Swarm Intelligent Routing in Managing Congestion-Awareness and Performance in Mobile Ad Hoc Networks

by

Gibson Chengetanai

Submitted in accordance with the requirements for the degree of

DOCTOR OF PHILOSOPHY

in the subject of

COMPUTER SCIENCE

at the

School of Computing, College of Science, Engineering and Technology,

UNIVERSITY OF SOUTH AFRICA

Supervisor: Professor Isaac O. Osunmakinde

February 2020

DECLARATION

Name: GIBSON CHENGETANAI

Student number: 50886789

Degree: Doctor of Philosophy in Computer Science

Swarm intelligent routing in managing congestion-awareness and performance in Mobile Ad Hoc Networks

I declare that the above thesis is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the thesis to originality checking software and that it falls within the accepted requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at UNISA for another qualification or at any other higher education institution.

SIGNATURE
Gibson Chengetanai

___*12 February 2020*___
DATE

DEDICATION

I dedicate this thesis to my wife, my children and my parents

ACKNOWLEDGEMENTS

First, I would like to thank the Almighty God for his abundant blessings, without which this dissertation would not have been a success. To HIM be the GLORY!

Secondly, I would want to thank my supervisor Professor Isaac O. Osunmakinde for his invaluable guidance throughout this PhD studies journey. His insights, dedication, availability, and support throughout my studies has been exceptional. He has opened my eyes on areas of academic thinking and technical problem-solving skills. He is a straightforward person who raises the standards very high for students under his supervision. Under him, I have learnt much on writing good academic articles. I consider myself to be extremely lucky to be under his great supervision.

Thirdly, I would also want to extend my gratitude to Dr. Grant Blaise O'Reilly for introducing me to the area of swam intelligence.

Fourthly, I would like to extend my gratitude to UNISA for supporting postgraduate students with an extensive array of journals and uploading of workshops and seminar documents online. This was one way that made my learning easier, especially as student outside South Africa. For this I am very grateful.

Lastly, special thanks to my wife, my children for patience and being supportive to my studies from the start till the very end. I love you all.

ABSTRACT

Mobile ad hoc networks (MANETs) are infrastructureless temporary networks that can be deployed in areas that do not have predefined communication infrastructure, for example, earthquake-stricken areas. The dynamism of MANET network where nodes joins and leave the network anytime make routing decision a challenge. Routing of data packets in mobile ad hoc networks (MANETs) is a non- deterministic polynomial (NP) hard problem. Past scholars have been focusing on number of hops on determining the best path to route data packets on the network. Determining shortest path using number of hops method oblivious of congestion of the next-hop neighbours is detrimental to the performance of wireless ad hoc network, because it can ultimately result in high packet dropping rate especially on highly congested nodes in the network. Extending network lifetime by exploring on the congestion levels and stability factor of nodes in MANETs have not been addressed by past scholars. In this thesis a cooperative Queuing-Swarm based routing framework has been proposed. The contribution from this thesis were as follows: (1) development of a new routing method called Queuing with Particle Swarm Optimisation (Q-PSO). Q-PSO divides the MANET into logical groups and selects the cluster head depending on remaining battery life. Simulation results in both single path and multipath routing showed that the proposed Q-PSO performed better in terms of packet deliver ratio, average jitter, etc. relative to other swarm-based routing techniques and (2) the development of Queuing Ant Colony System (QUACS) routing method. QUACS method checked for node stability and the congestion metric of all possible next-hop neighbours before choosing the node to relay data packets. Performance evaluations of QUACS routing methods showed better results in terms of average end-to-end delay, throughput, etc. relative to other routing methods. Hybridising swarm intelligence with queuing optimisation in MANETs helped in extending the network lifetime and enabled quick information exchange. The proposed two routing methods can also help future MANET researchers who would want to explore more on wireless networks.

Keywords: Q-PSO, QUACS, stability factor, congestion metric, cluster head, routing optimisation, overall congestion metric, ant colony optimisation, particle swarm optimisation, pheromone evaporation, network lifetime, queuing theory

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

MANET	Mobile Ad Hoc Network
AODV	Ad hoc On-Demand Distance Vector
CM	Congestion Metric
OCM	Overall Congestion Metric
NS-2	Network Simulator version 2
MAC	Medium Access Control
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
TDMA	Time Division Multiple Access
WLANs	Wireless Local Area Networks
CH	Cluster head
ACS	Ant Colony System
ABC	Artificial Bee Colony
PSO	Particle Swarm Optimisation
ACO	Ant Colony Optimisation
BFO	Bacterial Foraging Optimisation
Q-PSO	Queuing with Particle Swarm optimisation
QUACS	Queuing Ant Colony System
PDR	Packet Delivery Ratio
IMOPSO	Improved Multi-Objective Particle Swarm Optimisation
ACO with ECPSOA	Ant Colony Optimisation with Endocrine C-operative Particle Swarm Optimisation
ABR	Associativity based Routing
E-MAntNet	Energy-MANET ant-based routing

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Technological advancements in Information and Communication Technology (ICT) nowadays are happening at a tremendous rate. In the 1980s there were wired networks, but today, there is a shift towards mobile computing which utilises wireless networks. This has been necessitated by the fact that people would want to access information, even when they are out of their usual workplaces and homes. The Internet Engineering Task Force (IETF), which is a body responsible for governing the internet standards has come up with what is called a Mobile Ad Hoc Network (MANET). A MANET is a wireless network that can be constructed on the fly (anytime and or anywhere) [1], [2] without the aid of base stations or access points. A MANET consists of a set of wireless mobile nodes (wireless devices on the network which can be smartphones, laptops or iPads) that can be quickly organised into a network - without the need for any infrastructure - and can start communicating using their wireless devices [3].

Nodes in MANETs have the capability of self-configuring and self-organising as they determine which other mobile nodes make up the wireless MANET. This is accomplished by observing nodes which are within each other's transmission range. Nodes in MANETs also have routing capabilities where some nodes can forward data packets (small chunks or a frame of data sent across the network) from one hop to the other until the data packets reach their intended destinations.

The increase in number of users owning mobile devices to access internet can be leveraged to enhance communication. There is a projected increase in the number of mobile internet subscribers even in the developing world (see Figure 1.1). This increase in number of mobile users can be utilised for communication in emergency medical rescue operations or battlefield communication, especially in the developing world where telecommunication infrastructure can be a challenge. Exchanging of data packets happens without any centralised administration, hence its applicability in emergency rescue operations.

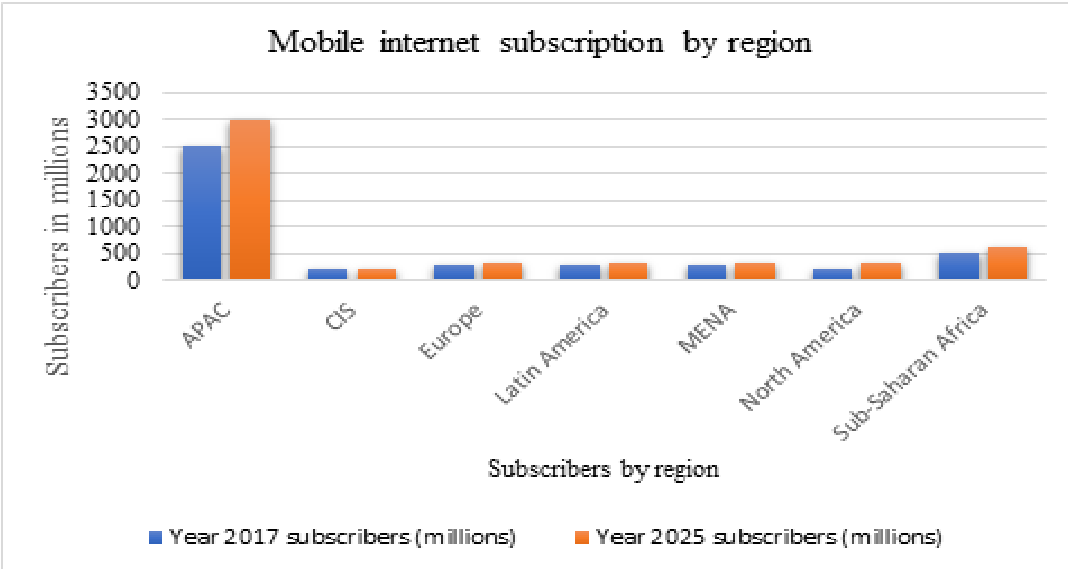

Figure 1.1 Mobile internet users' subscription in 2017 and 2025 projection adapted from [4]

There is need for efficient ways of routing data packets across all mobile devices in a MANET network, so that there is minimal delay for data reaching the intended recipients. This is referred to as the average end-to-end delay. A good MANET network is associated with low average end-to-end delay [5], [6]. Finding efficient ways of routing data packets using less congested routes is an important activity in the network containing several mobile nodes since exploring the best path on the network will ultimately result in data packets reaching the intended destination in the shortest period of time.

