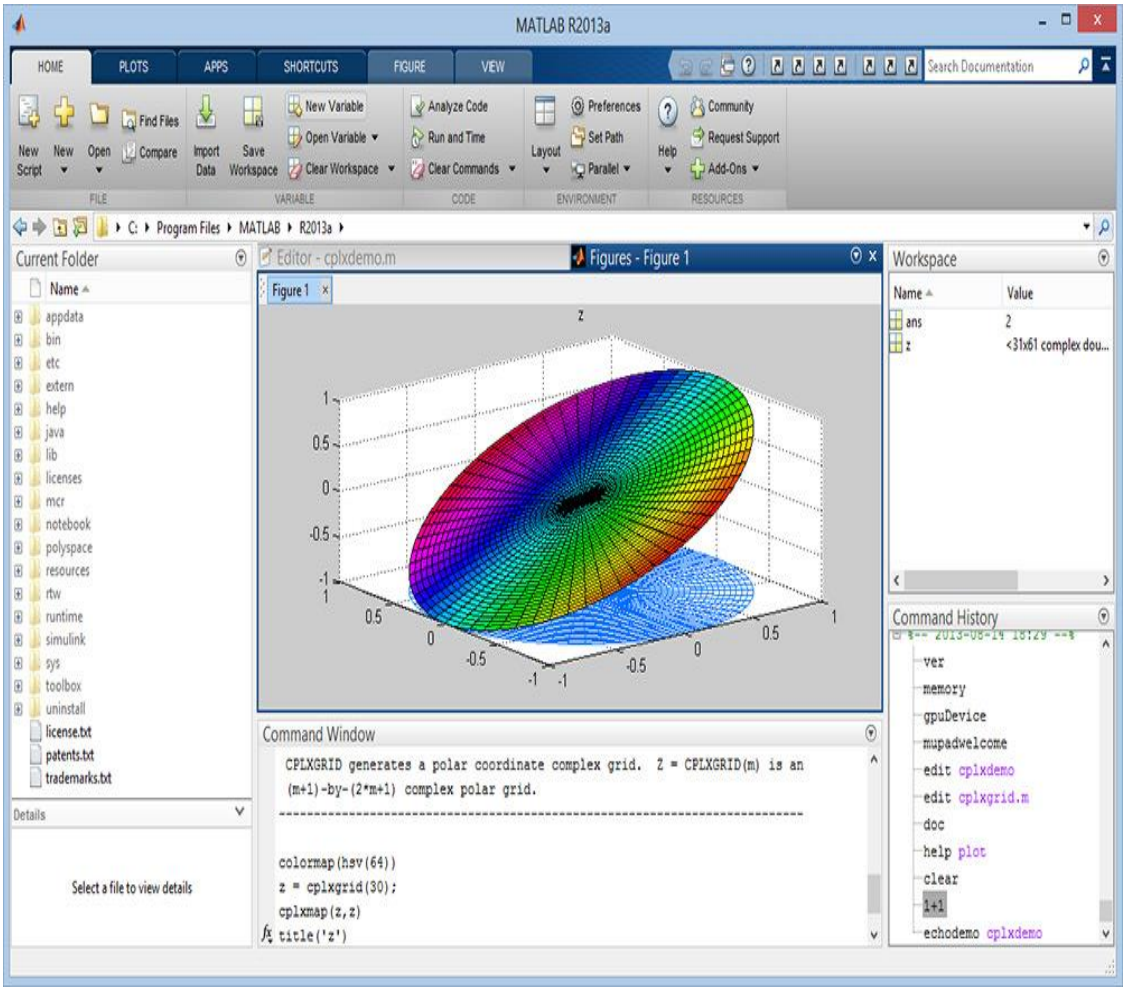

Figure 2.17: MATLAB simulator interface

MATLAB uses various programming languages that include C, C++, Java, FORTRAN, and Python. MATLAB uses the MuPAD symbolic engine to allow access to computing capabilities. Simulink is an additional package that adds graphical multi-domain simulation. Industrial enterprises, academic and research institutions commonly use MATLAB to test their proposed solutions.

MATLAB runs on cross-platforms that include Microsoft Windows, Linux, and Mac OS X (Wang et al., 2016; Kishore et al., 2016; Thurston et al., 2019). Using this software requires deep MATLAB knowledge in order to deal with all programming errors.

Table 2.2: Advantages and Disadvantages of Network Simulators

Network Simulators	**Advantages**	**Disadvantages**
NS-2	• Complex scenarios can be easily tested. • NS-2 supports protocols such as TCP, UDP, FTP, HTTP, etc. • NS-2 allows for add-ons and modification of protocols. • Online support group.	• Real system too complex to model. • Bugs are unreliable.
NS-3	• Can simulate larger-scale wireless and wired network. • NS-3 provides features not available in NS-2, such as an implementation code execution within the environment.	• Relatively complex and time-consuming to learn
GloMoSim	• Can simulate a larger-scale wireless and wired network. • Supports asymmetric and multicast paths configuration.	• Setting up of QualNet on the Linux operating system is very difficult.

OMNeT ++	• Expendable, modular, component-based C++ simulation. • Can simulate large-scale wireless and wired networks.	• It does not support a variety of protocols.
MATLAB	• MATLAB runs on cross-platforms that include Microsoft Windows, Linux, and Mac OS X. • Uses various programming languages that include C#, C++, Java, etc.	• Requires deep MATLAB knowledge to deal with all programming errors.

This research study presented the most-used open-source network simulators in this section. The comparison of these network simulators is discussed in the next section.

2.9.2. Comparison of network simulators

This research study provided the characteristics of the discussed network simulators using Table IV. As exemplified in Table IV, NS-2 is not suitable for simulating large communication networks, yet it is widely used by many researchers all over the world. This is because NS-2 is easier to configure, instal, and learn, compared with other network simulators, namely, MATLAB, NS-3, and QualNet (Chernyshev et al., 2017, Kishore et al., 2016, Bojovic et al., 2018).

Table 2.3: Comparison of Network Simulators

Features	NS-2	NS-3	QualNet	OMNET++	MATLAB
Easy to set up	Easy	Easy	Difficult	Moderate	Moderate
Ease of use	Moderate	Difficult	Difficult	Difficult	Difficult
Scalability	Poor	Poor	High	High	High
Programming Language	C++	C++	C#	C++	C#, C++, Java, Python, & FORTRAN
Larger Networks	No	No	Yes	Yes	Yes
Continuous development	Yes	Yes	Yes	Yes	Yes
Graphical User Interface (GUI)	Yes	Yes	Yes	Yes	Yes
Obstacles	No	No	No	No	No
Accessibility	Yes	Yes	Yes	Yes	Yes

In addition, NS-2 has an online user support group, which permits users to help one another with their NS-2 simulation project challenges. NS-2 is a graphical user interface (GUI)-based simulator that supports the simulation of all IEEE 802.11

models. It also supports the simulation of various routing protocols, queuing protocols, as well as multicast protocols for both wired and wireless networks. In addition, NS-2 is open source; and its source code is freely available online (Pearlin and Rekha, 2016; Chernyshev et al., 2017; Borboruah and Nandi, 2014). In the next section, we provide an insight into the NS-2 environment.

NS-3 has a better wireless channel model than NS-2: it has an improved interference model, while QualNet, OMNET++, and MATLAB have the same interference model as NS-2. Furthermore, the advantage of passive scanning is low power and bandwidth requirements. However, this may increase the latency of the discovery phase for low activity channels, as it does not proactively generate traffic in NS-2, NS-3, QualNet, OMNET++, and MATLAB. Since the risk occurs of switching to the channel immediately after the beacon, the listening time in NS-2, NS-3, QualNet, OMNET++, and MATLAB must be at least the same as the beaconing interval of the protocol to prevent the channel from being considered empty while nodes are working in it. In addition, NS-2 has a built-in IEEE 802.21 standard.

This standard supports algorithms that are used between wired and wireless networks of the same type, as well as the transferring of packets between various wired and wireless networks. In addition, the IEEE 802.21 standard specifies link-layer intelligence and other related network information to upper layers in order to

optimize the packet traffic in WSNs (Qadir et al., 2016; Ghaleb et al., 2019). This makes it easier to implement the proposed ITRM algorithm in NS-2.

2.10. The Network Simulator-2 Environment

In this section, this research study provides an insight into the NS-2 environment, which includes the NS-2 basic architecture, directory structure, class hierarchy, and format of trace files which recorded the results of traffic congestion in an agricultural environment.

2.10.1. NS-2 Basic architecture

NS-2 is made up of two main languages: OTcl for scripting a network topology, and C++ for core functionality of the algorithm. NS-2 also includes the NAM that provides a GUI and visualization of the designed and simulated network, as illustrated in Figure 2.18 (Katkar and Ghorpade, 2016; Sheynin et al., 2017; Ullah et al., 2018). In addition, since NS-2 uses C++ to implement network algorithms, it was easier to implement FFD, TPFC, CCP, and AI-SIoT.

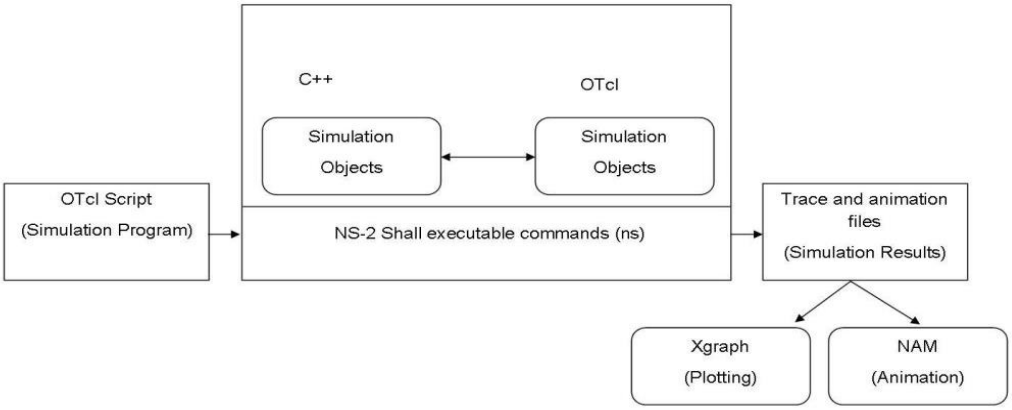

Figure 2.18: Basic NS-2 architecture

2.10.2. NS-2 Directory structure

NS-2 software comes in the form of one integrated package, the NS-allinone, in order to simplify the installation; therefore, all the dependent packages are installed from one package. This research study used NS-allinone-2.35. The study illustrated the NS-2 directory structure, as shown in Figure 2.19. Both TCL and C++ source code directories are located within the NS-2.35 directory. In order to compile the NS-2 C++ source code, this research study executed the following: configure, make, and make instal commands in the terminals.

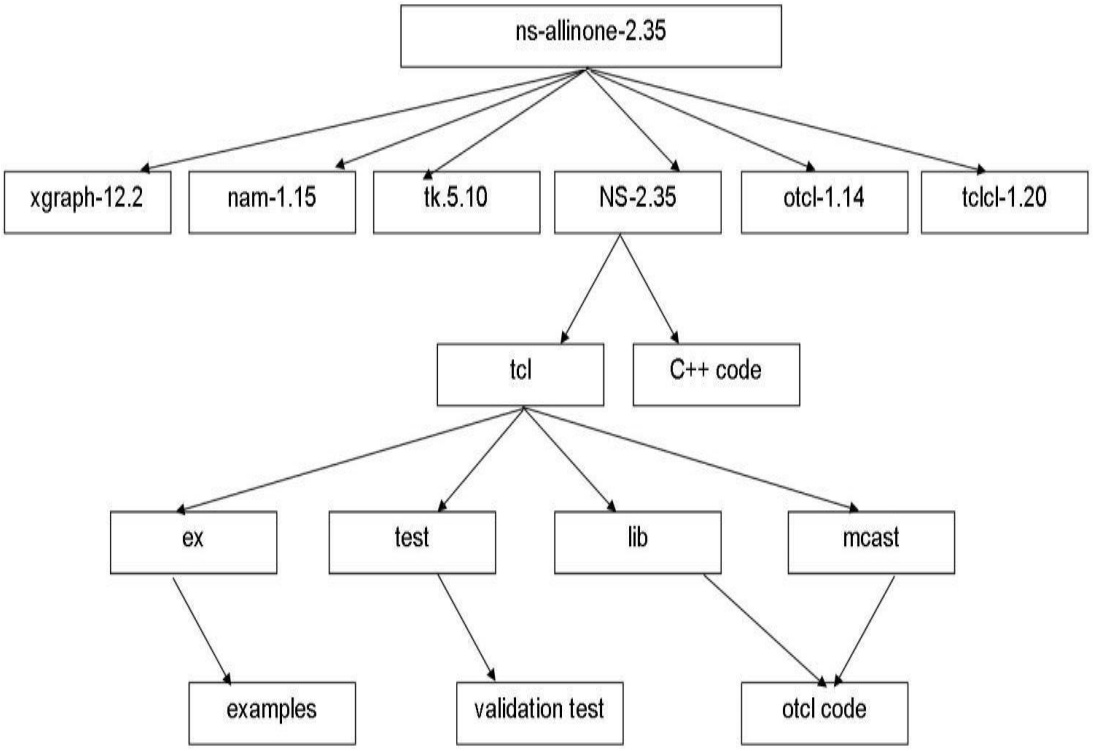

Figure 2.19: NS-2 Directory structure

2.10.3. NS-2 Class hierarchy

This research study illustrates a typical NS-2 C++ class hierarchy, as shown in Figure 2.20, which represents the class relationship between all the C++ classes. From the class hierarchy, the root of every object that belongs to the OTcl library is the TclObject. Such comprises a scheduler, timers, network components, and NAM-related objects. The NsObject is the base class for most basic network components that forward packets using two groups, namely, Connector, and Classifier. The

Connector defines the class of network objects that consist of a single output data route (i.e., downstream route).

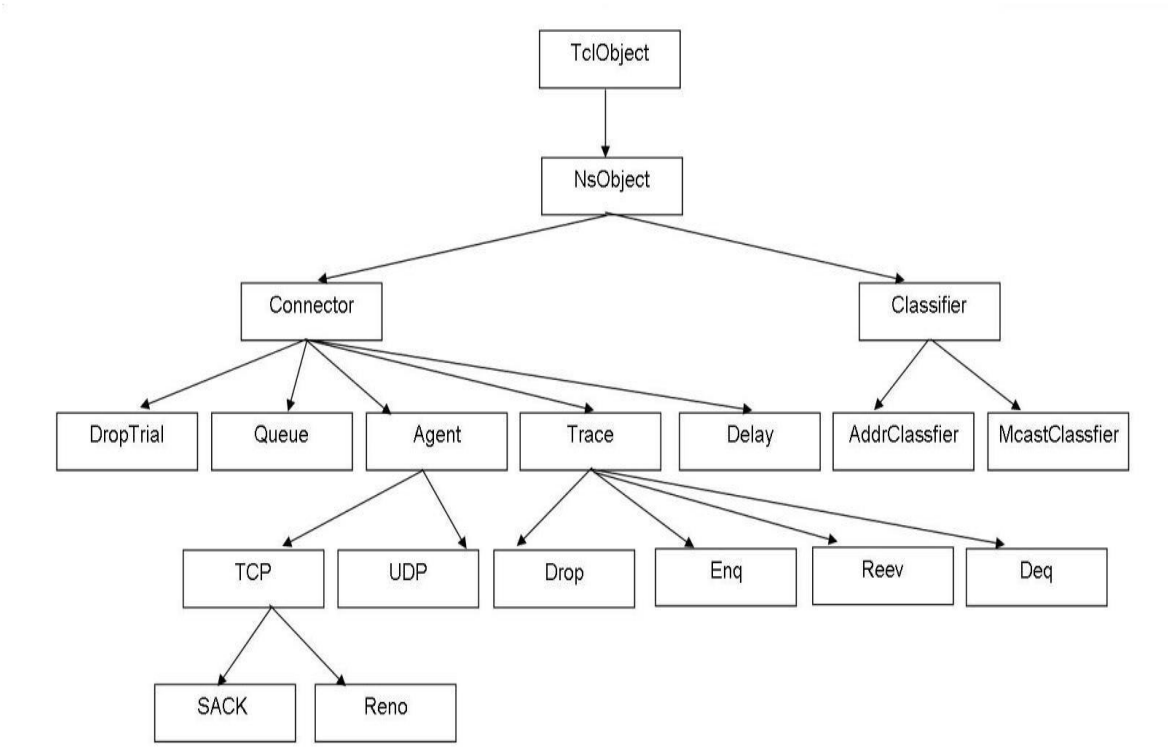

Figure 2.20: NS-2 C++ hierarchy

2.10.4. Trace file output format

A trace file contains information about the data transferred on the network between nodes in NS-2. The cmu-trace.cc file in the NS-2.35 directory defines the format for wireless networks. In addition, trace files are auto-generated by the simulator during simulations. In most cases, trace files contain 12 fields, discussed below:

1. Type Identifier **+** indicates enqueue operations, **-** indicates dequeue operations, **r** indicates receive events, **d** indicates drop event, **c** indicates packet collisions at the MAC level.
2. Time indicates the simulated time at which each event occurred, and is measured in seconds.
3. Source node indicates the node that created the packet.
4. Destination node indicates the node that received the packet.
5. Name indicates the descriptive name for the type of packet shared.
6. Size indicates the size of the packet shared.
7. Flags indicate the flag arrays in trace.cc.
8. ID indicates the IP flow identifier.
9. Source and destination addresses indicate the packet's source and destination node addresses, respectively.
10. Seq indicates the sequence number.
11. Uniq ID indicates a unique packet identifier assigned to each packet created.

This research study coded AWK scripts in order to analyse/interpret the trace files data.This helped to gain useful information such as the number of packets lost, and the throughput of the network. AWK is a command/tool available in all the Linux/Unix flavours for text filtering, manipulation, etc. AWK can process text, reporting with greater ease than with other text-parsing tools available in Linux/Unix. The AWK is a

programming language designed to process the content of text files, to validate data, to manage small database files, to generate reports, to parse command outputs and to log files. The AWK can parse more than one file at a time, as illustrated using Appendix C.

2.11. Summary

In this chapter, this research study presented the overview, design, classification, and application of WSNs. In addition, the research study provided various traffic-management algorithms, artificial intelligence-based algorithms, and artificial neural networks-based algorithms according to their common methodology applied. Furthermore, this research study discussed several identified gaps from the existing algorithms presented in Section 2.9. This research study provided a review of network simulation tools, and a comparison of the studied network simulation tools. The chapter discussed the reason for choosing NS-2 rather than other network simulators. In addition, this research study discussed the NS-2 environment, which included its basic architecture, directory structure, and class hierarchy. In the next chapter, this research study presents the design of the proposed ITRM algorithm.

Chapter 3: System Modelling

3.1. Introduction

WSNs are observed as a revolutionary information-gathering method, which forms communication and information systems to significantly improve the consistency and efficiency of the system infrastructure (Cisse et al., 2017; Martinez et al., 2019; Álvarez et al., 2019; Parramon et al., 2019). With the recent technology, the wireless network implemented in the agricultural environment is increasing daily; therefore, farmers need the improved QoS and greatest network connectivity anytime anywhere. Packet transportation in WSNs has become more intricate because of differing wireless communication technologies such as infrared communication (support short and medium distance), satellite communication (the transmission speed is up to 300 000 km/s between source transmitter and receiver), Wireless Fidelity (Wi-Fi), which uses radio signals to transmit data per an antenna, and others (Amutha et al., 2020). These wireless communication technologies make use of different channels, speed, and distance, to transmit packets from source to the destination node.

In this chapter, the research study presents the design of the proposed ITRM algorithm and related assumptions. Section 3.2 provides the system architecture. In

Section 3.3, this research study presents the design of the proposed ITRM algorithm. Finally, Section 3.4 provides a chapter summary.

3.2. System Architecture

WSNs users are unrestricted in terms of movement when connecting to the network, as long as there is network coverage in that particular area. The process of various nodes communicating by sending packets from source node to destination node in an agricultural environment is termed packet transmission, as this research study illustrated in Figure 3.1 (Tshilongamulenzhe et al., 2019; Kiani and Seyyedabbasi, 2018b; Ramdoo et al., 2019; Marques and Pitarma, 2018; Khan and Kumar, 2020). Furthermore, all SNs collect the information from the agricultural environment separated by different zones (Zone 1 to Zone 6) to send the information to the access point (AP). An ITRM algorithm must perform the traffic management to avoid head-of-line blocking which occurs when the first packet holds up a line of packets during packet transmission within an agricultural environment. The goals of managing the packet congestion may include less packet loss, minimizing packet delay, and improving network throughput during packets transmission in WSNs.

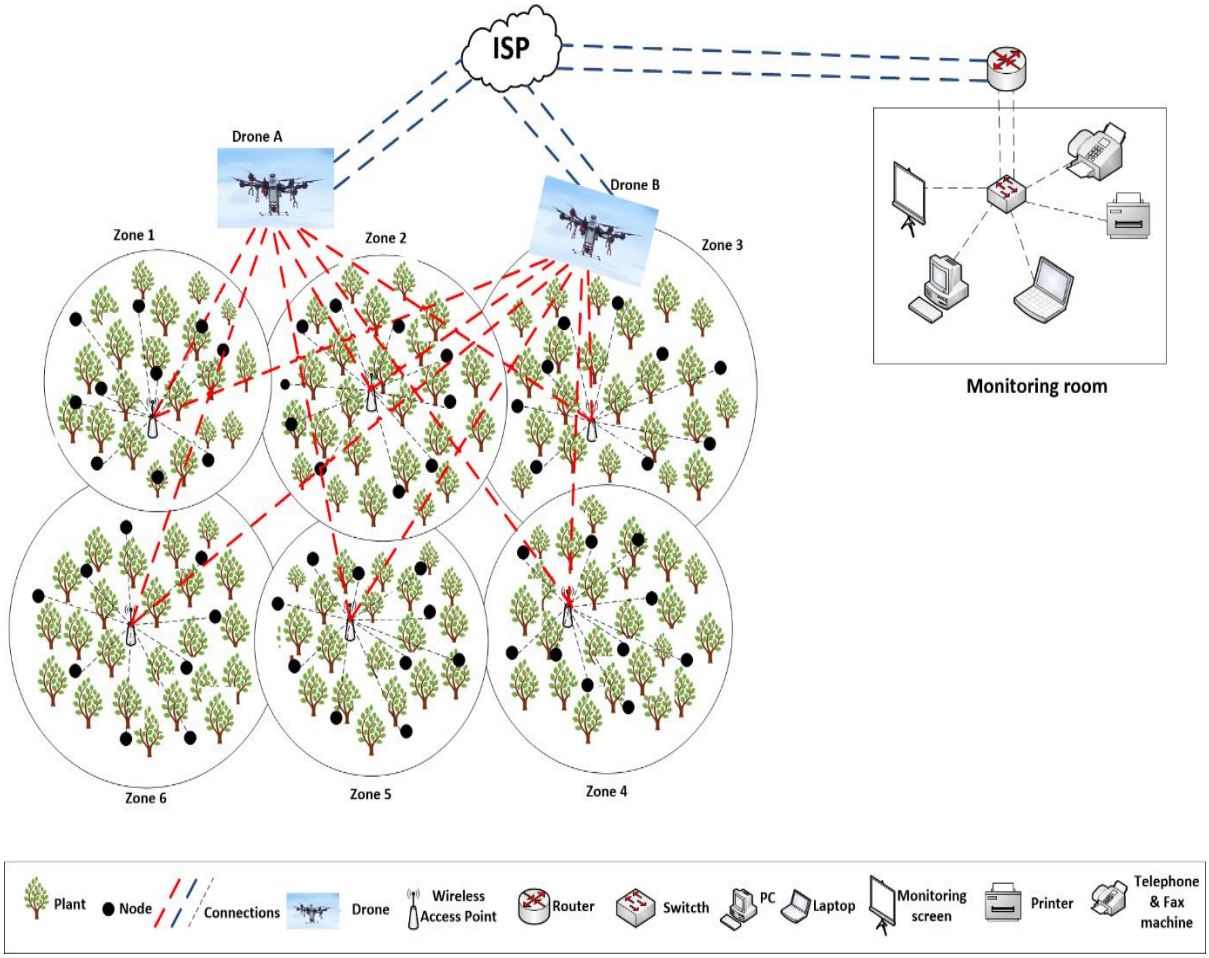

Figure 3.1: WSNs system architecture

As indicated in Figure 3.1 of the presented WSNs system architecture, before the access points (APs) send packets to the next drone, SNs will first collect all the relevant information from the ground in the zones; thereafter, SNs send the collected information to the AP. The AP will transmit packets to the drones (drone A and B) which are moving from Zone1 to Zone 6. Thereafter, the drones transmit the received packets from the APs to the cloud. Here the network users monitoring the zones will be able to access all the information. Furthermore, if the first drone (Drone A) reaches the maximum number of packets to be collected from APs, the other

packets will be re-directed to the second drone (Drone B), for packets to be transmitted to the internet service provider (ISP). This process reduces traffic congestion in the agricultural environment because the load balance is maintained. All information will be saved on the servers; and the printer will be used to print out the reports for all the events that took place within the entire system architecture. In the next section, this research study presents the design of the proposed ITRM algorithm by showing its system model and pseudo code.

3.3. Design of Intelligent Traffic Routing Management Algorithm

This research study assimilated the existing solutions methods such as machine learning congestion control (MLCC), and load balancing routing mechanism (LBRM) when designing the proposed ITRM algorithm, to minimize the packet loss and delays, and to improve network throughput during packet transmission in WSNs within an agricultural environment.

3.3.1 Machine learning congestion control

The proposed ITRM algorithm integrates the MLCC method with the LBRM to overcome packet congestion caused by head-of-line blocking within an agricultural environment. The proposed ITRM algorithm used the MLCC for predicting possible packet congestion. It offers some decision-making mechanisms based on packet transmission within the network in the agricultural environment from different zones,

using links that connect the AP with drones and the ISP. The MLCC provides a high flexibility of packet transmission, which is implemented by the decision-tree algorithm when distributing packets within the network environment. The MLCC is used for estimating the amount of packet flow in a dynamic network environment, by predicting the traffic pattern using parameters including traffic speed and delay. The MLCC ensures that the transmission of each packet in the network is conducted appropriately from one node to another node without delays or congestion. This research study applied this machine learning (ML) technique to predict the possibility of packet congestion. Thus one can make a decision on the packet flow to avoid packet congestion. If such occurs during packet transmission, this may result in head-of-line blocking within WSNs in an agricultural environment. The prediction of packet congestion is calculated using Equations (3.1), (3.2), and (3.3) as stated by (Kamble et al., 2020).

$$P_s = \frac{1}{n}\sum_{i=1}^{n}(|V_i - \overline{v_i}\,|) \tag{3.1}$$

where P_s represents the packet set initialized from the network, n represents the total number of nodes, and V_i represents the traffic packet flow. Meanwhile $\overline{v_i}$ represents the possible predicted traffic packet congestion during packet transmission within the network.

$$T_s = \frac{1}{\mathrm{n}}\sum_{i=1}^{n}\left(\frac{|\bar{v}_i - v|}{|\overline{v_i}| + |v|/2}\right) * 100 \tag{3.2}$$

where T_s represents the traffic speed based on the bandwidth in a network during packet transmission from various nodes within the agricultural environment.

$$C_i = \sqrt{\frac{\sum_{i=1}^{n}(\bar{v}_i - v_i)^2}{n}} \quad (3.3)$$

where C_i represents the congestion index experienced during the prediction of traffic flow in the network. Furthermore, the decision-making as to how the packets will be distributed or be re-routed during packet transmission in the network is calculated using Equation (3.4).

$$D_m = \frac{C_i}{T_s + P_s} \quad (3.4)$$

where D_m represents the decision-making process that controls the flow of packets routed from APs to drones and from drones to ISPs to avoid packet congestion in the network. Later, in Section 3.3.5, this research study shows the integration of all the equations used when designing the proposed ITRM algorithm.

3.3.2 Load balancing routing mechanism

This research study integrated the LBRM and the MLCC into the proposed ITRM algorithm to manage the packet flow by providing the available link which needs to be utilized by the MLCC during packet transmission from APs to drones, and from drones to ISPs in the network. The LBRM uses multipath routing method with load balancing to increase the flexibility and stability of network. This research study

implemented the LBRM to provides possible path for packet to avoid traffic congestion within the agricultural environment and increases its capacity for packet flow. Moreover, the LBRM have significant responsibility for distributing traffic packets among different routes by selecting better path which are used for packet transmission in WSNs within the agricultural environment (Martinez et al., 2019). The imbalance of traffic packets across the network in agricultural environment causes delays, packet loss and decreases the network throughput.

In LBRM all nodes initially perform a cluster head selection process before sending their packets to the base station within the WSNs (Cui et al., 2019). After the base station receives the packets from all nodes, it searches for an optimal probability of nodes being cluster heads via a genetic algorithm, by minimizing the total energy consumption required for completing one round in the sensor field. Furthermore, the Load balance in a network can reduce hot spots, maintain network connectivity and prolong lifetime (Doibale and Kurundkar, 2019).

Therefore, when packets in the network are well managed, this results in reduction of delay, packet loss, packet congestion, and further reduced head-of-line blocking in the network. Hence, this research study used an LBRM to perform the load balancing by managing the traffic flow in the network.

The LBRM integrated with MLCC to predicts possible packet congestion, and makes a decision based on the traffic flow within the network. To determine the link availability, it is more important to consider the stability of the link. Therefore, to determine link stability (LS), the concept of link expiry time (LET) plays a vital role in a network. This is used to calculate the time during which the connection between two nodes can continue without interruption. The LET between the two nodes x and y, is calculated using the equation proposed by Khudayer et al. (2020), and defined in Equation (3.5).

$$LET = \frac{-(\mathrm{ab} + \mathrm{cd}) + \sqrt{(a^2 + c^2)r^2 - (ad - bc)^2}}{a^2 + c^2}$$

With

$$\begin{aligned} \mathrm{a} &= \mathrm{vx}\ \cos\theta\mathrm{x} - \mathrm{vy}\ \cos\theta\mathrm{y} \\ \mathrm{b} &= \mathrm{wx} - \mathrm{wy} \\ \mathrm{c} &= \mathrm{vx}\ \sin\theta\mathrm{x} - \mathrm{vy}\ \sin\theta\mathrm{y} \\ \mathrm{d} &= \mathrm{zx} - \mathrm{zy} \end{aligned} \qquad (3.5)$$

where, vx, and vy are the speeds; and θx and θy are the moving directions of nodes x and y, respectively. On the other hand, (wx, zx) and (wy, zy) are the coordinates of nodes x and y, respectively.

Furthermore, to design the LS, the LET for two connected nodes is equal to infinity if both nodes are moving at the same speed and in the same direction. Consequently, the LS between two nodes is proportional to the LET value. The form of LS can, therefore, be calculated using Equation (3.6).

$$LS = 1 - e\frac{-LET}{\alpha} \quad (3.6)$$

where α is a constant; its value should be improved to enhance the LS and to be able to predict any future network link failure.

In addition to balancing the load, this work also considers the issue of packet prioritization. Traffic prioritization is a way of ensuring that specific applications or subnets are guaranteed a certain amount of uplink bandwidth at all times. This is very important, especially when the network is using all of the pre-configured bandwidth on the uplink. Meanwhile, it is also more important to note that the allocation of bandwidth can always change, especially when link aggregation is enabled, because the uplink changes per stream based on the ratio specified. The prioritization of transmitted packets follows a technique normally known as the traffic-shaping rule, in which each packet is assigned as either low, normal, or high, according to priority levels. In general, when the network starts to transmit, all traffic packets will be given the normal priority level. The ratios of these priority levels are as follows: low is 1/7, normal is 2/7, and high is 4/7.