In MANETs the mobile nodes also have the capability of acting as routers, thus they can forward data packets to the next hop neighbours (i.e. mobile nodes which are closest to the sending node) until the data reach the intended recipient. This is done by looking into the data packet's source and destination addresses and then forwarding those data packets accordingly. The fact that some nodes on the MANET will forward data to other nodes has its challenges, namely: limited energy (battery power), bandwidth and security [3], [6]–[10].

Nodes close to the sink, that is, access point (AP) which is a specially configured node in a wireless local area network which acts as a central transmitter and receiver of radio signals, may run out of energy or be low on energy since they are battery powered [7], [11]. Limited node memory and processing capabilities are also present in MANET network because nodes have limited buffer for storage of data packets that need to be relayed to other nodes. The data packets that have to be sent by a particular node will be stored in the device's buffer, before sending it to the next hop neighbours and this can ultimately result in more space being needed for storage prior to the data being sent, but the space is limited. Security is also another challenge in mobile ad hoc networks as nodes in the MANET can join and leave the network at anytime [3]. This may be a result of the node in a MANET running out of battery power and therefore having to leave or disconnect from the MANET [12], [13]. New nodes will also join the MANET arbitrarily.

There is need for a proper way of determining the proper route to take so as to ensure that the survival of the MANET is much longer. This is crucial in the sense that some nodes in the MANET can run out of battery power whilst other nodes still have sufficient battery life. Hence, there is a need to adopt both a distributive and collaborative techniques in order to ensure that heavily used routes relinquish some of the data packets to other nodes on the network. This is because nodes do possess the same capabilities as the heavily used mobile nodes on the MANET.

The use of swarm intelligence techniques, which is an inspiration from the way biological ants, bees and birds behave, can be modelled in the MANET network through the adoption of stigmergy approach. Stigmergy is an indirect way of coordinating among agents in a network [14], [15]. Stigmergy in swarm intelligence help in the route or path discovery that the agents, also known as artificial ants, have to take through following trails left by previous ants. The path that has the highest concentration of pheromone (odorous substance left by previous ants) will be chosen as the best path from the food source to the nest. This is because this is the path that would have been traversed by many ants in a short period of time as compared to the other routes.

'Swarm intelligence' can be defined as a set of agents that cooperate through either direct or indirect (by acting on their local environment) communication with each other to solve a problem. The agents are independent entities with limited intelligence (that is a defined rule set). Agents monitor the environment via their built-in sensors and then respond to those sensors using an internal stimulus-response mechanism. Swarm intelligence is the collective behaviour of self-organised and decentralised systems whether natural or artificial [14]–[17]. This collective interaction will ultimately lead to the emergence of a global behaviour or collective characteristic which is unknown to the participating individual agents. This emergent collective behaviour is attributed to the decentralised and self-organising characteristics of the collective coordination of the agents.

A routing approach involving exploring the quality of service factors at once such as queue length and residual energy to improve network lifetime has been explored by [11]. However, it does not factor the congestion levels of buffer-limited space on nodes in the network. A lifetime aware routing protocol that is based on ant colony optimisation principles was presented by [18] to prolong the network life time of a wireless ad hoc network. Clustering the network to enable few chosen cluster head nodes to handle communication ensures equitable distribution of load on the ad hoc network. Multicasting routing using energy efficient lifetime aware multicast was presented by [19] to select the nodes on the MANET network that has got high residual battery life for routing data packets on the network.

The approach that was followed in this thesis was to address quick communication in MANET networks. This was achieved through the designing of a reliable and efficient routing approaches which are based on swarm optimisation hybridised with queuing theory. Queuing theory was used for congestion metric computations and stability factor is computed based on geographical position of the nodes. Exploring of paths from source to the destination was based on nature-inspired approaches. Adopting hybridised approaches from literature [1] has shown a remarkable improvement in network lifetime compared to using single optimisation routing approach.

1.2 PROBLEM STATEMENT

A MANET can be created when two or more mobile wireless devices communicate with one another or share information using radio links. MANETs are extremely useful in emergency situations when there is a need to relay data from one person to another in a quick and efficient manner. MANET can be deployed in combat scenarios, during earthquakes evacuations, floods or in other emergency health care situations. In emergency health care situations such as during Ebola pandemic control operations doctors, nurses and paramedics would want to exchange data as quickly as possible. However, there would be no existing communication infrastructure such as access points or base stations nor time to setup the telecommunication infrastructure in such operating environments [13].

As communication will be taking place via multi-hop (the data packets being relayed from one node to the other), some nodes will run out of energy (since mobile nodes are battery powered); as they will be forwarding data packets from their respective node(s) to the other nodes until they reach their intended destination(s) [12], [13]. Figure 1.2 shows multi-hopping in MANET, from node 4 to node 3. Some nodes that will be relaying data can be congested resulting in data packets being dropped, or waiting for their turn in the node's memory buffer to be sent to the given destination.

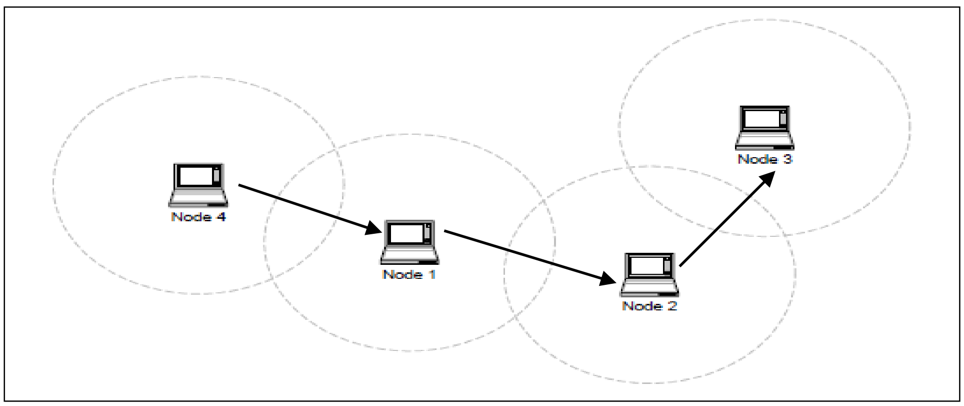

Figure 1.2 Multi-hopping in mobile ad hoc network

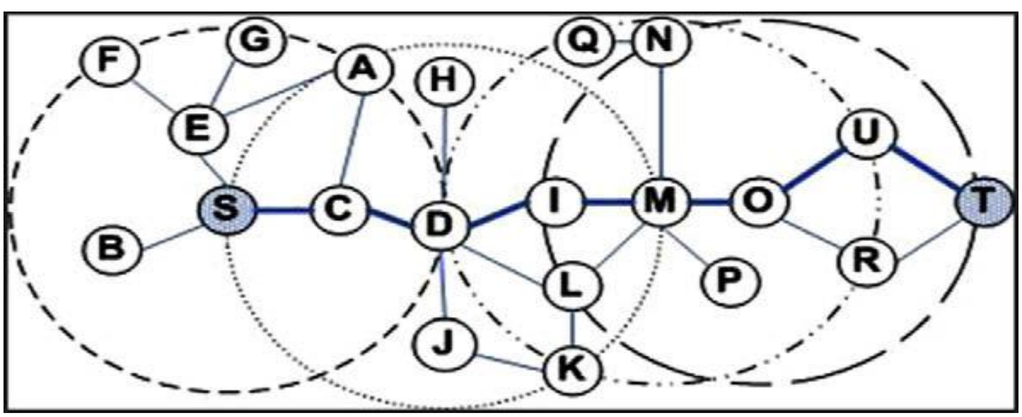

Figure 1.3 Establishing the shortest path in a MANET (adapted from [16])

Figure 1.3 shows the shortest path that can be used in sending data packets from node *S* to *T*. Assuming node *O* has joined the network, it can then be used to route data packets from *S* rather than using *P* as they are now one hop neighbours of *M*. Since node *O* is closer to node *M* than node *P*, it uses that route of passing data packets via node *O*, hence establishing the shortest possible route. Likewise, if node *I* were to run out of power, which means it would no longer be part of the MANET, then the data packet from node D would be relayed through node L, since it would be the closest neighbour of node D relative to nodes J and Q.

However, just finding the shortest path between source and destination nodes by checking on the number of hops and nodes being close, can lead to congestion on the links. This is detrimental to the wireless networks since more data packets end up being dropped and increased average end-to-end delay. A more scalable and load balancing approach that explores the load distribution on the network is required to prolong the lifetime of the MANET network. Again, nodes in the MANET network join and leave arbitrarily and updating of routing tables would be done frequently, which is not the case, especially with table driven routing protocols for MANETs.

The problem statement has been broken into the following declarations:

The approaches advocated in finding the shortest path in MANET networks are pleasing, but there are some gaps in addressing load balancing and congestion on the links in wireless networks.

> "Due to the fast changing nature and the ad hoc necessity of the network, no centralised solution is possible which can decide the best route based on different parameters like path length, congestion and load" [20].

> "A multipath routing protocol needs to be governed by a load balancing scheme in order to escape from devouring the energy of participating nodes. Unbalanced battery energy consumption may lead to node breakdown consequently affecting the reliability of the given network in general" [21].