This means that traffic-shaping rules given the same priority level share the same fraction of their respective levels. For example, should there be five traffic loads given high priority on a 10 Mbps pipe, each traffic load would have access to 1.1 Mbps, respectively. Furthermore, the proposed ITRM algorithm enforces that each

priority level supersedes those below it, making it crucial to ensure that those below it strictly adhere to their fractional bandwidth limits. For instance, in a network of 7 Mbps uplink, if there is high prioritized traffic but no low prioritized traffic configured, the high prioritized traffic would have access to 5/7 of the available bandwidth on the uplink, and normal prioritized traffic would have 2/7. Meanwhile, if there is no high prioritized traffic, then normal prioritized traffic receives 6/7 of the bandwidth, and low prioritized traffic gains 1/7 of the uplink bandwidth. This research study makes use of both low and high priority packets during the simulation process.

Below is an example of packet transmission on a 9 Mbps uplink:

- With 4 high priority levels, each gains 1.5 Mbps, equal to 6 Mbps in total.
- With 4 normal priority levels, each gains 0.5 Mbps, equal to 2 Mbps in total.
- With 1 low priority level the gain is 1 Mbps, therefore 1 Mbps in total.

However, in any network, not all packets will be successfully transmitted. Therefore, it is important to compute packet loss as shown in Equation (3.7).

$$pkt_{loss} = \left\{ \frac{\sum_{t_1}^{t_n} \mathrm{pkt}_{dropped}}{\sum_{t_1}^{t_n} \mathrm{pkt}_{\mathrm{sent}}} \right\} * 100 \tag{3.7}$$

where t_1 represents the time in which the first packet was sent from the source node; and t_n represents the time in which the last packet was sent from the source node.

Furthermore, this research study uses LBRM to perform the load balancing. This will assist in reducing packet congestion caused by the head-of-line blocking which

results in delays, packet loss, and packet congestion. This research study also used the MLCC to provide the prediction of possible packet congestion; it offers a decision-making mechanism based on packet transmission within the network. The integration of these two methods improved the consistency of packet transmission within the WSNs in an agricultural environment.

In the next section, this research study presents the flowchart of the proposed ITRM algorithm.

3.3.3 Intelligence traffic routing management algorithm flowchart

The proposed ITRM algorithm flowchart is illustrated in Figure 3.2.

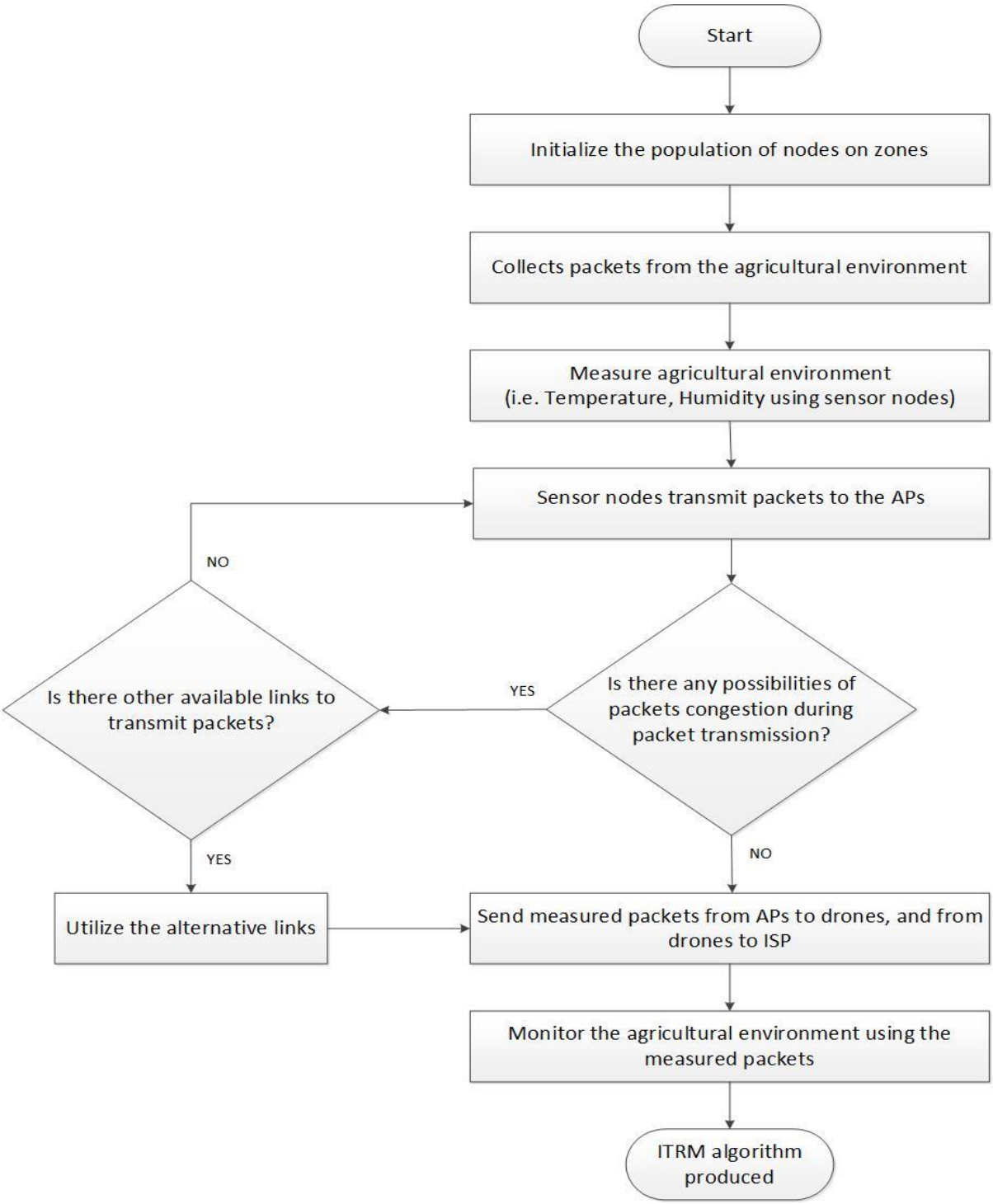

Figure 3.2: ITRM algorithm flowchart

In this section, this research study provided a flowchart of the proposed ITRM algorithm. Next, in Section 3.3.4, this research study presents the developed ITRM algorithm.

3.3.4 Intelligence traffic routing management algorithm

This research study integrated the MLCC and the LBRM to design the proposed ITRM algorithm. The aim is to minimize the packet loss, packet congestion, and delays caused by head-of-line blocking, thus improving network throughput during packet transmission in WSNs within an agriculture environment, as given by Algorithm 3.1.

Initialization: *set of nodes*

Initialization: *set of links / link utilizations*

Event: *routing packets from the different nodes in the zones to the ISP using links*

1. Initialize the population of nodes on zones
2. Nodes gather information from different zones
3. Initialize the set of links in the environment to transmit the packets
4. Check the availability of links to send packets from APs to ISPs
5. **Do while** when packets are ready to be transmitted from sensor nodes to APs.
6. **If** $P_s = \frac{1}{n}\sum_{i=1}^{n}(|V_i - \overline{v_i}|)$ **Then**
7. Initialize the packet set to be transmitted from the network
8. **Or else**
9. Use Equations (3.1) and (3.2)
10. **End if**
11. Checking the possibilities of packet congestion during transmission
12. **If** $C_i = \sqrt{\frac{\sum_{i=1}^{n}(\overline{v_i}-v_i)^2}{n}}$ **then**
13. aviod the possibilities of packet congestion from APs to ISP
14. **Or else if** there is a possibility of packet congestion **then**
15. utilize Equations (3.4) and (3.5)
16. **End**
17. Keep transmitting packets from APs to ISP using the initiated links
18. Calculate the number of packets transmitted successfully using Equation (3.7)
19. Monitor the agricultural environment using the collected data
20. **Loop**

Algorithm 3.1: ITRM algorithm

3.4. Summary

This chapter presented the design of the proposed ITRM algorithm by integrating the MLCC and the LBRM to minimize the packet loss, congestion, and delays, and to improve network throughput during packet transmission in WSNs. When designing the proposed ITRM algorithm, this research study used the MLCC approach to

predict possible packet congestion, and for decision-making based on packet transmission within the agricultural environment. This was to improve the network performance and to reduce packet congestion and delays during packet transmission. Furthermore, this research study introduced the LBRM into the proposed ITRM algorithm, to maintain the load balancing routing for every link that transmits packets within the agricultural environment. This means that each link maintains a single queue of packets from all flows passing through the APs to drones, and from drones to the ISPs in the network.

Chapter 4: System Implementation

4.1 Introduction

In this chapter, the implementation of the proposed ITRM algorithm for WSNs in the agricultural environment is discussed. The proposed ITRM algorithm using the IEEE 802.11ac model was developed via the NS-2 version 35. The NS-2 simulation tool was installed on the Linux Ubuntu 14.04 operating system, with 512 RAM, and 10 gigabytes of storage. In addition, this research study used the tool command language (Tcl) script to simulate the network topology as given in Appendix B. Since NS-2 uses C++ to implement network algorithms, it was easier to implement the MLCC and the LBRM methods into the NS-2.

In this research study, each zone (zones 1 to 6) occupied 8 sensor nodes (SNs) and one AP implemented into the agricultural environment. The SNs are labelled as follows: Zone 1 (Nodes 8 to 15), Zone 2 (Nodes 9 to 23), Zone 3 (Nodes 24 to 31), Zone 4 (Nodes 32 to 39), Zone 5 (Nodes 40 to 47), and Zone 6 (Nodes 48 to 55); with 6 APs labelled as follows: Zone 1 (AP-0), Zone 2 (AP-1), Zone 3 (AP-2), Zone 4 (AP-3), Zone 5 (AP-4), and Zone 6 (AP-5). The 2 drones labelled Drone 1 (Node 6) and Drone 2 (Node 7) are used to collect packets from the APs within the zones. This research study configured the simulation to start transmitting packets at 10 seconds, and to stop transmitting at 100 seconds. This research study recorded the

performance results gained in out.tr script, before applying R programming language to display the results as given in Appendix D. This research study used R programming because the source code for the R software environment is written primarily in C++ and is freely available under the GNU general public licence. Moreover, various operating systems are provided with a pre-compiled binary version. The R software uses command-line interface along with graphical user interfaces (GUI) such as RStudio and integrated environment, to make it simple for a researcher to analyse the results. This research study structured this chapter as follows: Section 4.2 provides a detailed discussion on how this research study simulated and tested the proposed ITRM algorithm implemented into the agricultural environment. Finally, Section 4.3 provides a chapter summary.

4.2 Simulator of the Intelligent Traffic Routing Management Algorithm

In this section, this research study provides an insight into the implementation of the proposed ITRM algorithm using the NS-2. The simulation of the ITRM algorithm was conducted to evaluate its performance in WSN traffic congestion caused by head-of-line blocking occurring within agricultural environments.

4.2.1. Network topology

This research study illustrates the NAM simulation scenario based on the topology which is created for the simulations using Figure 4.1. This research study implemented two nodes which are demonstrated as Node 6 (Drone 1) and Node 7 (Drone 2) which acted as the moving drones within the NS-2 simulator in order to gather information from all six (6) zones within the agricultural environment.

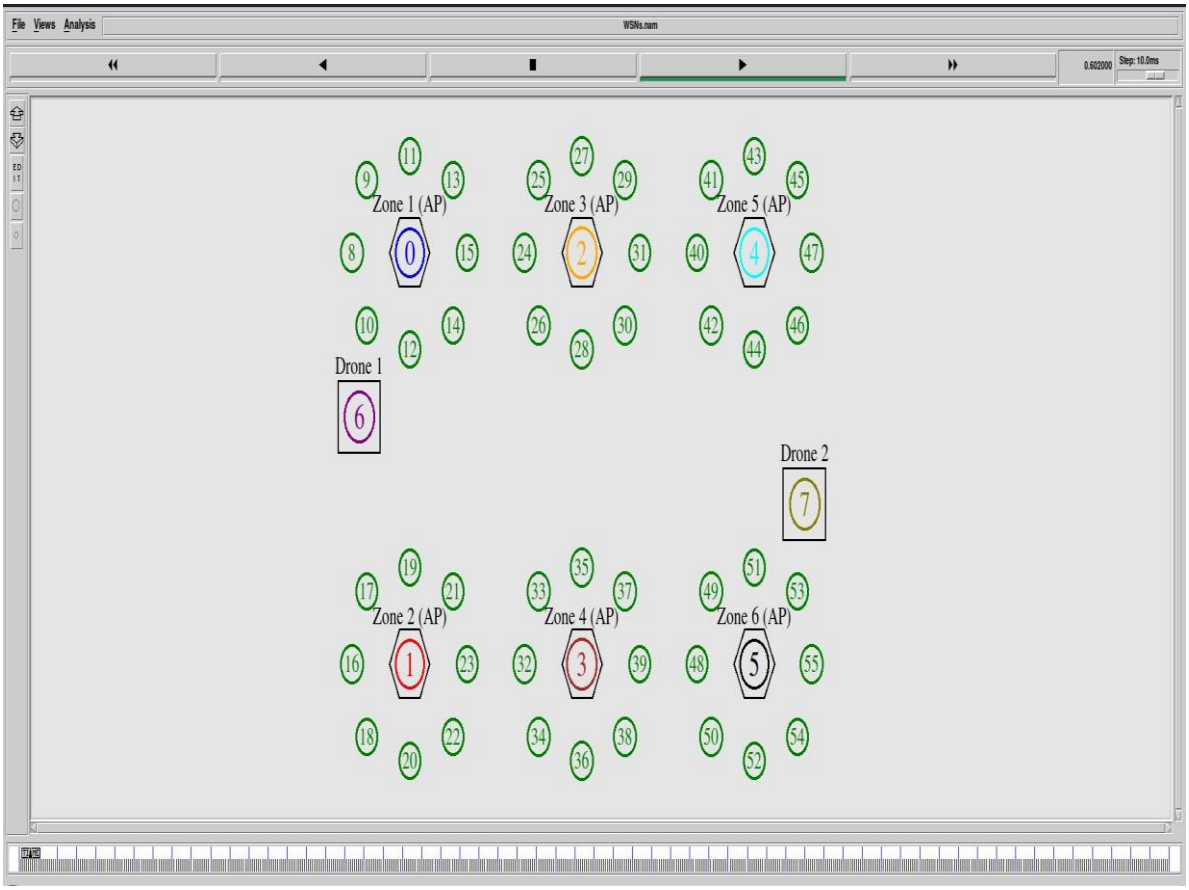

Figure 4.1: WSNs Simulation Scenario 1

The topology illustrated in Figure 4.1 represents the WSN architecture, which was used to carry out the simulations. In the simulations, this research study had a network topology of 900mX900m with 6 fixed located access points (APs) in the zones, labelled (AP-0, AP-1, AP-2, AP-3, AP-4 and AP-5), and 8 randomly located nodes for each zone (labelled Nodes 8-55), used to compare the three algorithms, as exemplified in Figures 4.1 and 4.2.

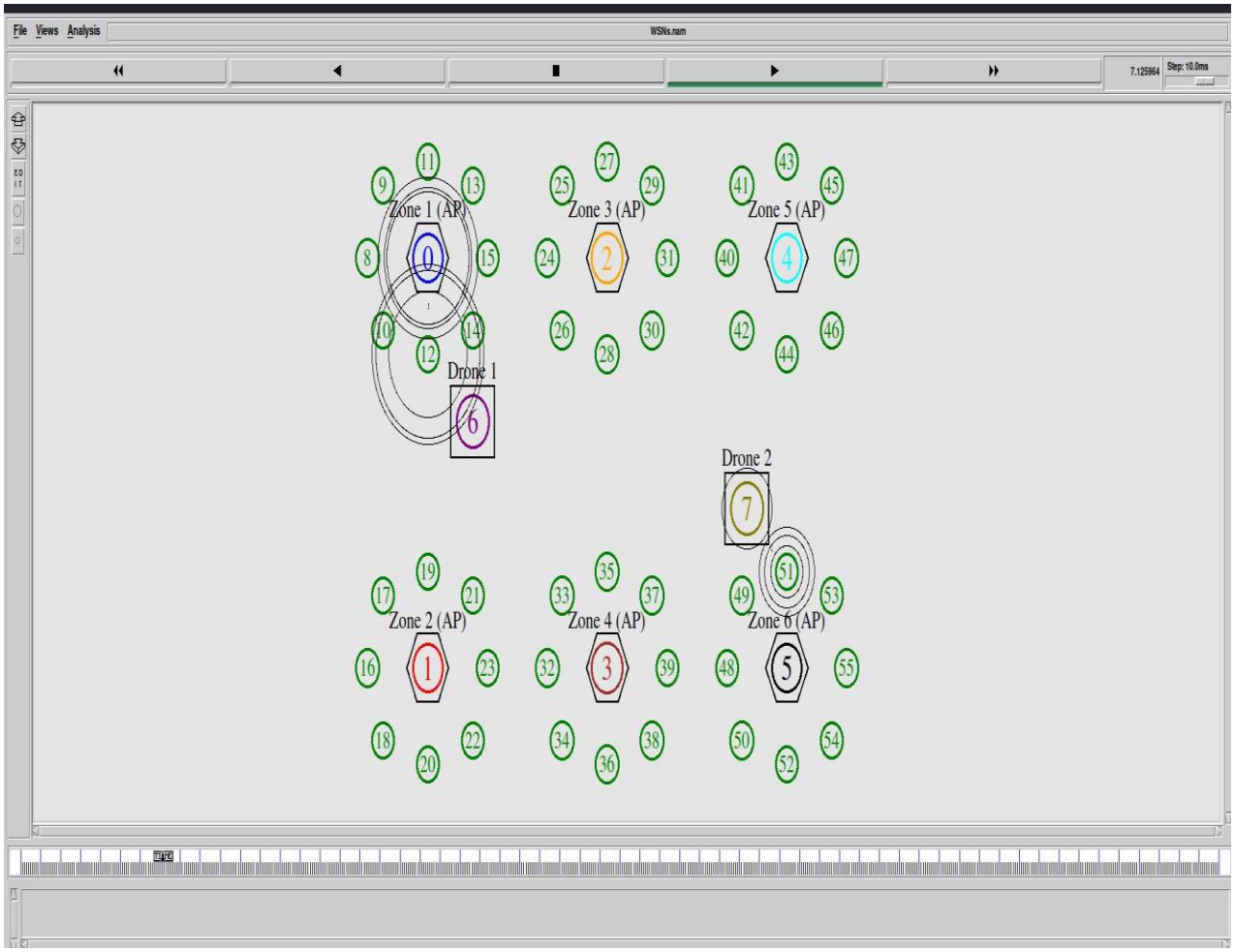

Figure 4.2: WSNs Simulation Scenario 2

The above Figure 4.2 illustrated that when Drone 1 and Drone 2 move around the zones within the agricultural environment, they start by collecting information through APs from the zone which is near to the drone. All APs collect packets from the SNs within the zones which are implemented into an agricultural environment. Therefore, when Drone 1 starts moving, it collects the packet from Zone 1 using AP-0; while Drone 2 starts collecting information from Zone 5 using AP-6 when it starts moving around the agricultural environment. This process occurs because, during the configuration of the simulation in this research study, Zone 1 was configured as the first zone to send its packets to Drone 1 using AP-0; while Zone 6 was configured as the first zone to send its packets to Drone 2 using AP-5. When the drones have collected the packets from Zones 1 and 6, they will move to the next zones which are Zones 3 and 4, being close to Zones 1 and 6. The drones will begin collecting packets on Zones 3 and 4 using the AP-2 on Zone 3 and the AP-3 on Zone 4, as illustrated in Figure 4.3.

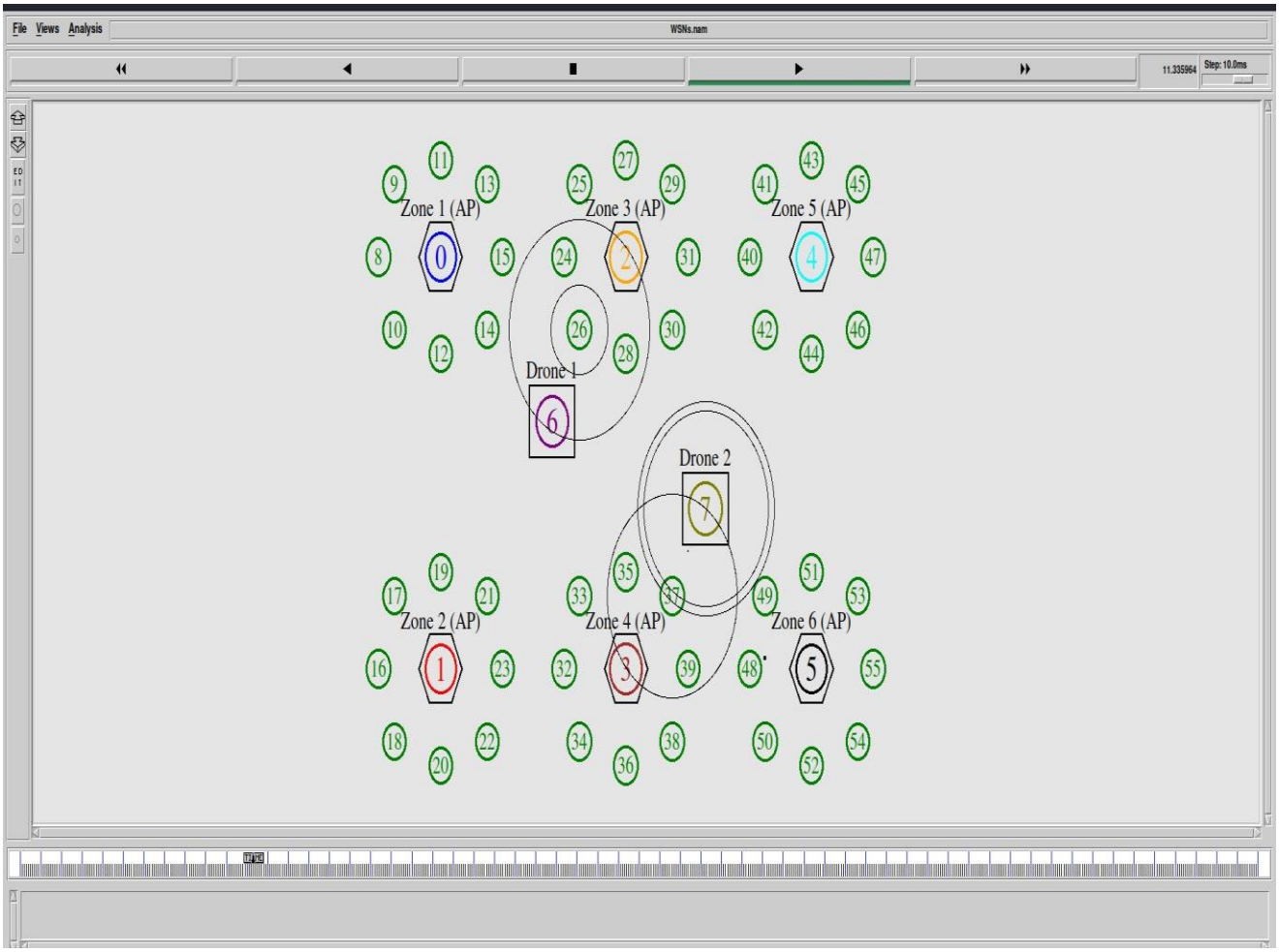

Figure 4.3: WSNs Simulation Scenario 3

The above Figure 4.3 shows Drone 1 collecting packets from Zone 3 using AP-2 within the agricultural environment. This process was configured as AP-2 in Zone 3 which sends packets to Drone 1 immediately after having collected packets from Zone 1 using AP-0; while Drone 2 is collecting packets from Zone 4 using AP-4 immediately after collecting packets from Zone 6, using AP-5. When the drones have collected the packets from Zones 3 and 4, they will move to the reaming zones, which are Zones 2 and 5, as illustrated in Figure 4.4.

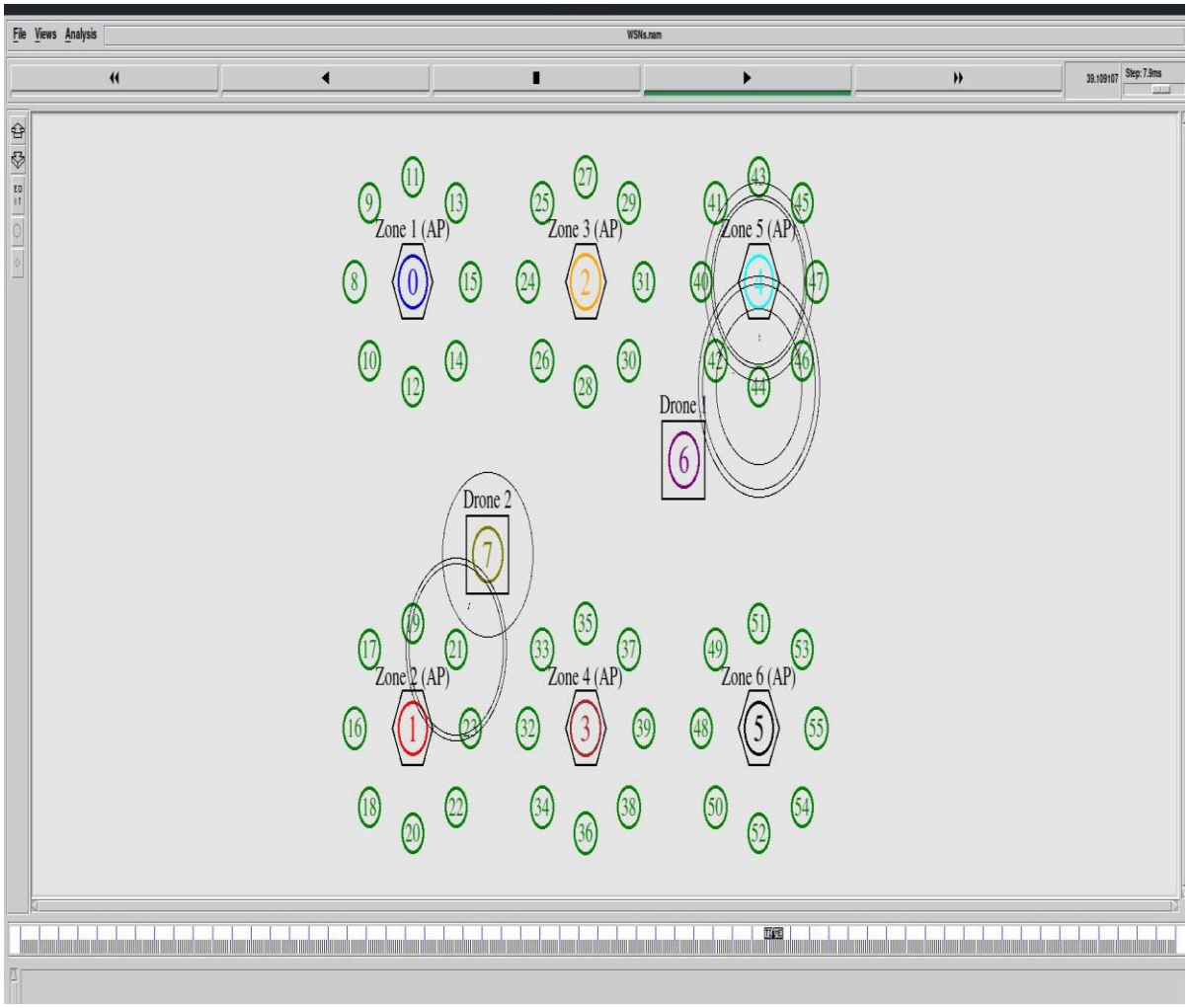

Figure 4.4: WSNs Simulation Scenario 4

The above Figure 4.4 shows the AP-4 in Zone 5 sending its packets to Drone 1 immediately after having collected packets from Zone 3. This means that during the configurations on NS-2, Zones 3 and 5 are configured as the last zones within the agricultural environment for sending their packets to the drones. When the drones have collected the packets from all zones (Zones 1 to 6) within the agricultural environment, the drones will then forward all the packets to the ISP. The agriculturalist will be able to access all the information collected at the farm.

Therefore, this research study assumes that each AP simulated within the agricultural environment covers a radius of 900 metres. This research study configured the simulation to start transmitting packets at 10 seconds, and to stop transmitting at 100 seconds from each zone, as shown in Figures 4.1, 4.2, 4.3, and 4.4 within the agricultural environment. This research study performed the simulations ten times in order to achieve very convincing results.

This research study used NS-2.35 out.tr script to record performance results gained in order to compare the three algorithms, namely, the ITRM algorithm, the PCC algorithm, and the ANNA algorithm. The packet loss, end-to-end delay and network throughput are the performance metrics analysed in our simulations. This is because these performance metrics were those that this research study needed most urgently to improve on within the agricultural environment. This research study summarises the simulation parameters and values used in the simulations in Table V.

Table 4.1: Simulation Parameters

Parameters	Values
Channel Type	Wireless Channel
Network Interface Type	Wireless Phy
Number of Nodes	55
Max Packets in ifq	100
Propagation Model	TwoRayGround
Antenna Model	OmniAntenna
Link Layer Type	LL
Simulation Area	900mX900m
Simulation Time	100 seconds
Bandwidth	20 GB/s for each AP
Routing Protocol	AODV
Communication Standard	TCP
MAC Protocol	IEEE 802.11ac
Queue Type	Queue/DropTail/PriQueue

This research study used the ad-hoc on-demand vector (AODV) routing protocol because this protocol creates routes only when they are needed, which makes it easier to be implemented into WSNs within the agricultural environment. In addition, AODV supports both unicast and multicast routing packet transmissions. The AODV builds routes between APs when source nodes (sensor nodes) need to establish and maintain communication with the APs on a wireless network. This research study further used the transmission control protocol (TCP) for high error rate handling. In

addition, this research study used the dual-band wireless technology (802.11ac) which supports more than one connection at the same time on both 5 GHz Wi-Fi and 2.4 GHz bands. Furthermore, 802.11ac is compatible with 802.11b/g/n which gives it more advantages than others. The 802.11b/g/n bandwidth is rated up to 1300 Mbps on a 5 GHz band and 450 Mbps on 2.4 GHz. This research study chose to use a propagation model, because its value is two-ray-ground reflection model. It is also more suitable for our computer simulation as it makes use of both the ground reflection and a direct path for communication. This is for a small wireless network simulation, and is more realistic than using a free-space model which adds simulation time. This research study configured the APs to use an omnidirectional antenna for both transmission and reception. For the processing and forwarding of packets, this research study used the Link Layer (LL). Furthermore, this research study used LossMonitor, for a packet sink that checks for packet losses. In conclusion, the simulations were run for 100 seconds and were repeated ten times in order to obtain the most convincing results.

4.3 Summary

This research study in this chapter provided a detailed discussion regarding the implementation and simulation of the proposed ITRM algorithm using NS-2. Furthermore, this research study discussed how the results were recorded and which plotting tool was used to graphically display the results obtained during the simulations. In the next chapter, this research study presents the simulation results recorded during the several simulations conducted to evaluate the performance of the proposed ITRM algorithm.

Chapter 5: Results and Discussion

5.1 Introduction

Network simulators allow researchers to evaluate protocols and applications under varying network configurations. Simulators allow researchers to model the network in order to gain approximate behaviour of the real communication networks, it being expensive and time-consuming to set up a real network. In this chapter, this research study discusses the performance of the proposed ITRM algorithm, based on the results analysed when conducting the simulations with respect to the three performance metrics that this research study considered: packet loss, packet delay, and network throughput. This is because QoS relies on these three performance metrics during packet transmission in WSNs.

This research study used trace files to record the results obtained during simulations, to analyse the average packet loss, packet delay, and network throughput. This research study used the Python programming language to display the analysed results graphically obtained from the several simulations conducted. In Appendix D. The sample Python programming source code is provided. This research study further provides the code AWK written to calculate the total average of the performance metrics considered in this study.