> "Routing in dynamic wireless ad hoc networks still attracts researchers as it constitutes a corner stone to the proper functioning of such networks. Choosing the most stable routes allows extending the routing period of proactive routing which in turn amounts to a lower signaling overhead" [13].

> "Due to the dynamic nature of vehicle nodes and unstable wireless links, the design of an efficient and effective routing scheme is a serious challenge for Vehicular ad hoc network" [22].
> "In recent years, designing highly efficient energy-saving fault tolerant methods, ensuring robustness of data transmission and improving the performance of networks have become the key point of mobile wireless sensor networks"[23].

> "Existing mechanism of routing using ACO of MANETs have faced challenges in load balancing and energy efficiency" [24].

Different routing protocols have been developed by previous scholars to address routing in MANET networks. Nature-inspired approaches have been researched on finding shortest path in wireless ad hoc networks by [1], [6], [14], [25]. The focus was mainly based on number of hops and the remaining energy levels of nodes, when determining the best possible path to route data packets between the source and the destination nodes. The existing work from literature pointed out that using ant colony optimisation for MANETs faces challenges such as load balancing and energy efficiency [24]. Unfortunately, finding the shortest path using hybridised approach involving queuing theory and nature-inspired optimisation techniques has not been explored. Since nodes in the MANET network are deployed in areas where it is not possible to replenish battery power, increasing the network lifetime of the network is necessary. This is to enable communication to take place for a much longer time. The proposed solution factors in congestion levels of the nodes, stability of the nodes and load distribution on the MANET network to prolong network lifetime which ultimately bridges the gaps have been identified from literature.

1.2.1 *Finding the shortest path route in MANET networks is key in ensuring quick communication in emergency rescue operations and, ultimately results in better network performance of a wireless MANET*

> "Also, no single node takes up the job of centralized manager due to limited energy and limited processing capabilities. Thus, routing in MANET is a challenging topic of research" [20].

> "Notwithstanding the important contributions of the existing solution, there is still a need for a power-aware routing approach that supports coexistence of nodes equipped with heterogenous wireless interfaces" [26].

Nature-inspired routing approaches such as: ant colony optimisation, particle swarm optimisation, bacterial foraging optimisation, bee colony optimisation and genetic-based approaches have been explored in routing data packets in MANET networks [1]–[3], [5]–[7][12][27]. However, the focus of the previous scholars was on finding the shortest path looking into route length and available energy levels on the links only. Inclusion of stability factor and congestion metric/levels of the nodes have been explored separately in trying to improve the lifetime of the MANET network. Integration of nature-inspired optimisation with stability factor and congestion metric of nodes can assist in closing the gaps that are currently existing in literature.

1.2.2 *Load balancing and fault tolerance affect network performance in MANET networks*

> "Because routing is performed by nodes with limited resources, load should be efficiently distributed throughout the network. Otherwise, heavily-loaded nodes may make up a bottleneck that lowers the network performance by congestion and larger delays. Regrettably, load-balancing is a critical deficiency in MANET shortest-path routing protocols, as nodes at the center of the network are heavily-loaded than others" [6].

> "But with this dynamic topology, mobile ad hoc networks have some challenges like design of an efficient routing protocol and controlling the congestion, hence balancing the load in MANET is important since nodes with high load will deplete their batteries quickly, thereby increasing the probability disconnecting or partitioning" [28].

Without load balancing, some nodes can be quickly drained especially the relay nodes between the source node and destination node(s). Clustering technique using genetic based method has been proposed by [29] in selecting energy-efficient cluster heads and balancing the network load effectively.

Finding the shortest path that factors in load balancing (which results in fault tolerance) and nodes' stability factor to help in improving the network lifetime and increase data packet delivery rate of a MANET network has not be addressed in literature. Efficient ways of load distribution are critical if the network's lifespan is to be increased.

1.2.3 *Determination of shortest path is a challenge in wireless ad hoc networks because of congestion on buffer-limited nodes*

"Congestion may occur in a network if the load on the network (the number of packets being sent through the network) is greater than the capacity of the network (the number of packets the network can handle). Thus, network congestion can cause to severely increase the delay and packet loss and reduces network throughput" [30].

"Congestion control (CC) and avoidance includes measures taken for manipulating traffic within the network in order to combat congestion and avoid congestion collapse" [31].

"In mobile ad hoc networks the congestion is a major issue, which affects the overall performance of the networks. The load balancing in the network alongside the congestion is another major problem in mobile ad hoc network (MANET) routing due to difference in link cost of the route. Most of the existing routing protocols provide solutions to load balancing or congestion adaptivity separately" [32].

In MANET networks, congestion can occur at any intermediate node due to limited processing capabilities of the node, when many data packets are being transmitted across the network. Unfortunately, congestion avoidance based on queuing theory and ant colony optimisation or particle swarm optimisation has not been explored. Failure to determine possible congestion links and stable nodes on the network can worsen data packet delivery in ad hoc networks. This creates a gap where congestion levels of nodes and stability factor can be explored to improve data packets delivery in ad hoc networks. When congestion links are detected, alternative paths are explored to determine the next less congested route. Existence of multipath routing can help in routing data packets by avoiding congested paths. This improves the packet delivery ratio in wireless ad hoc networks [20], [33].

1.2.4 *There is not enough work on the routing framework based on nature-inspired routing techniques*

> "Lot of work has been done to improve the energy efficiency of existing routing protocols for MANETs. There is little work done that address the lifetime issue of MANET" [8].

Limited research has been done on the area of swarm-based routing frameworks, making it difficult for future researchers to come up with new routing protocols that focus on stability factor and congestion avoidance to increase the wireless ad hoc network lifetime. With the nature-inspired ad hoc network routing framework, it is easier to see the areas that are less researched and provide a basis for research by academics and wireless networks practitioners in future.

1.3 RESEARCH AIM AND OBJECTIVES

In trying to solve the problems associated with efficient routing of data packets in MANET networks, the main objective of this study was:

To develop a shortest path routing protocol that is congestion-aware and improve the wireless ad hoc network performance

There is need for such a research because nodes in wireless ad hoc network have buffer-limited space. Therefore, they are prone to congestion especially the relay nodes, when many nodes are involved in the exchange of data packets. This ultimately results in loss of data packets and high average end-to-end delay. This is detrimental to routing of data packets in wireless ad hoc networks especially in emergency rescue operations. This is because communication needs to be done quickly to save lives. Nature and non-nature inspired techniques that factor in congestion and load balancing in ad hoc networks has not been adequately addressed. It is the aim of this thesis to come up with shortest path routing protocol that is nature-inspired and congestion-aware to improve wireless ad hoc network performance.

1.4 RESEARCH QUESTIONS

In trying to solve the problems associated with efficient routing of data packets in MANET networks, the main research question is:

How can a swarm intelligent routing capability support management of congestion-awareness and performance in MANETs?

The need for such a research is because nodes in wireless ad hoc networks usually have buffer-limited space and therefore, are prone to congestion when many nodes are involved in the exchange data. This ultimately results in loss of data packets during emergency rescue operations. Communication needs to be done quickly in ad hoc networks to save lives. Therefore, data packets that are lost and high end-to-end delays are detrimental to routing of data packets in wireless ad hoc networks. Nature and non-nature inspired techniques that factor in congestion and load balancing in ad hoc networks during route exploration have not been adequately addressed. It is the aim of this study to come up with shortest path routing protocol that is nature-inspired and congestion-aware to improve wireless networks performance.

1.5 RESEARCH CONTRIBUTIONS

1.5.1 Contributions to the scientific body of knowledge

- A new framework that integrates swarm intelligence and queuing theory was proposed. This new framework, called Queuing Swarm optimisation framework assist in improving quick exchange of data packets in the MANET environment.
- Literature survey on swarm-based routing in MANET constrained environment was done. Uncovering of weaknesses on the previously proposed routing methods leads to the development of the new routing methods, namely Q-PSO and QUACS.
- A new routing method called QUACS based on ant colony system and queuing theory was developed. QUACS routing method includes the computation stability factor of nodes and congestion metrics of relay nodes that forwards data packets to other nodes before the

destination node(s) can be reached. The results from simulations show that QUACS routing method does identify the shortest path with least congestion from the source node to the destination node(s).

- Q-PSO routing method was developed based on the concept of particle swarm optimisation and queuing theory. The former was used to divide the network into logical groups called clusters. From each cluster, a cluster head node was chosen based on the node with the highest remaining battery life in each group. Cluster head nodes handle communication for cluster node members. Choosing next -hop cluster heads for relaying data packets to the destination node(s) was based on the congestion levels of the next-hop neighbours (also known as cluster head relay nodes). Simulations were done on the proposed routing method and results were compared to other nature-inspired routing methods. The proposed Q-PSO outperformed the other routing methods in terms of packet delivery ratio, average jitter and average end-to-end delay.
- A framework for MANET routing has also been developed and it acts as a reference guide for future wireless network protocol design to understand more on areas that they can focus on in designing future new routing protocols for wireless networks. The MANET latent topics which have received less attention from scholars have been presented as well.

1.5.2 Declaration of publications resulting from this study

The following publications relating to this research undertaking were produced, submitted, accepted and published by various accredited journals and conference proceedings:

Journals articles

1. Chengetanai G.; Osunmakinde I.O., (2018). **QUACS: Routing data packets in ad hoc networks on buffer-constrained load balancing conditions during emergency rescue operation**. *Wireless Personal Communications Journal, Springer International Publishers USA, (ISI journal) Vol. 99 (3)* pp.1345-1375. Online ISSN: 1572-834X
   View/download link DOI https://doi.org/10.1007/s11277-017-5188-x
2. Chengetanai G.; Osunmakinde I.O., (2020) **Q-PSO: Hybridisation of particle swarm optimisation with queuing theory for mitigating congestion on MANETs while optimising network lifetime.** *International Journal of Ad Hoc & Sensor Wireless*

Networks, (*ISI journal*) *Vol. 48 (1-2)* pp.37-65. ISSN:1551-9899 (Print) ISSN: 1552-0633 (online).

3. Chengetanai G.; Osunmakinde I.O.,(2019). **Swarm intelligence on MANET routing issues: An empirical study revealing latent research topics**. *International Journal of Mobile Network Design and Innovation (IJMNDI), Inderscience publishers, ISSN: 1744-2869, (Scopus-Elsevier indexed*) Vol 9 No3/4 pp.119-133
   View/download link DOI: 10.1504/IJMNDI.2019.107704

Conference Proceedings

1. Chengetanai G.; O'Reilly G.B. (2015). **Review of swarm intelligence routing algorithms in wireless mobile ad hoc networks.** *2015 IEEE 9th International Conference on Intelligent Systems and Control (ISCO),Coimbatore, India, 9-10 January 2015*, pp.1-7.
   View/download link **DOI:** 10.1109/ISCO.2015.7282367
2. Chengetanai G.; O'Reilly G.B. (2015). **Survey on simulation tools for wireless mobile ad hoc networks.** *IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, 5-7 March 2015*, pp.1-7.
   View/download link **DOI:** 10.1109/ICECCT.2015.7226167

1.6 RESEARCH ETHICAL CONSIDERATIONS

Ethical considerations as required by the University of South Africa (UNISA) were adhered to during this study. Ethical clearance was obtained from the College of Science, Engineering and Technology (CSET) at UNISA under the following reference number: 052/GC/2018/CSECT_SOC which was issued on 28 September 2018. All the sources used have been cited and referenced in this thesis. The pillars of ethical considerations include:

- Honesty- this involves striving to be honest in all scientific communications. Experimental procedures adopted during problem inquiry, data and results from research should not be falsified or misrepresented to deceive the sponsoring organisations and the research community at large. The research has not misrepresented any data, results as well as experimental procedures.
- Objectivity- this involves striving to avoid bias that can emanate from experimental design, data analysis and disclose personal interests where objectivity is needed. The researcher

strived to maintain highest level of objectivity in discussions and analysis throughout the research.

- Integrity- involves acting with genuineness and maintaining consistency of judgement and action throughout the research. This minimises or avoids bias in research.
- Carefulness- this involves critically examining one's work and keeping a record of activities like data collection, research design and critically examining work of other scholars who have also published in similar domains as the researchers. The work of other scholars has been used in the literature review to get the current state of research in the area.
- Openness- this involves sharing of data, results, ideas and experimental tools that have been used in the study. The researcher should be open to criticism from other scholars or peers. This has been accomplished through disseminating the research findings through some publications as part of the study. There is no any known conflict of interest in this research.
- Respect for Intellectual Property- this includes honouring patents, copyright and any other forms on of intellectual property. The researcher did not plagiarise any author's work, but instead cite and give all credit to the authors for their information which have been used in this dissertation.
- Confidentiality- this involves protecting confidential information such as: personnel records, and patients records in the medical field. For the data collected from interviews, focus group discussions and questionnaires, informed consent was required from the participants. The right to privacy should be maintained always. It is worth noting that this research was an experimental research which did not involve human beings.
- The researcher ensured that the research project adhered to the values and principles expressed in the UNISA Policy on Research Ethics.
- Any changes in the methodology or substantial changes in the original research proposal components had to be communicated in writing to the UNISA College of Science, Engineering and Technology's (CSET) Research and Ethics Committee
- The researcher conducted the study in accordance to the methods and procedures set in the approved Ethics certificate document.

- The researcher ensures that the research project adheres to applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards that are relevant to the field of computing such as, Protection of Personal Information Act No.4 of 2013.
- Any changes that affect the study-related risks for research participants, particularly with regards to privacy and confidentiality of data, had to be reported to the CSET Ethics Committee in writing.

1.7 THE SCOPE AND CONTEXT OF THE STUDY

This section brings in the area under which swarm intelligent routing in mobile ad hoc network belongs together with research limitations.

1.7.1 Research scope

This study can be categorised as one that falls between the field of wireless networks and artificial intelligence. The routing of data packets in mobile networking are classified under wireless networking and that of swarm intelligence falls under the broad area of artificial intelligence. This research is about the adoption of nature-inspired techniques to solve the routing problems that are normally associated with wireless ad hoc networks, prolonging the lifetime of the network and preserve energy.

1.7.2 Research limitations

This research focussed on swarm intelligence in mobile ad hoc networking. It generated two new protocols which are based on nature-inspired approaches hybridised with queuing theory toward finding the best path in wireless mobile ad hoc networks. The two new nature-inspired protocols take into consideration the nodes' congestion levels and node stability factor before deciding on the path to be chosen. Improving the network lifetime is achieved through using the shortest possible path that has least congestion thereby not prolonging the network lifetime but also extending the battery-life of nodes on the wireless ad hoc network.

Benchmarking of proposed routing protocol against other nature-inspired protocols has been done to check on the performance of the proposed routing methods with regard to packet delivery ratio, average end-to-end delay, average jitter, network lifetime, routing overhead and throughput. Ad hoc on-Demand Distance Vector (AODV) method is a de facto standard unto which new routing protocols can benchmark on. AODV has been widely used as comparison to the newly developed routing protocol. The developed nature-inspired protocols are implemented using Network Simulator version 2 (NS-2). Performance comparison of proposed routing methods were done in relation to other swarm-based routing methods. Maybe, some comparison with non-nature based simulations might have produced different results.

1.8 RESEARCH SYNOPSIS

This thesis covers mobile ad hoc networks, nature-inspired routing protocols and queuing theory for MANET networks. New routing methods for MANET networks being Queuing Ant Colony System (QUACS) and Queuing Particle Swarm Optimisation (Q-PSO) and their (QUACS and Q-PSO) respective frameworks will be presented. The rest of this dissertation is organised as follows:

Chapter 2 reviews literature on mobile ad hoc network together with its characteristics and areas of application. It also covers how routing is done in mobile ad hoc networks and challenges in routing data in MANET networks. Lastly an introduction to swarm intelligence, exhaustive review of nature-inspired routing techniques associated with MANETs and queuing theory will be discussed.

Chapter 3 deals with the swarm intelligent framework design and nature-inspired protocols development. Two new routing protocols that are based on the concept of nature-inspired optimisation hybridised with queuing theory are presented. Queuing Ant Colony Systems (QUACS) which is based on the ant colony optimisation and queuing is presented. This is followed by Queuing Particle Swarm Optimisation (Q-PSO) and performance metrics that are used to evaluate the performance of routing protocols in wireless networks.

Chapter 4 introduces the experimental setup and presents the results of different experiments from simulations. Q-PSO simulations results are presented in this chapter together with comparison with nature-inspired routing and AODV routing techniques.

Chapter 5 introduces the experimental setup and presents the results of different experiments from simulations on QUACS routing protocol. QUACS simulations results are compared with other ant-inspired routing techniques.

Chapter 6 provides an overview of research publications in the MANET routing optimisation future areas of research. Pattern of publications based on year of publication, journals and topics are presented and open areas for around MANET optimisation routing are presented together with evaluations of optimisation routing techniques.

Chapter 7 concludes the thesis by presenting the resolutions to the research questions and highlighting the contributions both theoretical and methodological from the study. Recommendations, limitations and future directions are also explored.

1.9 CHAPTER SUMMARY

In this chapter, an introduction to MANET background and motivation has been presented. The fact that mobile penetration has been increasing over the past 20 years in the developing world can greatly assist in enabling communication to take place even in physical resource limited environment such as in emergency medical rescue operations, earthquake evacuation and battlefields. The research problem statement has also been identified, and this research problem is on exploring the best path to route data packets across the MANET. Five (5) sub-problems to the research problem have also been identified and these were mainly focussing on the mimicking of swarm-based approaches in finding the shortest path and framework for swarm-based optimisation that should act as a guidance to future wireless networking researchers.