This research study organized the remainder of this chapter as follows: In Section 5.2, this research study presents the computer simulation evaluation. In Section 5.3, this research study presents the simulation results and discussions. In Section 5.4, this research study presents the computational complexity validation and limitations. Finally, Section 5.5 provides a chapter summary.

5.2 Computer Experimental Evaluation

This research study created a simulation topology using a TCL script to evaluate the proposed ITRM algorithm. In addition, this research study used NAM interface/simulation topology, as explained in Section 4.2, and illustrated in Figures 4.1, 4.2, 4.3, and 4.4, to observe node movement and transmission of packets during the simulations. Python programming language was implemented to display the obtained and analysed simulation results in graphical format. Moreover, this research study coded AWK programmes to calculate the total average of the performance metrics considered in this study, such as the amount of packet loss, packet delay, and network throughput.

5.3 Findings and Discussion

In this section, this research study provides insight into the analysis of the results obtained from the simulations performed to evaluate the proposed ITRM algorithm *vis-à-vis* the MLCC and the LBRM. This research study ran the simulation multiple

times in order to present reliable results. The performance metrics analysed in our simulations include:

- Packet Loss – occurs when one or more packets fails to reach the intended destination during the process of packet transmission. For many users, packet loss manifests itself in the form of network disruption, slowing the network performance or even total loss of network connectivity.
- Packet delay – occurs when one or more packets takes time to reach its destination from the source node, as per allocated time within the network environment. This reflects that the packet transmitted has been delayed in reaching its destination, resulting in the process slowing the network performance.
- Network throughput – is the amount of data moved successfully from one place to another in a given time period. Typically, the period is measured in bits per second (bps); as in megabits per second (Mbps) or gigabits per second (Gbps).

This research study compared the ITRM algorithm with the MLCC and the LBRM mechanisms. This research study chose the MLCC, mainly because the algorithm provides high flexibility of packet transmission which is implemented by the decision-tree algorithm during packet distribution within the network environment. Furthermore, the MLCC is used for estimating the congestion in a dynamic network

environment by predicting the traffic flow, using parameters such as traffic speed and delay, as discussed in Section 3.3.1. The LBRM was chosen to perform the load balancing routing for each link that transmitted the packets in WSNs within an agricultural environment, as discussed in Section 3.3.2. Furthermore, each link in the load balancing routing is used to maintain a single queue of packets from all flows passing through the various nodes within the network environment.

Both the MLCC and the LBRM use multiple parameters to reduce packet congestion in WSNs within the agricultural environment. The review of the literature claims that both the MLCC and the LBRM work best when it comes to reducing packet congestion in WSNs within the agricultural environment. Therefore, this research study attempted to ascertain whether the proposed ITRM algorithm could outperform those two algorithms.

This research study evaluated the proposed ITRM algorithm, the MLCC, and the LBRM using two scenarios based on both low priority packet and high priority packet during packet transmission of WSNs within the agricultural environment. Scenario 1 deals with the transmission of packets for low-priority packets in which the packet size is less than 10 bytes. Meanwhile, Scenario 2 deals with the transmission of packets for high-priority packets with the packet size at 100 bytes. This study separated the results for both the low priority packet and the high priority packet.

5.3.1. Scenario 1: Performance evaluation for low-priority packets

5.3.1.1 Average packet loss

Packet loss refers to the process that occurs when one or more packets fail to reach the intended destination during the packet transmission within the network. Therefore, it is important that this research study minimizes packet loss, in order to improve the network performance during packet transmission of WSNs within the agricultural environment. The proposed ITRM algorithm was compared with the MLCC and the LBRM to test the effectiveness of the proposed algorithm, as illustrated in Figure 5.1. Furthermore, Figure 5.1 compares the average packet loss of the three algorithms based on low-priority packets. The simulation results showed that the proposed ITRM algorithm, the MLCC, and the LBRM each experienced an average packet loss of 0.27%, 0.83%, and 0.52 %, respectively. The packet loss was reduced by 0.27%. Experimental evaluations show that the proposed ITRM algorithm outperforms both the MLCC and the LBRM in terms of packet loss, in general. The process traffic prioritization designed in Section 3.2 aided in this improved performance. Load balancing also plays an enormous role in this regard.

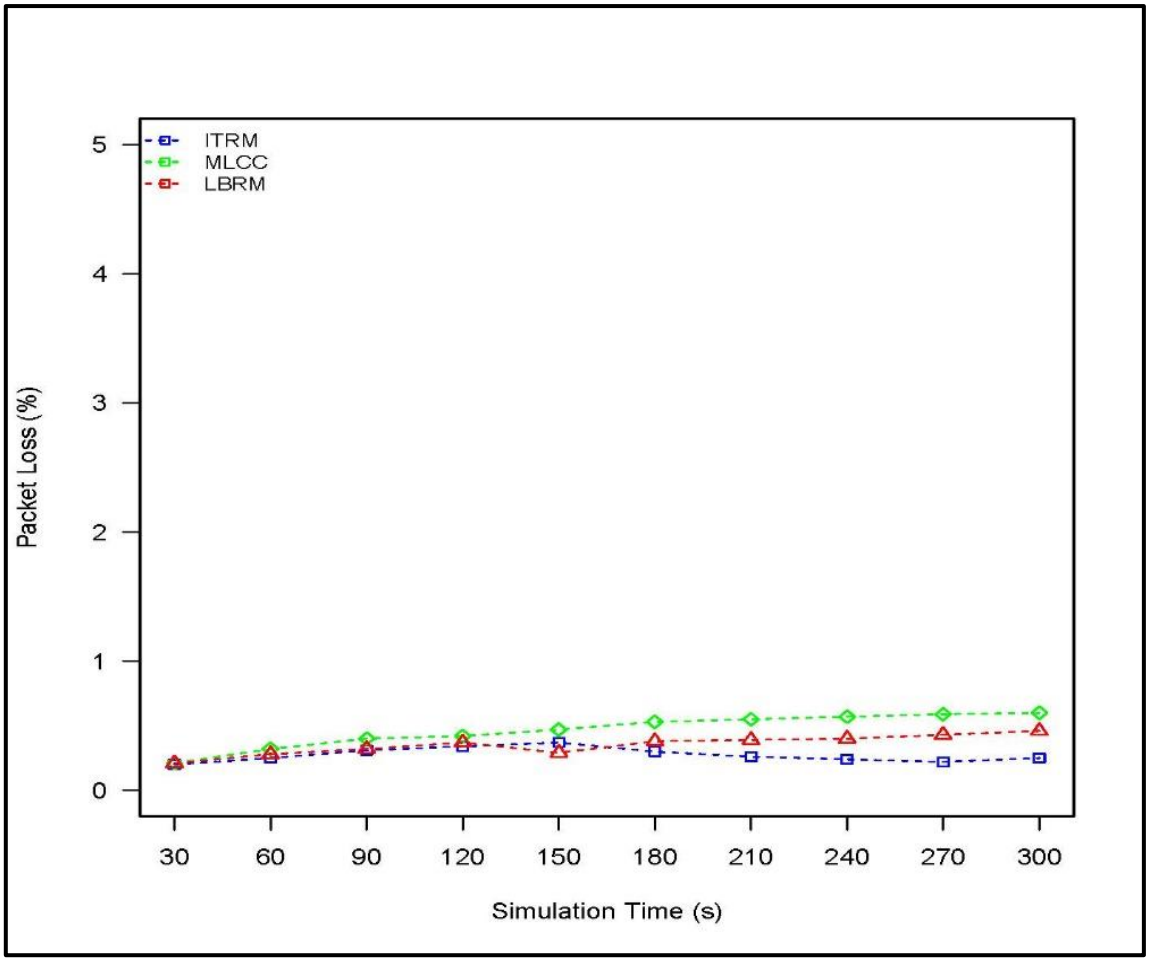

Figure 5.1: Average amount of packet loss

5.3.1.2 Average packet delay

Normally, packet delay is defined as the time it takes one or more packets to reach the destination node from the source node, according to the allocated time within the network. Therefore, it is important for this research study to minimize packet delay during transmission of WSNs deployed within an agricultural environment. The experimental evaluations for packet delay are illustrated in Figure 5.2. This is to determine the effectiveness of the proposed algorithm compared with the MLCC and the LBRM. The proposed ITRM algorithm, the MLCC and the LBRM, each obtained

an average packet delay of 0.4%, 1.3%, and 0.9%, respectively. The proposed ITRM algorithm produces less packet delay, as it reduced delay by 0.4% compared with the others. Figure 5.2 compares these algorithms in terms of low-priority packet transmission. As can be seen from the experiment, the proposed ITRM outperforms the MLCC and the LBRM from the start of the simulation to the end. The reason behind this is that this study considered traffic prioritization to ensure that specific applications or subnets are guaranteed a certain amount of uplink bandwidth at all times. The packets are assigned low, normal, and high priority according to the priority levels within the network, as defined in Section 3.3; as well as the importance of the data being communicated to the agricultural environment.

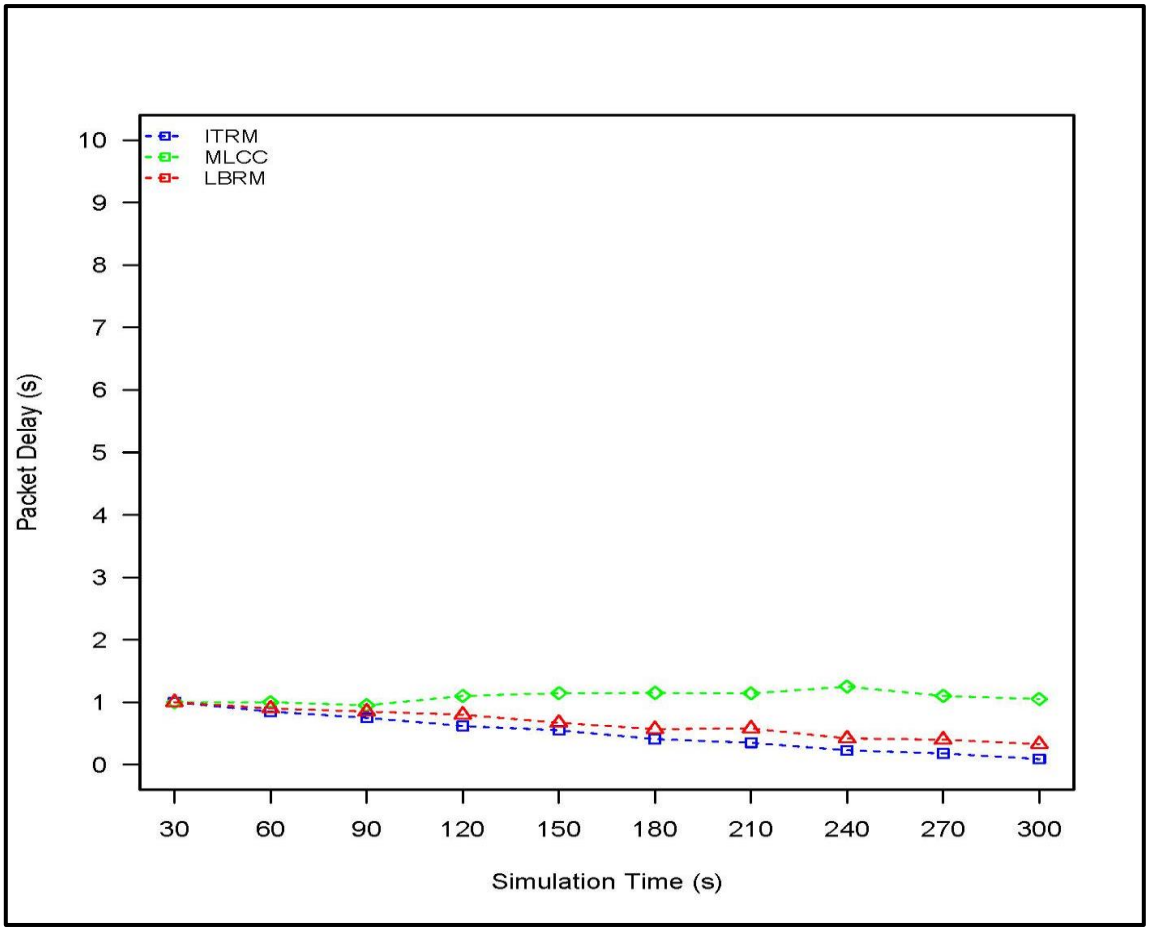

Figure 5.2: Average amount of packet delay

5.3.1.3 Average network throughput

In general, network throughput refers to the amount of data moved successfully from one place to another in a given time period, and typically measured in bits per second (bps), as in megabits per second (Mbps) or gigabits per second (Gbps). This section discusses the evaluation and analysis of the effectiveness of network throughput performance on low-priority packets for the proposed ITRM algorithm *vis-à-vis* the MLCC and the LBRM. The proposed ITRM algorithm produces improved network throughput, as illustrated in Figure 5.3. When compared, the proposed ITRM

algorithm, the MLCC, and the LBRM, each obtained an average network throughput of 98.3%, 89.2 %, and 40.4%, respectively. The ITRM algorithm produced an average network throughput of 98.3%. This is due to the integrated algorithms. Each plays a huge role in ensuring that there is a guaranteed QoS, such that the LBRM focuses on balancing the network load. Meanwhile, the MLCC helps predict possible packet congestion; and offers some decision-making mechanisms based on packet transmission within the network, as discussed in Section 3.3.

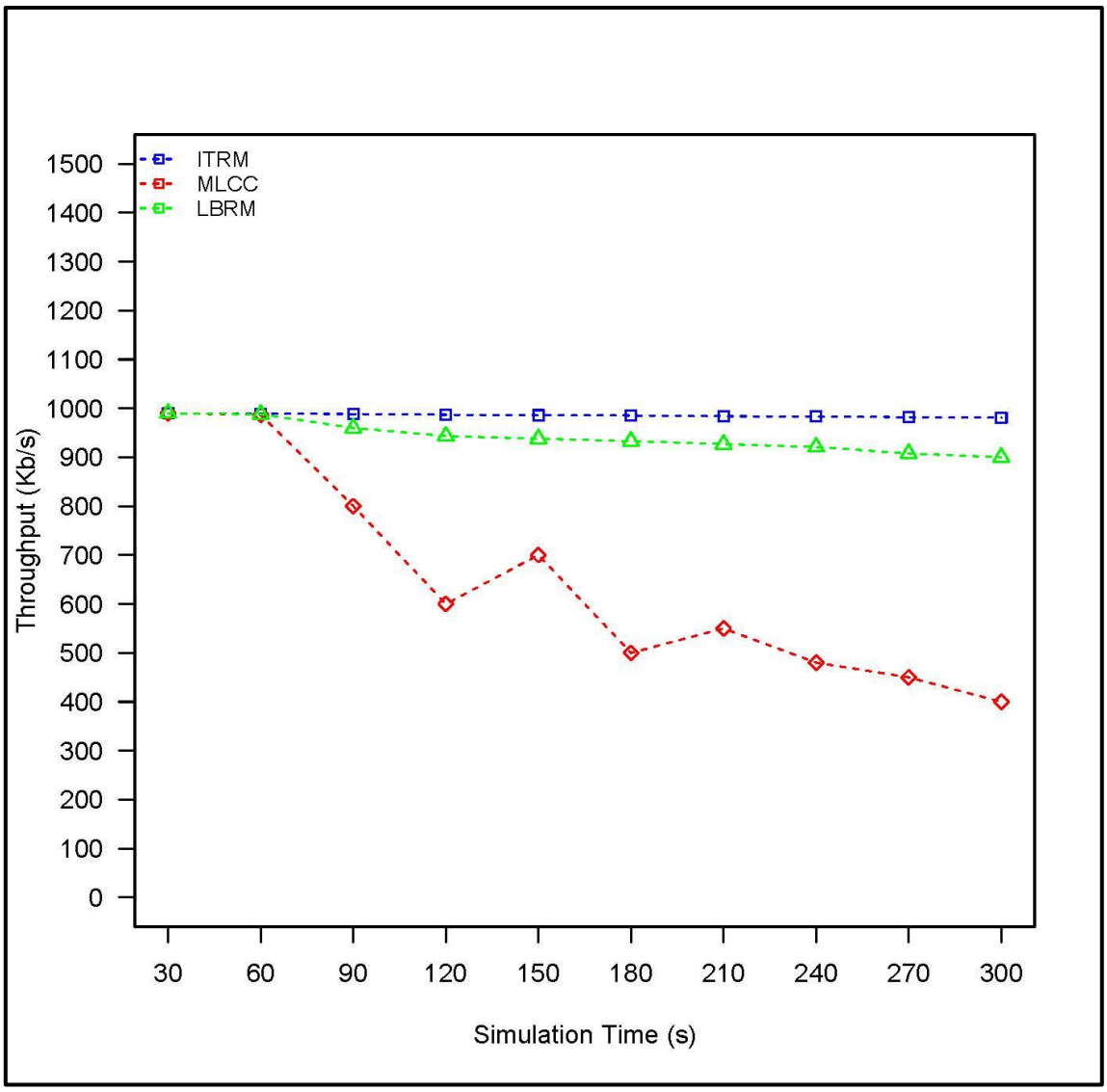

Figure 5.3: Average network throughput

5.3.2. Scenario 2: Performance evaluation for high-priority packets

5.3.1.4 Average packet loss

A packet loss occurs when one or more packets do not reach their intended destination during the packet transmission process within the network. Therefore, it is essential that this research study minimizes packet loss during packet transfer of WSNs within the agricultural environment, to enhance network performance. According to Figure 5.4, the proposed ITRM algorithm was compared with the MLCC and the LBRM to test the effectiveness of the proposed algorithm. Furthermore, Figure 5.4 shows the comparison of average packet loss of the three algorithms based on high-priority packets. The simulation results showed that the proposed ITRM algorithm, the MLCC, and the LBRM suffered on average packet losses of 1.3 per cent, 1.8 per cent, and 1.6 per cent, respectively. In general, experimental evaluations demonstrate that the proposed ITRM algorithm outperforms both the MLCC and the LBRM algorithms in terms of packet loss. As a result of the process traffic prioritization designed in Section 3.2, this improved performance was achieved. Load balancing also plays an important role in this regard.