Research objectives and research questions which are related to the problem statement have been articulated. The research objectives and research questions act as a guide on what ought to be researched and what should be collected and answered. The research objectives include exploring the literature on routing protocols that are nature-inspired, developing improved bio-inspired routing protocols that are hybridised with queuing theory to determine congestion on the network during data discovery. There is also the MANET optimisation routing framework that seeks to guide future wireless networking researchers. Network Simulator 2 (NS-2) was used to check on the proposed routing protocol performance relative to other nature inspired routing protocols. Research contributions both to the scientific body of knowledge and publications coming from this study have been presented. Five articles have been published. All the published articles are part of this study.

The first publication is on using ant colony systems combined with queuing theory in MANET network. The second article is on hybridisation of particle swarm optimisation together with queuing theory for mitigating congestion on MANETs while optimising network lifetime (accepted article). The last article is on routing framework for MANET networks that is based on swarm-based optimisation techniques and revealing of less researched areas in MANET networks. Issues around ethics such as: honesty, integrity, openness, confidentiality and respect for intellectual property rights was discussed. The scope and research limitations together with organisations of the thesis conclude this chapter.

CHAPTER 2. LITERATURE SURVEY

2.1 PRELIMINARIES

This chapter will focus on literature about the mobile ad hoc network. Definitions of mobile ad hoc networks will be presented. The MANET model will be presented and how it fits into the OSI model. The IEEE 802.11 standard Wi-Fi are presented together with the various standards including IEEE 802.11a, IEE 802.11b, IEEE 802.11g and IEEE 802.11n. The areas of applications of MANET will be presented together with benefits of using the MANET technology. The process of how routing is done in ad hoc networks will be followed by challenges associated with routing data packets in MANETs. Swarm intelligence concept is introduced together with various swarm-based routing techniques that are found MANET network routing. Comparisons of various swarm-based routing optimisation strategies will be articulated, and lastly queuing theory will be presented.

2.2 MOBILE AD HOC NETWORKS

The proliferation of mobile wireless devices, ranging from smart phones, personal digital assistants, laptops to iPads, enables people to communicate with each other anytime without being confined to the office to exchange data or files wirelessly (wireless networks) [34]. Wireless networks can be classified into two categories being infrastructure-based wireless networks and infrastructure-less independent wireless networks [35][36].

With infrastructure-based wireless networks, communication is done via a fixed gateway which can be an access point that bridges the mobile nodes through the base station. Nodes cannot communicate directly, but the communication is handled by the access point from authenticating the users to exchange of data packets. When a mobile device moves outside the access point coverage, it joins the adjacent access point by switching the mode seamlessly [37]. The mobile nodes can access the access point (AP) directly. Therefore, infrastructure-based wireless networks are also known as single-hop wireless networks.

Infrastructure-less independent wireless networks do not have an AP or base station as is the case with infrastructure dependent wireless networks. The nodes themselves have the capabilities of routing data packets to other nodes in the network. Nodes that cannot directly communicate can use intermediate nodes to reach far away nodes. Infrastructure-less independent wireless networks are thus also known as multi-hop wireless networks [1], [27]. The nodes in this network are all peers and there is no centralized node(s) that controls or governs the communication process in infrastructure-less independent wireless networks. Infrastructure-less independent wireless networks are also known as mobile ad hoc networks (MANETs).

Mobile ad hoc networks are self-configuring, self-organising and infrastructure-less networks that are formed when mobile nodes move randomly and connect to other nodes dynamically using wireless radio links. MANET nodes do not need any existing fixed telecommunication infrastructure for communication to take place. Nodes in the MANET network can join and leave anytime without prior warning to other nodes in the network. The nodes communicate directly with one another if the node is within the radio range to the other nodes, or indirectly communicate via multi-hopping which is done using other intermediary nodes. The Internet Engineering Task Force (IETF) defined a mobile ad hoc network as:

"*A Mobile Ad hoc Network (MANET) is a self-configuring (autonomous) system of mobile routers (and associated hosts) connected by wireless links -the union of which form an arbitrary topology. The routers are free to move randomly and organize themselves arbitrarily; thus, the network's wireless topology may change rapidly and unpredictably. Such a network may operate in a standalone fashion, or may be connected to the larger Internet operating as a hybrid fixed/ad hoc network*."

The Institute of Electrical and Electronics Engineers (IEEE) defined a MANET as, a special wireless network that has the characteristics of self-organisation, peer-to-peer, and multi-hopping capabilities. The word 'ad hoc' is a Latin word which means temporary and for this purpose only. This therefore means the MANET network is formed to enable exchange of data and communication for a limited period of time in environments where there is limited communication infrastructure such as: in battle fields, emergency medical rescue and earthquake evacuation [27].

Mobile nodes that make up the network have two functions. First, they can be source or destination nodes [38]. Secondly, they have routing capabilities, that is, they can be used for relaying data packets to other nodes in the network. Nodes move arbitrarily in the network and thus they can join and leave the network anytime. MANET networks can be integrated with cellular networks or internet, whereby the MANET is connected to an existing wired network in the form of the stump network.

2.2.1 OSI model and IEEE 802.11 standards

The Open Systems Interconnection (OSI) network reference model was first developed in 1984 jointly with the International Standards Organisation and International Telecommunications Union. The objective of the OSI network reference model was to serve as a general framework in which various standards can be developed for interconnecting systems [39], [40]. The OSI network reference model ensures that different developments efforts should be ultimately compatible with others as long as they follow the framework. The model is made up of seven layers with each layer performing a distinct function. Each layer in the model relies on the layer below it and provides services to the layer above it. The different responsibilities assigned to each layer enables seamless communication among computers on the internet, regardless of the manufacturer of the computer. Thus, computers from different vendors can connect to the internet using different means, ranging from wireless connection, high-speed cable modem and dial-up modem. Table 2.1 shows the layers of the OSI model. Layer 5 to layer 7 are upper layers, layer 3-4 are middle layers and layer 1-2 are the lower layers.

Table 2.1 OSI layers

7 Application layer
6 Presentation Layer
5 Session Layer
4 Transport Layer
3 Network Layer
2 Data Link Layer
1 Physical Layer

The MANET network architecture model implements the OSI model in five layers. It combines the application, presentation and session layers into one and is called Application layer. The transport layer remains the same, as well as the network layer which is commonly known as the ad hoc routing layer. Layer 2 is the link layer and layer 1 is still the physical layer, just as in the OSI model.

Table 2.2 MANET network architecture model structure

5 Application Layer
4 Transport Layer
3 Network or Ad hoc routing Layer
2 Link Layer or MAC layer
1 Physical Layer

In the physical layer of the ad hoc network (Layer 1), there is encoding and decoding of wireless signals. In this layer, there is physical connection of the wireless transmission through radio waves. The link layer (Layer 2) of the MANET network is subdivided into two, namely logic link layer and medium access control sublayers. Error detection and control is handled in second layer. The logic link control sublayer provides addressing, error control and flow control whilst the Medium Access Control (MAC) sublayer determines how the channel is allocated to different users, for example, allocation based on time slots, that is, Time Division Multiple Access (TDMA). The network layer in ad hoc network is mainly for route discovery, packet routing and internetworking. This third layer (network layer) is the most critical layer of the MANET network where there is unicast and multicast routing protocols. Multicast routing protocols enable group communication which happens in MANET network during emergency medical rescue or during conference meeting in environments where there is no predefined communication infrastructure in place. The unicast routing protocol ensures maintenance of routing tables in dynamic MANET network.

The transport layer in MANET network model is responsible for providing reliable end-to-end services to the other layer, that is, application layer. Since the transport layer in ad hoc network has adopted the transport layer in the wired networks, the protocols at this layer must be improved so that they can adapt to the wireless environment. In the application layer, applications protocols such as hypertext transfer protocol (HTTP) and file transfer protocol (FTP) are found here.

The Medium Access Control (MAC) layer is used in MANETs which is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which is based on request to send, clear to send, sending data and acknowledgment exchange process. If this four-stage exchange process is not completed, it is assumed that the data packets have been lost or there are no next-hop neighbours that might have been identified.

The IEEE 802.11 standards operate within the limits of Industrial, Scientific and Medical (ISM) frequency bands [27]. These frequency bands can be shared by many users since there are no licensing requirements required for one to transmit within those frequency bands. The IEEE 802.11 is thus a set of media access control which has been implemented for wireless local area networks (WLANs). These standards are created and maintained by IEEE LAN/MAN standards committee. The IEEE 802.11 enable communication to take place wirelessly at homes or offices with the use of smartphones, laptops, printers, iPads and tablets. Since the release of the base version in 1997, there has been a continual improvement on Wi-Fi brands. Table 2.3 shows the summary of major IEEE 802.11 Wi-Fi standards. The Wi-Fi standards are the ones which use radio waves to transmit data packets from one node/terminal to another.

Table 2.3 Summary of major IEEE 802.11 Wi-Fi standards

IEEE standard	802.11a	802.11b	802.11g	802.11n
Maximum data transfer rate	54mbps	11mbps	54mbps	600mbps
Modulation in use	Orthogonal Frequency Division Multiplexing	Direct Sequence Spread Spectrum	Orthogonal Frequency Division Multiplexing or Direct Sequence Spread Spectrum	Orthogonal Frequency Division Multiplexing or Direct Sequence Spread Spectrum
Radio Frequency Band in GHz	5	2.4	2.4	2.4 or 5
Channel width in MHz nominal	20	20	20	20 or 40
Number of spatial streams	1	1	1	1,2,3 or 4
Date of standard approval	July 1999	July 1999	June 2003	October 2009

2.2.2 Characteristics of MANET networks

This section presents the characteristics of MANET networks. Since they are peer-to-peer networks, there is no centralised node(s) that govern how other nodes should communicate in exchanging data ‘on the fly’. The intrinsic routing proficiencies of nodes that participate in the MANET make it possible for nodes to relay data to other nodes on the dynamic network.

2.2.2.1 No fixed communication infrastructure and automatic configuration

There is no centralised communication controller in MANET network. All the nodes are peers and have similar capabilities. All nodes have both routing capabilities and host functions [41]. Unlike in infrastructure independent wireless networks where there are base stations and access points, in MANET networks there is no predefined and configured telecommunication infrastructure in place that will enable communication to take place. In MANET networks, communication take place using radio links whereby data packets move from one node to the other until they reach their intended destination via a process called multi-hopping.

2.2.2.2 Dynamic topology

In MANET networks, a node can join and leave the network anytime [42]. Nodes in MANET network are usually battery-powered and communication is done in environments where there is no predefined telecommunication infrastructure. So, once a node’s battery gets depleted, it ceases to be part of the network (leaving the network). Other nodes also join arbitrarily. This entails frequent update in the routing tables to reflect the status of the MANET network [43].

2.2.2.3 Limited wireless transmission range

Wired networks rely on symmetric links which are fixed, but in MANET networks, there are asymmetric links and nodes which are mobile, and they sometimes frequently change their positions. Communication in MANET network is done using radio waves. Because of the characteristics of the wireless channel itself, the bandwidth of the wireless channel is lower than the bandwidth of the cable channel [27], [44]. Attenuation, signal fading and interference between channels all contribute to less bandwidth in the wireless channel.

2.2.2.4 Multi-hopping routing

The transmission power of radio waves is limited. Nodes that are far away from each other cannot communicate directly [34]. When destination node cannot be reached directly, intermediate nodes can be used to relay data packets to the destination node. The process of the data packets being forwarded to intermediate nodes before they reach their intended destination is called multi-hopping. The forwarding of data packets is done by the nodes themselves since nodes in MANET network all have routing capabilities, unlike in wired networks, where there is a router that controls and handles the data exchange among nodes.

2.2.2.5 Poor security

Nodes in MANET network can join and leave the network arbitrarily. Once there are new nodes that might join the network, there are trust relationship problems because some malicious nodes can eavesdrop or counterfeit other legitimate nodes. This results in denial of service attacks on the network [3][42] [45]. The wireless links of MANET network are vulnerable to attacks of the data link layer including replay attacks and distributed denial of service attacks.

2.2.2.6 Interference

Available links for communication among nodes come and go depending on the node's position in the MANET network. One transmission might interfere with another transmission(s) and one mobile user might hear the communication not destined for them because of collisions, and there might be signal fading, attenuation and noise from the wireless channel itself [46].

2.2.2.7 Short network lifetime

Once a node starts to be involved in exchange of data packets with other nodes, its battery life gets diminished. Over some time, the nodes battery power gets finished and would therefore cease to be part of the network because MANET networks are deployed in a situation where there is no battery replenishment. The network lifetime of MANET networks is inherently shorter than that of fixed networks.

2.2.2.8 Limited energy, limited storage and processing capabilities

The buffer space in MANET networks is limited. The space does not increase in size and when data packet arrives in the network, it is put in the node's buffer before it can be relayed to the next node towards the destination node [47]. Once the node's buffer is full, incoming packets cannot be stored for onward transmission and will end up being dropped. Mobile nodes are battery-powered and once battery power gets diminished, the node will cease to be part of the MANET network.

2.2.3 Benefits of ad hoc networks

There are benefits which are associated with the use of ad hoc networks. These benefits are as follows:

2.2.3.1 Scalability

There is no limit to the number of nodes that can participate in the network unlike in traditional wired network where there is a limited number of terminals that can be connected on each subnetwork. A new node joins the network any time provided it has the necessary hardware and the network stack that can allow it to be part of the MANET network.

2.2.3.2 Enhanced user mobility

There is roaming in ad hoc network and as long as the mobile users can access other mobile devices within range, they are still able to communicate. They can exchange files and other resources without having to be connected to wired networks.

2.2.3.3 Quick installation

The time required to setup the ad hoc network is insignificant. MANET network can be deployed in an environment where it may be impossible to lay out cables and does not want any existing predefined telecommunication infrastructure in place.

2.2.3.4 Flexibility

Ad hoc network can be configured depending on the applications and installations needs in any given environment. Since MANET can be deployed in battlefield communications, emergency medical rescue or in conference meeting, the layout and installations requirements might be different. The time it takes to setup the MANET network is negligible.

2.2.4 Areas of applications of MANETs

The application of MANET networks is distinguished and can be deployed in several areas where it maybe practically impossible to deploy a wired network. The following are areas in which MANET networks can be used, but the list is not exhaustive.

(a) Battle field scenario- MANET network can be deployed in battle field communication where there is no predefined telecommunications infrastructure. MANET network thus supports tactical network for military communications.

(b) Emergency medical rescue- in catastrophic areas, MANET networks through the node forwarding capabilities can enable communication in emergency medical rescue operations such as; during Ebola pandemic or earthquake evacuations. Use of MANET network can provide disaster recovery in place of fixed networks in areas where they wired networks might have been destroyed, for example, during tsunamis or earthquakes.

(c) Free internet connection and device networks- using the MANET network enables sharing of files, data and internet access with other users.

(d) Sensor networks- the sensor network is made up of devices that can sense, compute and transmit data wirelessly. They can be used in agriculture, for monitoring humidity and temperature. The sensors send signal detectors to the farmer in case of some anomalies on the farm without human being interference.

(e) Personal area networks (PANs)- a user can connect his or her mobile devices such as alarms, laptop, iPad and television. These devices are able to transfer files among themselves. With the increase in digital devices manufactured nowadays, PANs are a promising technology in which users can monitor their homes away from home. This is possible if mobile devices are integrated with sensors.

(f) Public areas communication- users can use MANET network in areas such as: cafeteria, conference meetings and airports.

2.3 ROUTING IN MANET NETWORKS

2.3.1 Routing techniques

Routing is the process of moving data packets from the source node to the destination node within an internetwork environment. The process of routing involves determining the optimal path that the data packets have to move on the network. The data packets are actually being transferred from one node to the other. In MANET networks, nodes move out of the network and others join at anytime. Therefore, the routing updates should be done frequently as compared to the traditional wired networks. This is because new links are established [27], [42] and old link get destroyed as new nodes join and leave the network respectively. In wireless networks, new routes have to be discovered before any routing of data packets takes place.

The process of routing in MANET networks involves the source node broadcasting the route request (RREQ) data packets to all next -hop neighbours that it can reach directly. If the destination node can be reached directly, that is single-hopping routing, the connection link is established, and data exchange can happen. However, if the destination node cannot be reached directly, multi-hopping routing process is adopted till the destination node is reached. Multi-hopping is done with the help of intermediate nodes since all nodes in the network has routing capabilities. Intermediate nodes receiving the data packets check their cache memory requests to see if the route to the destination has been previously found. If the route exists previously, that is the same route request ID has been sent before, then RREQ data packets are dropped. Otherwise the next-hop neighbours forward the data packets to other next-hop neighbour until the destination node is reached . When RREQ data packets are being sent across the network, they have a time to live counter and this is decreased each time a new intermediate node is encountered. If the TTL becomes zero, the RREQ data packet is dropped.

Once the destination node is found, the route reply (RREP) data packet is sent to the source node using the same path that the RREQ data packets have traversed. The routing tables are updated to show the path that the data packets can take from the source node to the destination node. Table 2.4 shows the structure of a routing table extracted from Figure 2.1. The route with the least number of hops to the destination node is favoured in comparison with the routes that have higher number of hops. Figure 2.1 show route discovery from source node, N_1, to destination node, N_8.