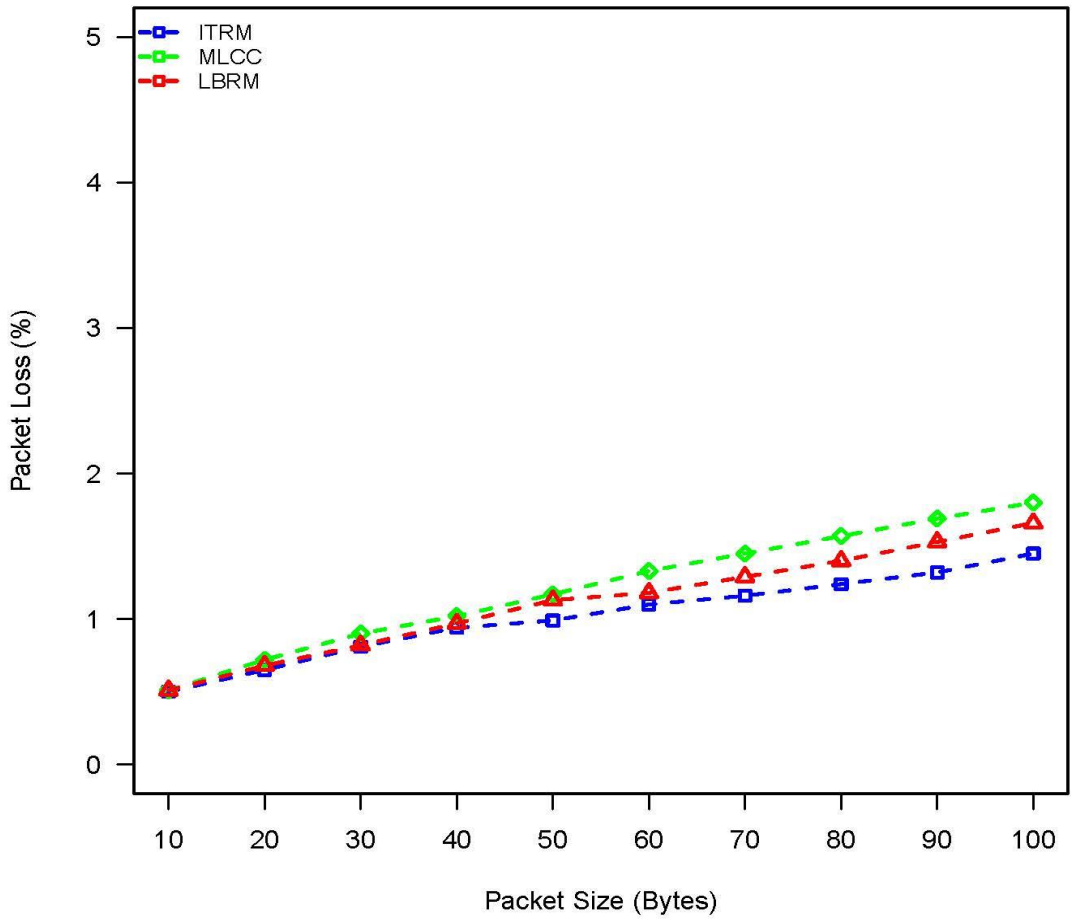

Figure 5.4: Average amount of packet loss

5.3.1.5 Average packet delay

Typically, packet delay is defined as the length of time it takes to transmit a packet from the source node to the destination node according to the allocated time within the network. Consequently, the goal of this research study is to minimize packet delays during the transmission of WSNs in a field environment. The experimental evaluation for packet delay is presented in Figure 5.5. The purpose here is to assess

the efficiency of the proposed algorithm compared with that of the MLCC and the LBRM. The proposed ITRM algorithm, that of the MLCC and the LBRM, each obtained an average packet delay of 1.06%, 1.14%, and 2.06%, respectively. According to Figure 5.5, these algorithms are compared in terms of high-priority packet transmission. The proposed ITRM consistently outperforms the MLCC and the LBRM from the beginning to the end of the simulation, as shown in the experiment. The reason for this is that traffic prioritization was considered in order to guarantee that specific applications or subnets would always receive a certain amount of uplink bandwidth. The packets are assigned as low, normal, and high priority according to the priority levels defined within the network as reflected in Section 3.3. The importance of the data being communicated to the agricultural environment is also taken into account.

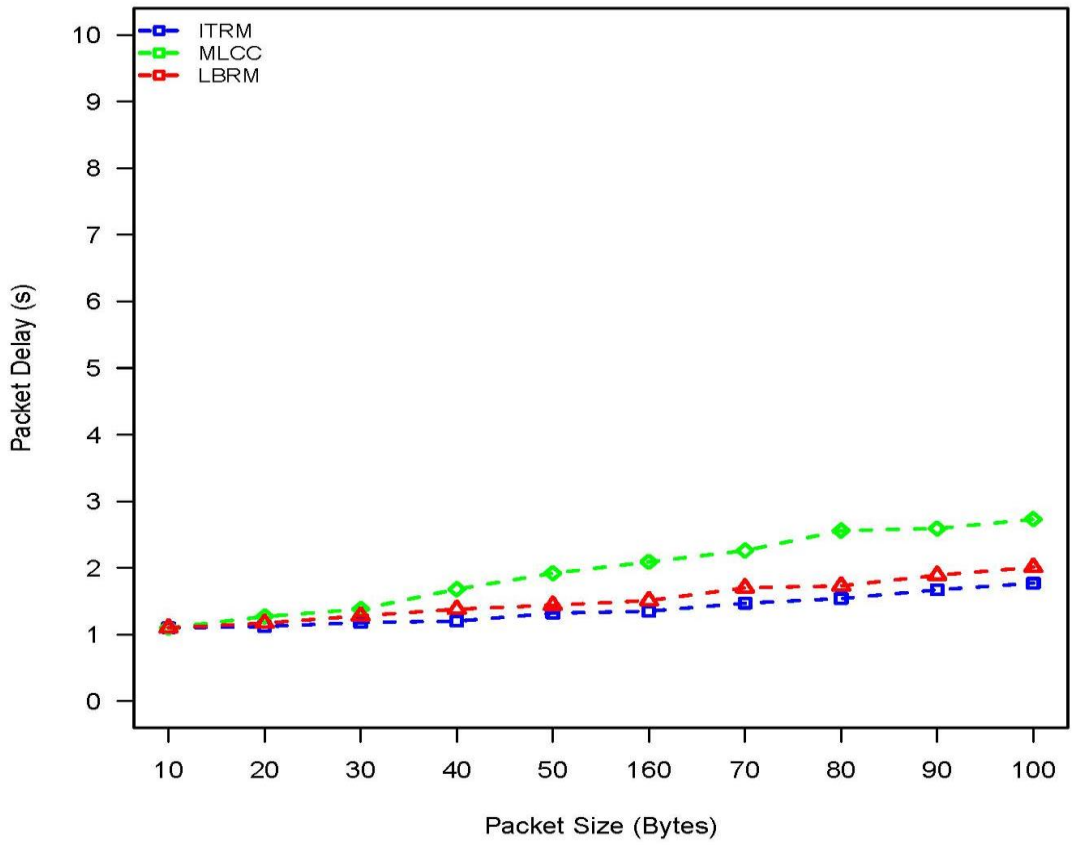

Figure 5.5: Average amount of packet delay

5.3.1.6 Average network throughput

The concept of network throughput refers to how much data is transmitted from one place to another in a given period of time. This usually measured in bits per second (bps), such as megabits per second (Mbps) or gigabits per second (Gbps). For the proposed ITRM compared with both the MLCC and the LBRM, this section analyses and evaluates the network throughput performance for high-priority packets. Based on Figure 5.6, the proposed ITRM algorithm produces increased network throughput. The proposed ITRM algorithm and that of the MLCC and the LBRM each achieved

an average network throughput of 95.7%, 81.2 %, and 38.7%, respectively. This is because each of these algorithms contributes to ensuring that there is a guaranteed quality of service, so that the LBRM can focus on balancing the network load. The MLCC, on the other hand, provides some decision-making mechanisms for predicting packet congestion and determining how packet transmission within the network is managed.

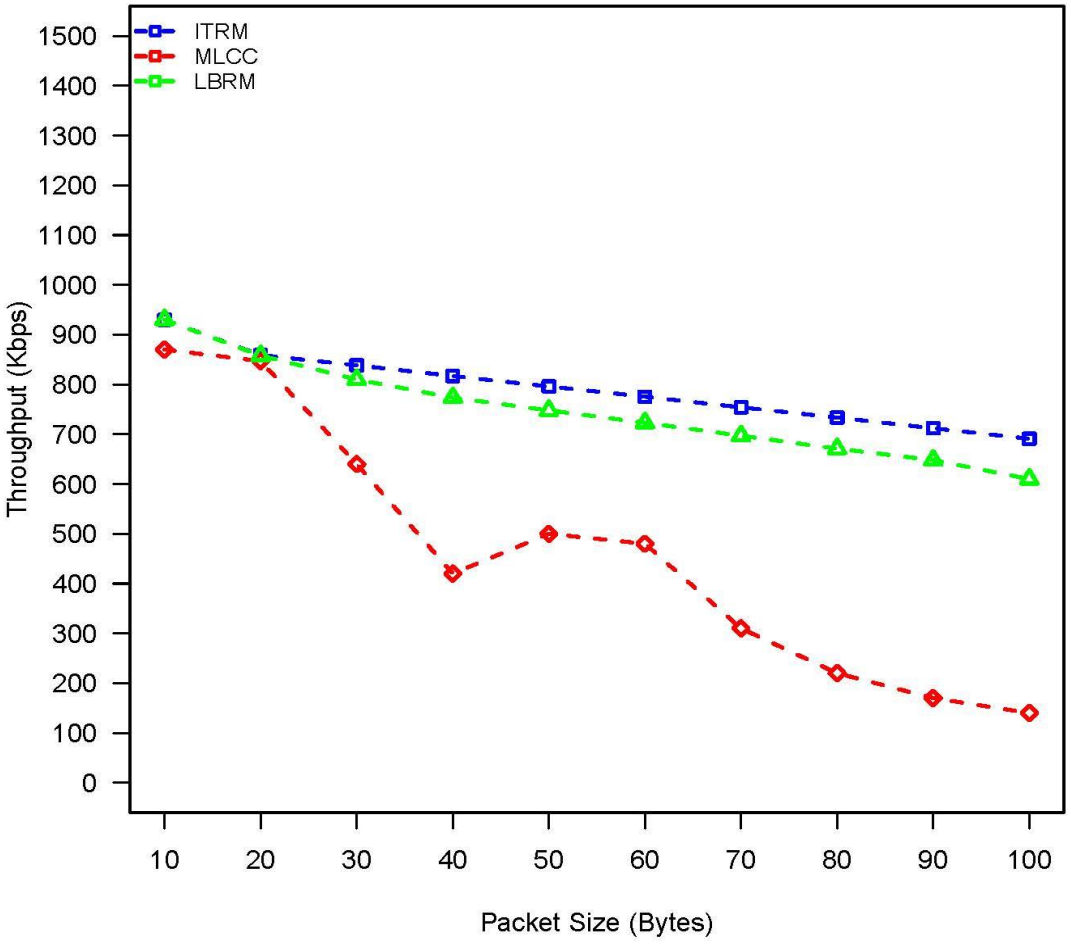

Figure 5.6: Average network throughput

In this study, the simulation results demonstrated that the proposed ITRM algorithm experienced minimal packet congestion for both the low-priority and high-priority packet using WSNs within the agricultural environment when compared with the MLCC and the LBRM, as illustrated by the experimental evaluations. This research study used the machine learning mechanism to predict the possible packet congestion within a network. This was in order to transmit the packet to its destination without any delay or packet loss, meanwhile ensuring improved throughput.

Moreover, the proposed ITRM algorithm obtains better results by employing the load balancing and machine learning methods to ensure the most efficient distribution of packet in WSNs. Both the MLCC and the LBRM seem to experience somewhat more packet congestion than the proposed algorithm. The benefits of integrating these traditional methods lie in the application of a decision-tree algorithm, as well as considering link stability prior to distributing packets within the network. However, during the simulation, both the MLCC and the LBRM experienced increased packet delay and packet loss, while poor network throughput is also observed by comparison with that of the proposed ITRM algorithm.

As a result, this study integrated the MLCC and the LBRM, mainly to reduce communication breakdown for farmers using WSNs and drones to collect and share data, as discussed in Section 1.1. The MLCC is used to predict possible congestion

problems in time, while the LBRM is used for controlling the transmission of packets using multiple parameters within the network. This has led to reduced packet delay, packet loss, and better network throughput, thus providing better QoS.

5.4 Computational Complexity, Validation, and Limitations

This section presents the computational complexity and limitations of the evaluated ITRM, MLCC, and LBRM algorithms, as shown in Table VI.

Table 5.1: Computational Complexity, Validation, and Limitations

Algorithm	Packet Transmission	Computational Complexity	Limitation
ITRM algorithm	The ITRM algorithm uses machine learning and load-balancing algorithms to improve QoS.	The computational complexity can be caused by the increase in the number of SNs within the network.	The increase in the number of drones might require some changes in the algorithm, especially during load balancing.
MLCC	This mechanism used a decision-tree algorithm when transmitting packets within the network.	This depends on whether it is dealing with high, normal, or low prioritized packet transmission in the network.	The mechanism does not predict possible congestion that may occur in the network.
LBRM	This mechanism determines the link stability to transmit packets within the network.	Link stability might not be correctly identified as a result of too much load not balanced accordingly.	The mechanism cannot handle high network load at the same time using the available link within the network.

5.5 Summary

This chapter discussed the computer simulation evaluation, and provided result discussions based on the simulation scenarios provided in Section 5.3. This research study discussed the results of the three performance metrics considered in this chapter, namely, packet loss, packet delay, and network throughput. The network performance or better QoS relies on these performance metrics during the packet transmission process in WSNs within the agricultural environment. As illustrated in Figures 5.1 – 5.6, this research study demonstrated a behavioural comparison of the proposed ITRM algorithm, the MLCC and the LBRM. In the next chapter, this research study presents a conclusion and suggests future work. Furthermore, this research study discusses issues that are not addressed in this research study.