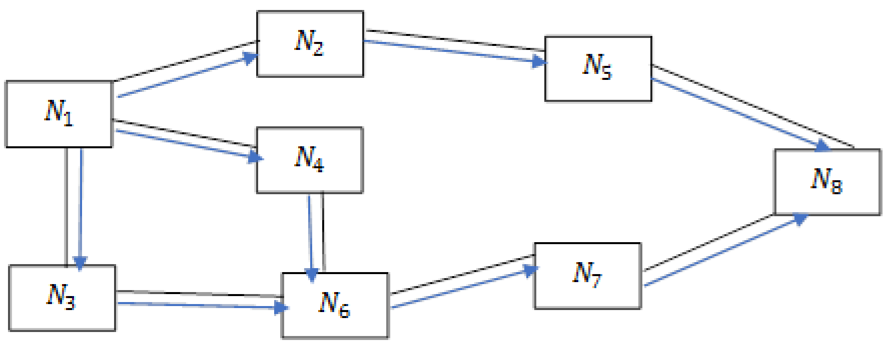

Figure 2.1 MANET route discovery from source node $\boldsymbol{N_1}$ to destination node $\boldsymbol{N_8}$

Table 2.4 Routing table for node $\boldsymbol{N_5}$

Destination	Next-hop neighbour	Number of hops
N_2	N_2	1
N_7	N_8	2
N_5	—	0
N_3	N_2	3

During routing of data packets, some links can be broken down or other links may be added . This entails frequent updating of routing tables by each node on the MANET network to reflect on the current status of the network. If broken links are detected on the network, the source node is notified about it by the intermediate nodes and the process of RREQ starts again [27]. An intermediate node can detect a broken link and can initiate a local repair message process towards the destination node by sending its own route request. This minimises the routing overhead associated with starting the RREQ process from the source node.

The routing classification for MANET networks falls into three broad categories, that is flat routing protocols, hierarchical routing protocols and geographical position-based routing protocols [27], [48]. With flat routing protocols, all the nodes are equally involved in the routing of data packets. The nodes are all peers. There are no superior nodes thus routing classification assumes a flat topology. A hierarchical routing protocols has some nodes which perform different functions such as: cluster head nodes, gateway nodes and regular nodes. Geographical position-assisted routing protocols consider the global positioning systems (GPS) of nodes when routing data packets across the wireless ad hoc networks. In each of these three-broad classifications of MANET routing protocols, routing can be done proactively, reactively and in some instances, hybridisation of proactive and reactive routing protocols can be practised. Figure 2.2 show the classification of MANET routing protocols

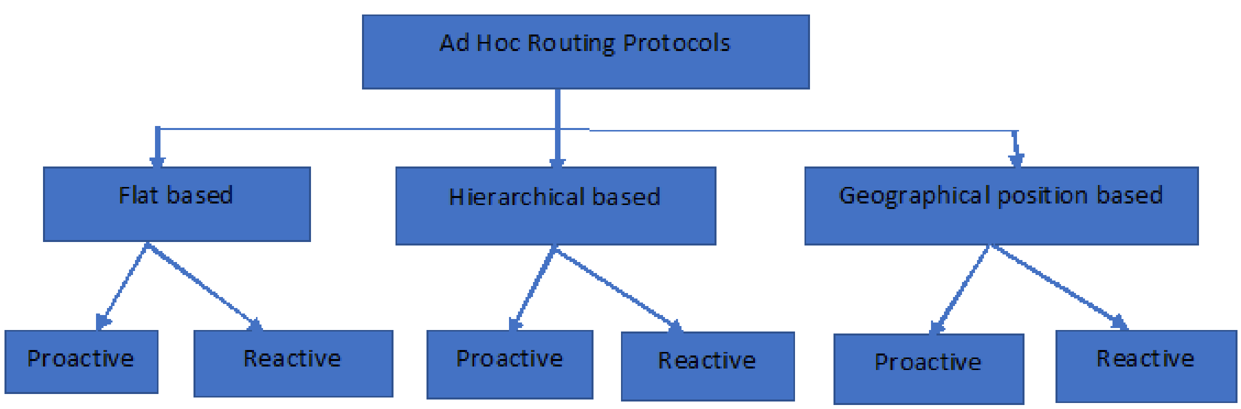

Figure 2.2 Classification of MANET routing protocols

2.3.2 Proactive routing

Proactive routing is also known as table-driven routing. The proactive routing shows the global network view. In proactive routing method, each node in the ad hoc network strives to maintain an up-to-date information of all the other nodes in the network. The routing information is always available, even if there are no data packets that are being transmitted. Periodically the routes are updated because new nodes join and others leave the network and this may be as a result of some triggered updates when the established links change [27], [49]. When new nodes join and others leave the network, the remaining nodes update their respective routing tables and inform every other node on the network about the changes that have occurred on the network.

The advantage of proactive routing methods is that routes are known even before routing can take place. This minimises the RREQ process when new routes need to be established between source and destination node and is efficient if routes saved on the routing tables are used often [50]. Disadvantages of proactive routing include large amount of overhead since bandwidth can be wasted on establishing and maintaining routing tables for paths which might not be used. Another disadvantage is that of scalability. As mobile nodes increase, more routing tables are needed to be maintained and the performance of routing protocols deteriorates because there will be many routing tables being maintained. This results in stale routes being cached but not being utilised. Popular examples of proactive routing protocols include; Dynamic Destination-Sequence Distance Vector (DSDV) and Optimised Link-State Routing (OLSR).

a. Dynamic destination-sequenced distance vector

The dynamic Destination-Sequenced Distance Vector (DSDV) is a proactive routing in which each node in the network periodically broadcasts its routing table to nodes that are one-hop away from it. Sequence numbers are used to show the freshness of the route. Each next-hop neighbour will then update their routing tables [46][10]. This procedure for new routing tables exchange by nodes is propagated throughout the network. Nodes in DSDV routing methods can discard received old metrics and duplicates because of the sequence numbers.

b. Optimised link-state routing

The Optimised Link-State Routing (OLSR) reduces traffic congestion or routing overhead on the wireless ad hoc network by using intermediate nodes which are known as multipoint relays

(MPRs) to forward data packets, instead of utilising all the nodes[51], [52]. MPRs are the intermediate nodes that forward data packets on the network. MPRs are selected based on the minimal set of one-hop neighbours that cover all the next-hop neighbours of the node. Information on the selection of nodes to be MPR nodes is gathered periodically from the Hello messages. OLSR is thus ideal for a large and dense network which are not too dynamic.

The Optimised Link-State Routing optimises the route update and it also introduces optimised flooding structure on intermediate nodes. To establish routes, each node periodically floods the network via the intermediate nodes list of its chosen intermediate nodes as with the case with link-state routing methods.

2.3.3 Reactive routing

Reactive routing protocols are also known as on-demand routing protocols. The nodes only evaluate and update routing tables only when there is data to be sent. The node will only check for valid route if it has the data to send. The advantage of reactive routing protocols is that data packets are only generated when necessary. Thus, routes are discovered only when there are data packets to be sent. The disadvantage associated with reactive routing protocol is that there is delay in the first packets being sent because of non-existence of the routes as compared to proactive routing protocols.

With reactive routing protocol, when data packets have to be sent to the destination node(s) which are not known by the current intermediate node, the route discovery process is initiated [49], [50]. The current intermediate node floods the network with the RREQ data packets and will wait for RREP packet to check if the destination node has been reached and update their routing tables. Once the route is found, it will be used until there has been route breakage. Route breakage can be due to nodes leaving the network or other nodes joining the network providing better optimal paths towards the destination node(s). Popular examples of reactive routing protocols include; Ad Hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) methods.

a. Ad hoc on-demand distance vector

The Ad Hoc On-Demand Distance Vector (AODV) routing protocol is a popular reactive routing protocol. Many routing protocols on extending network lifetime of an ad hoc networking are benchmarked on the AODV routing protocol. AODV was first proposed by Perkins and Royer in

1999 and it started as an extension for the Dynamic Destination-Sequenced Distance Vector routing protocol [38], [53]–[55]. When data packets are to be sent, a route request process is initiated. If no route exists, that is one-hop away from the source node, flooding approach is used to check on feasible path to reach the destination. The route request data packet has a timer which is decreased each time an intermediate node towards the destination is encountered. Sequence numbers are also embedded on the route request data packets to control exploring intermediate nodes more than once, hence, results in looping which ultimately wastes the available scarce bandwidth [55]. Hopping from one intermediate node to the other is done until the destination node is found, or destination host is unreachable.

If a destination is not reachable, an error message is sent back to the source node to start to initiate the route request process. When destination node is found, a route reply data packets is unicasted back to the source node. Intermediate nodes setup the routing information based on information which they receive from route reply data packets. Once the source node receives the route reply packets, the communication process can start by sending the data packets that have been buffered for the destination node. Periodically, nodes exchange Hello messages which are used to inform other nodes of their existence on the network.

b. Dynamic source routing

The Dynamic Source Routing (DSR) was proposed by Johnson and Maltz in 1996 [53]. It follows many of the processes that are in AODV routing protocol, for example, route discovery and maintenance of the broken links. The difference between DSR and AODV is that the DSR stores the entire route to the destination nodes instead of just next-hop neighbours unlike in AODV. During route discovery process, route request packets are flooded across the network in searching for the possible route to the destination [56][57]. Route reply messages are generated by the destination one or any intermediate node that has a valid route towards the destination node. If an intermediate node receives a data packet and it finds that the next link that it has to relay data to is broken, an alternative path should be explored. Otherwise, a route error message is sent back to the source node to initiate the route request process again.

The advantage of DSR routing protocol is that only communicating nodes need to maintain the route. Also, several paths are found between source and destination node that can be utilised in the event that the established shorter path becomes unavailable. The disadvantages of DSR routing protocol is that there is large overhead in keeping multiple paths from source to destination that ends up consuming lots of bandwidth of the wireless channel. Another disadvantage is that of increasing congestion, especially if there are many nodes and there can also be the existence of stale routes which are not used.