Chapter 6: Conclusion and Future Work

6.1. Introduction

This research study designed and implemented an ITRM algorithm to reduce packet congestion caused by head-of-line blocking which leads to packet loss, packet delay and poor network throughput in WSNs within an agricultural environment. The proposed ITRM algorithm is designed by integrating the MLCC with the LBRM to overcome packet congestion caused by head-of-line blocking in WSNs within an agricultural environment. This research study introduced the MLCC into the proposed ITRM algorithm to predict possible packet congestion; it offers a decision-making mechanism based on packet transmission within an agricultural environment. This means that packet transmission in WSNs becomes more intelligent, considering the process of avoiding packet congestion within the network in an agricultural environment.

This research study organized the remainder of this chapter as follows: In Section 6.2, this research study discusses in detail how the set aim and objectives were achieved. In Section 6.3 a summary of this study is presented. The challenges encountered during the study are discussed in Section 6.4. This research study suggests future work in Section 6.5. Finally, Section 6.6 provides a chapter summary.

6.2. Aim and Objectives Achievement

In this section, this research study discusses how the set aim and objectives have been achieved, as outlined in Section 1.5 of Chapter 1.

1. **To identify the current algorithms used for traffic management in WSNs within an agricultural environment.**

In Section 2.8, this research study identified and analysed packet traffic-management algorithms previously used. These algorithms helped to avoid packet congestion resulting in packet loss, packet delay, and poor network throughput during the packet transmission of WSNs within an agricultural environment. This research study identified that the previously proposed traffic-management algorithms had failed to minimize the head-of-line packet congestion during packet transmission within WSNs. As a result, these previously proposed traffic-management algorithms have caused high packet loss, packet delay, and poor network throughput during packet transmission within WSNs. This is mainly because these traffic-management algorithms cannot predict the packet congestion that occurs in a network environment during the packet distribution.

This research study proposed an ITRM algorithm to ensure that there is a prediction of packet congestion and load-balancing before packet congestion occurs during packet transmission in WSNs. This research study designed an ITRM algorithm by

integrating the MLCC and the LBRM to reduce packet loss and packet delay, and to improve network throughput during packet transmission of WSNs.

The proposed ITRM algorithm achieved this by using the ML method to predict the packet congestion and load balancing for packet distribution in WSNs. For the packet transmission, the proposed ITRM algorithm used multiple input parameters, as mentioned in Section 1.1 of Chapter 1.

2. To design an ITRM algorithm that reduces traffic congestion of WSNs within an agricultural environment.

This research study designed an ITRM algorithm by effectively integrating the MLCC and the LBRM in order to diminish packet loss and packet delay, and to improve network throughput, as presented in Section 3.2 of Chapter 3. This research study presented the WSNs system architecture using Figure 3.1. During the design of the proposed ITRM algorithm, this research study used the MLCC to predict the packet congestion before it occurs. The study used the LBRM for load balancing during packet transmission of WSNs within the agricultural environment. This process minimized the occurrence of packet congestion. It decreases packet loss and packet delay, and improves network throughput of WSNs within an agricultural environment.

3. To implement the proposed ITRM algorithm to reduce traffic congestion of WSNs within an agricultural environment.

This research study used NS-2.35 to implement the proposed ITRM algorithm as illustrated in Section 4.2 of Chapter 4. The NS-2 makes use of C++ to carry out core communication functions and uses an OTcl to create a simulation interface. This research study presented the WSNs topology in Figure 4.1 used in carrying out the simulations.

This research study ran the simulation over five times to gain convincing results. Moreover, this research study used NS-2.35 out.tr script to record performance gained when comparing the proposed ITRM algorithm with the MLCC and the LBRM. In addition, this research coded AWK scripts to interpret the trace files data, thus gaining useful information such as the number of packets lost, packet delay, and network throughput. Moreover, the R programming language was used to display the obtained and analysed simulation results in the form of graphs.

In this research study, Table VI was used to summarize the simulation parameters and values of the simulation. The proposed ITRM algorithm was displayed as the most effective algorithm to minimize the packet congestion in WSNs compared with the MLCC and the LBRM. The proposed ITRM algorithm managed to minimize the packet loss and packet delay; it increased the network throughput of WSNs within the agricultural environment.

4. To evaluate the efficiency of the proposed ITRM algorithm *vis-à-vis* current algorithms.

This research study has evaluated the performance of the proposed ITRM algorithm compared with the MLCC and the LBRM in WSNs within an agricultural environment. In this research study, the metrics performance of simulations analysed include packet loss, packet delay, and network throughput. This is because the network performance relies on these three performance metrics during packet transmission of WSNs. Simulation results were presented using Figure 5.1 – 5.6, as illustrated in Section 5.3 of Chapter 5.

The proposed ITRM algorithm outperformed the MLCC and the LBRM during performance evaluation. This is because the proposed ITRM algorithm utilizes the ML and load balancing mechanism to minimize the packet congestion in WSNs within the agricultural environment. Furthermore, the proposed ITRM algorithm used the prediction method to predict the packet congestion before it occurs in WSNs. This decreases packet loss and packet delay that affects the network performance negatively, while improving network throughput in comparison with the MLCC and the LBRM in WSNs within the agricultural environment.

6.3. Research Summary

This research study has tracked the expansion of wireless networks over the past decade. WSNs make use of wireless devices to communicate with one another within the network. WSNs make it easier for network users to monitor their environment using wireless devices. However, WSNs come with challenges of packet congestion which leads to packet delay, packet loss, poor network throughput, among many other features.

This research study proposed and designed the ITRM algorithm to overcome the challenge of head-of-line packet congestion resulting in packet loss, packet delay, and poor network throughput of WSNs within an agricultural environment. In Chapter 3, this research study discussed the design of a proposed ITRM algorithm by integrating the MLCC and the LBRM to reduce packet loss, and packet delay; and to improve network throughput in WSNs within the agricultural environment.

This research study used NS-2 to simulate the proposed IRTM algorithm. The NS-2 is less complex than other simulators such as OPNet, NS-3, as well as MATLAB. In Chapter 4, this research study discussed the implementation of the proposed ITRM algorithm using NS-2. In Chapter 5, this research study provided simulation results and analysis based on three performance metrics, namely, packet loss, packet delay, and network throughput, using Figure 5.1 – 5.6, as illustrated in Section 5.3 of Chapter 5. Simulation results presented using NS-2 demonstrated that the proposed

ITRM algorithm produces better results than the MLCC and the LBRM of WSNs within an agricultural environment. The proposed ITRM algorithm demonstrated an average of 0.25% packet loss, 0.89% packet delay, and a 98.3% better network throughput than the MLCC and the LBRM.

The demonstrated simulation results show that the proposed ITRM algorithm outperforms the MLCC and the LBRM in terms of packet loss, packet delay, and network throughput. Thus, the researchers in this study believe that they have successfully achieved the objectives of this study, and that the research will find applications in industries, academia, inter alia.

6.4. Challenges Encountered

This research study required much time to implement the required resources. The researcher had to work hard every day, even during the recess and holidays. Evaluating the proposed solution using other simulation tools such as QualNet, OMNeT++, and MATLab would have taken undue extra time. Hence, this research study used an open-source software named NS-2 to implement the proposed ITRM algorithm. In addition, this research study collaborated with other researchers to help with the required C++ programming skill, which this research study needed in implementing the proposed ITRM algorithm in NS-2.

6.5. Future Work

In this section, this research study suggests future work that can be considered to improve the performance of the proposed ITRM algorithm.

1. Future work can focus on evaluating the proposed ITRM algorithm to accommodate various other environments which include complex environments such as in the military, healthcare, traffic management fields, amongst others.
2. Furthermore, the proposed ITRM algorithm performance may be improved by testing it on real WSNs environments within an agricultural environment.
3. During the transmission of packets this research study did not consider any security issues that may arise in WSNs within the agricultural environment. Future work can thus also focus on possibilities of security issues during packet transmission.

6.6. Summary

In this chapter, this research study discussed how the set aim and objectives were achieved. This research study provided a summary, based on the presented simulation results, using Figures 5.1 – 5.6, as indicated in Section 5.3 of Chapter 5. This research study believes that the objectives of this study were successfully attained. This research study further discussed the challenges encountered when conducting the research, and how each challenge was tackled. In addition, this

research study suggested future research work, focusing on testing the proposed ITRM algorithm performance on WSNs within the agricultural environment.

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APPENDIX A: TABLE OF NOTIONS

i	node
v	Coalition value
P_n	A Packet with its packet number per link
P_i	Any packet in a network
N	Set of nodes
L	Link load
L_i	Link interference
H	Hop Count
H_P	Previous Hop Count
V	Number of vertices
M_P	Previous integrated metric value
M_N	New integrated metric value
C_{PE}	Previous Expected Transmission Count

C	Expected Transmission Count
T_P	Previous Round-trip time
T	Round-trip time
P_H	Hop count path
P_L	Number of packets lost
X_L	Network users having low bandwidth traffic
X_H	Network users having high bandwidth traffic

APPENDIX B: TCL SCRIPT

```
#==================================
#             Simulation parameters setup
#==================================
set val(chan)   Channel/WirelessChannel          ;# Channel type
set val(prop)   Propagation/TwoRayGround  ;# Radio-propagation model
set val(netif)  Phy/WirelessPhy                  ;# Network interface type
set val(mac)    Mac/802_11                       ;# MAC type
set val(ifq)    Queue/DropTail/PriQueue          ;# Interface queue type
set val(ll)     LL                              ;# Link layer type
set val(ant)    Antenna/OmniAntenna              ;# Antenna model
set val(ifqlen) 50                              ;# Max packet in ifq
set val(nn)     56                              ;# Number of nodes
set val(rp)     AODV                            ;# Routing protocol
set val(x)      1800                            ;# X dimension of topography
set val(y)      840                             ;# Y dimension of topography
set val(stop)   60.0                            ;# Time of simulation end

#==================================
#                         Initialization
#==================================
#Setting the simulator objects
set ns_ [new Simulator]

#Define different colors for data flows (for NAM)
$ns_ color 1 Blue
$ns_ color 2 Red

#create the nam and trace file:
set tracefd [open WSNs.tr w]
$ns_ trace-all $tracefd

set namtrace [open WSNs.nam w]
$ns_ namtrace-all-wireless $namtrace  $val(x) $val(y)

set topo [new Topography]
$topo load_flatgrid $val(x) $val(y)

# general operational descriptor- storing the hop details in the network
create-god $val(nn)

#Defining node configuration
$ns_ node-config \
                -adhocRouting $val(rp) \
                -addressingType flat \
                -llType $val(ll) \
                -macType $val(mac) \
                -ifqType $val(ifq) \
```

```
                -ifqLen $val(ifqlen) \
                -antType $val(ant) \
                -propType $val(prop) \
                -phyType $val(netif) \
                -topoInstance $topo \
                -agentTrace ON \
                -routerTrace ON \
                -macTrace ON \
                -movementTrace ON \
                -channelType $val(chan)

#Creating wireless nodes (access points)
set ZoneOne [$ns_ node]
$ZoneOne add-mark "" "" hexagon
set ZoneTwo [$ns_ node]
$ZoneTwo add-mark "" "" hexagon
set ZoneThree [$ns_ node]
$ZoneThree add-mark "" "" hexagon
set ZoneFour [$ns_ node]
$ZoneFour add-mark "" "" hexagon
set ZoneFive [$ns_ node]
$ZoneFive add-mark "" "" hexagon
set ZoneSix [$ns_ node]
$ZoneSix add-mark "" "" hexagon

#Creating wireless node (drones)
set DroneOne [$ns_ node]
$DroneOne add-mark "" "" square
set DroneTwo [$ns_ node]
$DroneTwo add-mark "" "" square

#Creating wireless nodes (sensor nodes)
for {set i 0} {$i < 48} {incr i} {
                set sensor_nodes($i) [$ns_ node]
}

#Setting initial positions for access points
$ZoneOne set X_ 200.0
$ZoneOne set Y_ 1050.0
$ZoneOne set Z_ 0.0

$ZoneTwo set X_ 200.00
$ZoneTwo set Y_ 200.0
$ZoneTwo set Z_ 0.0

$ZoneThree set X_ 800.0
$ZoneThree set Y_ 1050.0
$ZoneThree set Z_ 0.0

$ZoneFour set X_ 800.0
```

```
$ZoneFour set Y_ 200.0
$ZoneFour set Z_ 0.0

#Sort out the positions
$ZoneFive set X_ 1400.0
$ZoneFive set Y_ 1050.0
$ZoneFive set Z_ 0.0

$ZoneSix set X_ 1400.0
$ZoneSix set Y_ 200.0
$ZoneSix set Z_ 0.0

#Defining the drone
$DroneOne set X_ 0.0
$DroneOne set Y_ 710.0#1200.0
$DroneOne set Z_ 0.0

$DroneTwo set X_ 1600.0
$DroneTwo set Y_ 530.0#1200.0
$DroneTwo set Z_ 0.0

#Setting initial positions for sensor nodes
#Zone 1
$sensor_nodes(0) set X_ 0
$sensor_nodes(0) set Y_ 1050
$sensor_nodes(0) set Z_ 0.0

$sensor_nodes(1) set X_ 50
$sensor_nodes(1) set Y_ 1200
$sensor_nodes(1) set Z_ 0.0

$sensor_nodes(2) set X_ 50
$sensor_nodes(2) set Y_ 900
$sensor_nodes(2) set Z_ 0.0

$sensor_nodes(3) set X_ 200
$sensor_nodes(3) set Y_ 1250
$sensor_nodes(3) set Z_ 0.0

$sensor_nodes(4) set X_ 200
$sensor_nodes(4) set Y_ 850
$sensor_nodes(4) set Z_ 0.0

$sensor_nodes(5) set X_ 350
$sensor_nodes(5) set Y_ 1200
$sensor_nodes(5) set Z_ 0.0

$sensor_nodes(6) set X_ 350
$sensor_nodes(6) set Y_ 900
$sensor_nodes(6) set Z_ 0.0
```

```
$sensor_nodes(7) set X_ 400
$sensor_nodes(7) set Y_ 1050
$sensor_nodes(7) set Z_ 0.0

#Zone 2
$sensor_nodes(8) set X_ 0
$sensor_nodes(8) set Y_ 200
$sensor_nodes(8) set Z_ 0.0

$sensor_nodes(9) set X_ 50
$sensor_nodes(9) set Y_ 350
$sensor_nodes(9) set Z_ 0.0

$sensor_nodes(10) set X_ 50
$sensor_nodes(10) set Y_ 50
$sensor_nodes(10) set Z_ 0.0

$sensor_nodes(11) set X_ 200
$sensor_nodes(11) set Y_ 400
$sensor_nodes(11) set Z_ 0.0

$sensor_nodes(12) set X_ 200
$sensor_nodes(12) set Y_ 0
$sensor_nodes(12) set Z_ 0.0

$sensor_nodes(13) set X_ 350
$sensor_nodes(13) set Y_ 350
$sensor_nodes(13) set Z_ 0.0

$sensor_nodes(14) set X_ 350
$sensor_nodes(14) set Y_ 50
$sensor_nodes(14) set Z_ 0.0

$sensor_nodes(15) set X_ 400
$sensor_nodes(15) set Y_ 200
$sensor_nodes(15) set Z_ 0.0

#Zone 3
$sensor_nodes(16) set X_ 600
$sensor_nodes(16) set Y_ 1050
$sensor_nodes(16) set Z_ 0.0

$sensor_nodes(17) set X_ 650
$sensor_nodes(17) set Y_ 1200
$sensor_nodes(17) set Z_ 0.0

$sensor_nodes(18) set X_ 650
$sensor_nodes(18) set Y_ 900
$sensor_nodes(18) set Z_ 0.0
```

```
$sensor_nodes(19) set X_ 800
$sensor_nodes(19) set Y_ 1250
$sensor_nodes(19) set Z_ 0.0

$sensor_nodes(20) set X_ 800
$sensor_nodes(20) set Y_ 850
$sensor_nodes(20) set Z_ 0.0

$sensor_nodes(21) set X_ 950
$sensor_nodes(21) set Y_ 1200
$sensor_nodes(21) set Z_ 0.0

$sensor_nodes(22) set X_ 950
$sensor_nodes(22) set Y_ 900
$sensor_nodes(22) set Z_ 0.0

$sensor_nodes(23) set X_ 1000
$sensor_nodes(23) set Y_ 1050
$sensor_nodes(23) set Z_ 0.0

#Zone 4
$sensor_nodes(24) set X_ 600
$sensor_nodes(24) set Y_ 200
$sensor_nodes(24) set Z_ 0.0

$sensor_nodes(25) set X_ 650
$sensor_nodes(25) set Y_ 350
$sensor_nodes(25) set Z_ 0.0

$sensor_nodes(26) set X_ 650
$sensor_nodes(26) set Y_ 50
$sensor_nodes(26) set Z_ 0.0

$sensor_nodes(27) set X_ 800
$sensor_nodes(27) set Y_ 400
$sensor_nodes(27) set Z_ 0.0

$sensor_nodes(28) set X_ 800
$sensor_nodes(28) set Y_ 0
$sensor_nodes(28) set Z_ 0.0

$sensor_nodes(29) set X_ 950
$sensor_nodes(29) set Y_ 350
$sensor_nodes(29) set Z_ 0.0

$sensor_nodes(30) set X_ 950
$sensor_nodes(30) set Y_ 50
$sensor_nodes(30) set Z_ 0.0
```

```
$sensor_nodes(31) set X_ 1000
$sensor_nodes(31) set Y_ 200
$sensor_nodes(31) set Z_ 0.0

#Zone 5
$sensor_nodes(32) set X_ 1200
$sensor_nodes(32) set Y_ 1050
$sensor_nodes(32) set Z_ 0.0

$sensor_nodes(33) set X_ 1250
$sensor_nodes(33) set Y_ 1200
$sensor_nodes(33) set Z_ 0.0

$sensor_nodes(34) set X_ 1250
$sensor_nodes(34) set Y_ 900
$sensor_nodes(34) set Z_ 0.0

$sensor_nodes(35) set X_ 1400
$sensor_nodes(35) set Y_ 1250
$sensor_nodes(35) set Z_ 0.0

$sensor_nodes(36) set X_ 1400
$sensor_nodes(36) set Y_ 850
$sensor_nodes(36) set Z_ 0.0

$sensor_nodes(37) set X_ 1550
$sensor_nodes(37) set Y_ 1200
$sensor_nodes(37) set Z_ 0.0

$sensor_nodes(38) set X_ 1550
$sensor_nodes(38) set Y_ 900
$sensor_nodes(38) set Z_ 0.0

$sensor_nodes(39) set X_ 1600
$sensor_nodes(39) set Y_ 1050
$sensor_nodes(39) set Z_ 0.0

#Zone 6
$sensor_nodes(40) set X_ 1200
$sensor_nodes(40) set Y_ 200
$sensor_nodes(40) set Z_ 0.0

$sensor_nodes(41) set X_ 1250
$sensor_nodes(41) set Y_ 350
$sensor_nodes(41) set Z_ 0.0

$sensor_nodes(42) set X_ 1250
$sensor_nodes(42) set Y_ 50
$sensor_nodes(42) set Z_ 0.0
```

```
$sensor_nodes(43) set X_ 1400
$sensor_nodes(43) set Y_ 400
$sensor_nodes(43) set Z_ 0.0

$sensor_nodes(44) set X_ 1400
$sensor_nodes(44) set Y_ 0
$sensor_nodes(44) set Z_ 0.0

$sensor_nodes(45) set X_ 1550
$sensor_nodes(45) set Y_ 350
$sensor_nodes(45) set Z_ 0.0

$sensor_nodes(46) set X_ 1550
$sensor_nodes(46) set Y_ 50
$sensor_nodes(46) set Z_ 0.0

$sensor_nodes(47) set X_ 1600
$sensor_nodes(47) set Y_ 200
$sensor_nodes(47) set Z_ 0.0

#Defining sizes for access points
$ns_ initial_node_pos $ZoneOne 100
$ns_ initial_node_pos $ZoneTwo 100
$ns_ initial_node_pos $ZoneThree 100
$ns_ initial_node_pos $ZoneFour 100
$ns_ initial_node_pos $ZoneFive 100
$ns_ initial_node_pos $ZoneSix 100

#Defining size for the drone
$ns_ initial_node_pos $DroneOne 105
$ns_ initial_node_pos $DroneTwo 105

#Defining sizes for sensor nodes
for {set i 0} {$i < 48} {incr i} {
        $ns_ initial_node_pos $sensor_nodes($i) 75
        $sensor_nodes($i) color blue
        $ns_ at 0.0 "$sensor_nodes($i) color green"
}

#Defining labels for access points
$ns_ at 0.0 "$ZoneOne label \"Zone 1 (AP)\""
$ns_ at 0.0 "$ZoneTwo label \"Zone 2 (AP)\""
$ns_ at 0.0 "$ZoneThree label \"Zone 3 (AP)\""
$ns_ at 0.0 "$ZoneFour label \"Zone 4 (AP)\""
$ns_ at 0.0 "$ZoneFive label \"Zone 5 (AP)\""
$ns_ at 0.0 "$ZoneSix label \"Zone 6 (AP)\""
#Defining label for the drone
$ns_ at 0.0 "$DroneOne label \"Drone 1\""
$ns_ at 0.0 "$DroneTwo label \"Drone 2\""
```

```
#Defining colors for access points
$ZoneOne color blue
$ZoneTwo color red
$ZoneThree color orange
$ZoneFour color brown
$ZoneFive color aqua
$ZoneSix color black

#Defining color for the drone
$DroneOne color purple
$DroneTwo color olive

$ns_ at 0.0 "$ZoneOne color blue"
$ns_ at 0.0 "$ZoneTwo color red"
$ns_ at 0.0 "$ZoneThree color orange"
$ns_ at 0.0 "$ZoneFour color brown"
$ns_ at 0.0 "$ZoneFive color aqua"
$ns_ at 0.0 "$ZoneSix color black"
$ns_ at 0.0 "$DroneOne color purple"
$ns_ at 0.0 "$DroneTwo color olive"

#Setting node movements
#Zone 1, 3, and 5
$ns_ at 0.1 "$DroneOne setdest 1590.0 710.0 50.0"
##$ns_ at 11.0 "$DroneOne setdest 800.0 710.0 100.0"
##$ns_ at 21.0 "$DroneOne setdest 1400.0 710.0 100.0"
#Moving back
$ns_ at 31.0 "$DroneOne setdest 10.0 710.0 50.0"
##$ns_ at 19.0 "$DroneOne setdest 200.0 710.0 1.0"
##$ns_ at 24.0 "$DroneOne setdest 10.0 710.0 1000.0"

#Zone 2. 4. 6
$ns_ at 0.1 "$DroneTwo setdest 10.0 530.0 50.0"
##$ns_ at 4.0 "$DroneTwo setdest 800.0 530.0 500.0"
##$ns_ at 9.0 "$DroneTwo setdest 200.0 530.0 500.0"
#Moving back
$ns_ at 31.0 "$DroneTwo setdest 1590.0 530.0 50.0"
##$ns_ at 19.0 "$DroneTwo setdest 1400.0 530.0 1000.0"
##$ns_ at 24.0 "$DroneTwo setdest 1410.0 530.0 1000.0"

#Establishing communication between zones

#Sending to Zone One
set tcp7 [new Agent/TCP]
$tcp7 set class_ 2
$ns_ attach-agent $sensor_nodes(0) $tcp7
set sink [new Agent/TCPSink]
$ns_ attach-agent $ZoneOne $sink
$ns_ connect $tcp7 $sink
$tcp7 set fid_ 1
```

```
#Setup a FTP over TCP connection
set ftp7 [new Application/FTP]
$ftp7 attach-agent $tcp7
$ftp7 set type_ FTP

#Sending through Zone One
set tcp1 [new Agent/TCP]
$tcp1 set class_ 2
$ns_ attach-agent $ZoneOne $tcp1
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneOne $sink
$ns_ connect $tcp1 $sink
$tcp1 set fid_ 1
#Setup a FTP over TCP connection
set ftp1 [new Application/FTP]
$ftp1 attach-agent $tcp1
$ftp1 set type_ FTP

#Sending through Zone Two
set tcp2 [new Agent/TCP]
$tcp2 set class_ 2
$ns_ attach-agent $ZoneTwo $tcp2
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneTwo $sink
$ns_ connect $tcp2 $sink
$tcp2 set fid_ 2
#Setup a FTP over TCP connection
set ftp2 [new Application/FTP]
$ftp2 attach-agent $tcp2
$ftp2 set type_ FTP

#Sending to Zone Three
set tcp8 [new Agent/TCP]
$tcp8 set class_ 2
$ns_ attach-agent $sensor_nodes(16) $tcp8
set sink [new Agent/TCPSink]
$ns_ attach-agent $ZoneThree $sink
$ns_ connect $tcp8 $sink
$tcp8 set fid_ 1
#Setup a FTP over TCP connection
set ftp8 [new Application/FTP]
$ftp8 attach-agent $tcp8
$ftp8 set type_ FTP

#Sending through Zone Three
set tcp3 [new Agent/TCP]
$tcp3 set class_ 2
$ns_ attach-agent $ZoneThree $tcp3
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneOne $sink
```

```
$ns_ connect $tcp3 $sink
$tcp3 set fid_ 1
#Setup a FTP over TCP connection
set ftp3 [new Application/FTP]
$ftp3 attach-agent $tcp3
$ftp3 set type_ FTP

#Sending through Zone Four
set tcp4 [new Agent/TCP]
$tcp4 set class_ 2
$ns_ attach-agent $ZoneFour $tcp4
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneTwo $sink
$ns_ connect $tcp4 $sink
$tcp4 set fid_ 2
#Setup a FTP over TCP connection
set ftp4 [new Application/FTP]
$ftp4 attach-agent $tcp4
$ftp4 set type_ FTP

#Sending through Zone Five
set tcp5 [new Agent/TCP]
$tcp5 set class_ 2
$ns_ attach-agent $ZoneFive $tcp5
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneOne $sink
$ns_ connect $tcp5 $sink
$tcp5 set fid_ 1
#Setup a FTP over TCP connection
set ftp5 [new Application/FTP]
$ftp5 attach-agent $tcp5
$ftp5 set type_ FTP

#Sending through Zone Six
set tcp6 [new Agent/TCP]
$tcp6 set class_ 2
$ns_ attach-agent $ZoneSix $tcp6
set sink [new Agent/TCPSink]
$ns_ attach-agent $DroneTwo $sink
$ns_ connect $tcp6 $sink
$tcp6 set fid_ 2
#Setup a FTP over TCP connection
set ftp6 [new Application/FTP]
$ftp6 attach-agent $tcp6
$ftp6 set type_ FTP

#Schedule events for the CBR and FTP agents
#Zone 1 and 3 sending to the drone
$ns_ at 1.0 "$ftp1 start"
$ns_ at 60.0 "$ftp1 stop"
```

```
$ns_ at 1.0 "$ftp2 start"
$ns_ at 60.0 "$ftp2 stop"
$ns_ at 1.0 "$ftp3 start"
$ns_ at 60.0 "$ftp3 stop"
$ns_ at 1.0 "$ftp4 start"
$ns_ at 60.0 "$ftp4 stop"
$ns_ at 1.0 "$ftp5 start"
$ns_ at 60.0 "$ftp5 stop"
$ns_ at 1.0 "$ftp6 start"
$ns_ at 60.0 "$ftp6 stop"
##$ns_ at 0.0 "$ftp7 start"
##$ns_ at 60.0 "$ftp7 stop"
##$ns_ at 0.0 "$ftp8 start"
##$ns_ at 60.0 "$ftp8 stop"

#Zone 5 and 6 sending to the drone

##$ns_ at 11.0 "$ftp6 start"
##$ns_ at 16.0 "$ftp6 stop"

#Zone 5 and 6 sending to the drone
##$ns_ at 1.0 "$ftp6 start"
##$ns_ at 5.0 "$ftp6 stop"
##$ns_ at 5.0 "$ftp4 start"
##$ns_ at 10.0 "$ftp4 stop"

#Detach tcp and sink agents (not really necessary)
##$ns at 4.5 "$ns detach-agent $n0 $tcp ; $ns detach-agent $n3 $sink"

#Print CBR packet size and interval
##puts "CBR packet size = [$cbr set packet_size_]"
##puts "CBR interval = [$cbr set interval_]"

#Setting animation rate
$ns_ at 0.0 "$ns_ set-animation-rate 10.0ms"
# ending nam and the simulation
$ns_ at $val(stop) "finish"
#Stopping the scheduler
$ns_ at 60.00 "puts \"end simulation\" ; $ns_ halt"

#Procedure to stop the simulation
proc finish {} {
        global ns_ tracefd
        $ns_ flush-trace
        close $tracefd
        exec nam WSNs.nam &
        exit 0
}

#Starting scheduler
```

```
puts "Starting Simulation........"
$ns_ run
```

APPENDIX C: PYTHON CODE

```
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np

stime = [30, 60, 90, 120, 150, 180, 210, 240, 270, 300]

filename = 'D:\\Research\\2021\\Tshimangadzo\\Results Analysis\\TP.dat'
df = pd.read_table(filename, delim_whitespace=True, names=['ITRM', 'MLCC', 'LBRM'])
df = df.iloc[1:, :]

plt.plot(stime, df['ITRM'], 'o-r', linestyle='dashed')
plt.plot(stime, df['MLCC'], 'o-g', linestyle='dashed')
plt.plot(stime, df['LBRM'], 'o-b', linestyle='dashed')
plt.title('Throughput VS Simulation Time')
plt.xlabel('Simulation Time (s)', fontsize=14)
plt.ylabel('Throughput (Kb/s)', fontsize=14)
# legend
plt.legend(['ITRM', 'MLCC', 'LBRM'])
plt.ylim([-100, 50])
# plt.grid(True)
plt.show()
```

APPENDIX D: R CODE

We also used R Code to verify the results generated through Python.

```
#=========================================================
#   R code to graphically display the average throughput
#=========================================================
autos_data <- read.table("D:\\Research\\2021\\Tshimangadzo\\Results Analysis\\TP.dat",
header=T, sep="\t")
max_y <- 1500#max(autos_data)
# Colouring ITRM, LBRM, MLCC
plot_colors <- c("blue", "red", "green")
# graph autos using y axis that ranges from 0 to max_y.
# turn off axes and annotations (axis labels) so this study can specify them ourselves
plot(autos_data$ITRM, type="o", pch=22, lwd=1, col=plot_colors[1], ylim=c(0, max_y),
axes=FALSE, ann=FALSE, lty=2)
#make x axis using 1-6 labels, which was the percentage of throughput
axis(1, at=1:10, lab=c(30, 60, 90, 120, 150, 180, 210, 240, 270, 300))
# making the y axis with horizontal labels that display ticks at every 10 seconds.
10*0:max_y is equivalent to c(0, 10, 20, 30, …).
axis(2, las=1, at=100*0:max_y)
# create box around plot
box()
# graph MLCC with red dashed line and square points
lines(autos_data$MLCC, type="o", pch=23, lwd=1, col=plot_colors[2], lty=2)
# graph LBRM with green dotted line and diamond points
lines(autos_data$LBRM, type="o", pch=24, lwd=1, col=plot_colors[3], lty=2)
# label the x and y axes with black text
title(xlab= "Simulation Time (s)", col.lab=rgb(0,0.0,0))
title(ylab= "Throughput (Kb/s)", col.lab=rgb(0,0.0,0))
# create a legend in the top-left corner that is slightly smaller and has no border
legend("topleft", names(autos_data), cex=0.8, col=plot_colors, lwd=1, pch=22, bty="n",
lty=2);
# turn off device driver (to flush output to PDF)
dev.on()
```