2.3.4 Hybrid routing

A hybrid routing method combines both the features of proactive and reactive routing protocols by taking the advantages of each [58], [59]. Hybrid routing protocols are also based on the concept of a 'zone'. Every node in the ad hoc network belongs to a zone. The zone helps in minimising the number of data packets that are flooded into the network when broadcasting is done during route discovery. The Zone Routing Protocol (ZRP) is an example of hybrid routing protocol.

In ZRP each node has a zone consisting of next-hop neighbours with p hops from it, such as 2 hops from S to the border nodes that is node A and node G as shown in Figure 2.3. Nodes that are not at the border such as node B are less than two-hops from S. Nodes that are exactly at the border such as, node A are called border nodes and these are used for communicating with nodes that are outside the region that is covered by node S. Proactive routing is done within the zone because data packets are mostly likely to be sent to nodes that are near. Nodes within the zone can be reached directly from the sending node and again, the topology changes can be easily fixed in case of links being broken. Reactive routing is used for communicating with nodes that are outside the zone using border nodes. Depending on the choice of the radius, ZRP can behave as purely proactive routing protocol or purely reactive routing protocol or doing both proactive and reactive routing.

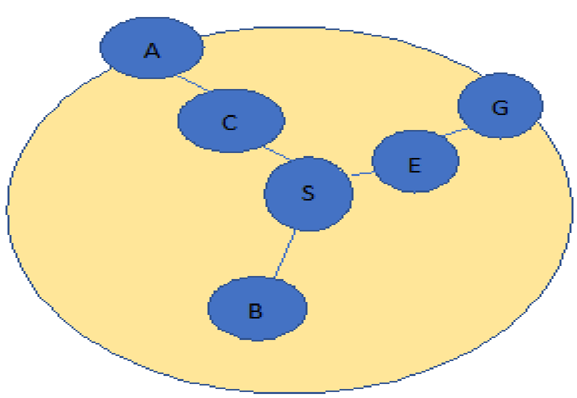

Figure 2.3 ZRP routing protocol

2.3.5 Gaps identified in the literature

Generally ad hoc network routing protocols focus on ending data packets using the shortest path. Most of the routing protocols in literature explore the shortest path by looking into the number of hops that have to be traversed from the source node to the destination node(s). The congestion on the links that has the shortest path can be detrimental to the successful delivery of data packets in ad hoc network environment if congestion aware approach is not infused in the routing method. Existence of the shortest path that has least number of hops can end up dropping more data packets if it is congested because the nodes in the MANET network have limited buffer space and limited computational and processing capabilities. Once data packets come to a buffer that is full they end up being dropped or taking more time waiting to be relayed to the next-hop neighbours.

Most ad hoc routing protocols do not factor in stability of nodes when routing data packet and scalability issues are a problem, when the network size increases in a dynamic MANET network. Framework based on MANET routing that acts as a guide to future wireless academics and network protocols designers has not be provided by previous scholars. Determination of congestion links on links that are based on nature-inspired approaches is a potential area that can be explored to determine stable and less congested links on the networks.

2.4 CHALLENGES ON ROUTING DATA PACKETS IN MANETS

Routing data packets in MANET networks is prone to challenges due to dynamism of the network. Challenges associated with routing data packets in MANET are presented below.

2.4.1 Network lifetime

Network lifetime is the most critical factor for wireless network. The network lifetime is a measure of how many nodes or part of the network will still be alive over a given period of time. The primary objective of a wireless network is to be available for use for a long time before a node's battery life is depleted [47]. Enhancing the network lifetime is made possible by ensuring that a node's battery life is checked prior to communication. As nodes in MANET are battery-powered, receiving and sending data entails energy consumption for those nodes that relays data. Frequent updating of routing tables in ad hoc networks also consumes energy resources.

The network lifetime is dependent on how the energy conservation strategies have been implemented in the ad hoc network. As the node's battery power gets depleted, the survival of the network is ultimately affected, as well as the changes in the routing tables to reflect the current status of the network. As data packets are being transmitted across the ad hoc network over sometime, some nodes that are frequently used in relaying data packets will have their battery power depleted. New routes should be established following less frequently used paths. Optimisation of routing protocols should aim to prolong the lifetime of the wireless network as shown in [27], [47].

2.4.2 Quality of service

Quality of service (QoS) involves a number of parameters such as: latency, jitter, routing overhead, node's residual energy, throughput, bandwidth and packet delivery ratio. Finding a path in ad hoc network that satisfies all QoS parameters is a challenge [11][43]. However, from literature it has proven that it is difficult to address all QoS factors at once as presented by [11][43][60]. MANET routing protocols explore routing protocols focussing on a subset of the QoS parameters. To solve all the QoS constraints requirements with multiple objectives, there is need for coming up with routing approaches that satisfy all the QoS parameters.

2.4.3 Energy

The nodes in the wireless network are usually battery-powered and once the battery is depleted, the node will no longer be able to forward and receive data in the network as presented by [19], [52], [61]–[63]. Conserving battery life of nodes in the ad hoc network positively influences the network lifetime. The majority of energy-aware routing protocols try to minimise energy consumption through utilising the energy efficient routing metric in its routing table computation instead [64]–[66]. The forwarding of data packets in ad hoc network should try to follow the path that has maximum energy levels bottleneck. Designing optimum routing protocols that integrate node energy levels and their congestion levels will help to prolong the lifetime of the ad hoc wireless network as presented by [30][19]. Reducing energy consumption within a wireless network is a critical aspect in the designing of ad hoc wireless network routing methods. This is because the battery life of mobile devices is limited and once a node's battery is depleted, the node ceases to be part of the wireless network and reconfiguration of the nodes with other nodes that still have battery power is required.

2.4.4 Security

A MANET network has an open nature approach, that is, nodes join and leave anytime hence, designing routing protocols that factor in security is one area that has been presented in [5], [42]. The dynamism of the MANET network makes it difficult to determine malicious users from non-malicious users when nodes join and leave anytime. Attacks such as; black hole and worm hole take advantage of the flooding approach used by the nodes in MANET network during route discovery are common in wireless networks. However, more work needs to be done in the event of collaborative attacks perpetrated by a number of malicious users on the network. Integration of security and privacy using nature-inspired approaches like ant colony optimisation techniques is a potential area for future research.

2.5 SWARM INTELLIGENCE

2.5.1 Introduction and definition of swarm intelligence

Swarm intelligence is a subfield of computational intelligence which provides solutions to problems which are generally complex to deal with conventional techniques [35], [67]–[69]. Swarm intelligence can be broken into two: swarm and intelligence. Swarm is the set of mobile agents that can be used to solve a complex problem. Intelligence is the property of the system in which unsophisticated local interaction can result in emergency of sophisticated global behaviour[1], [37], [47], [59], [70].

Swarm intelligence can be defined as a set of agents that cooperate through either direct or indirect (by acting on their local environment) communication with each other to solve a problem. The agents are independent entities with limited intelligence (i.e. a defined rule set) that monitor the environment via their built-in sensors and then respond to those sensors using an internal stimulus-response mechanism. The abilities of individual members in the group are limited, but the whole group has a strong vitality [71].

Swarm intelligence can also be defined as the collective behaviour of self-organised and decentralised systems whether natural or artificial. This collective interaction of agents will ultimately lead to the emergence of a global behaviour or collective characteristic which is unknown to the participating individual agents [48][72]. This emergent collective behaviour is attributed to the decentralised and self-organising characteristics of the collective coordination of the agents. Using swarm intelligence has a number of advantages ranging from [48]:

- Scalability-whereby the population of mobile agents are adapted to the problem size to be solved.
- Fault tolerance- is possible with swarm intelligence because there is no centralised control mechanism and the failure in one agent therefore does not affect the reliability of the system.
- Adaptation- here agents are capable of adapting to the changes in the system.
- Self- autonomy- this is achieved in swarm intelligence because there is no human interference and no human supervision is required
- Parallelism- the way agents function is intrinsically in parallel

2.5.2 Pheromone

Pheromone is a chemical substance that is excreted by ants in an ant colony system [20], [73]. Recruitment for other ants to the food source is done by laying of pheromones or following pheromone trails or bee dance in colony systems. For example, when an ant finds food, it will return to the colony reinforcing its trail of pheromones. The other ants are notified by the scent of the reinforced trail of pheromones leading back to the food source. The trail of pheromones left by the initial ant, will act as a guiding trail for the other ants to discover the food source [74]. Thus, there exists a trail of pheromones to the food source and then back to the colony. This pheromone trail will then act as an emergent guide for other ants from the colony to follow to the food source and then back to the nest. Each ant following this trail to the food source will reinforce the trail with pheromones so long as the food source exists. This continuous reinforcing of the pheromone trails leads to a distinct chemically marked trail that will be easily detected by the rest of the colony.

2.5.3 Stigmergy

Stigmergy comes from the word ‘stigma’ and ‘ergon’ which means stimulation by work. When an ant is looking for some food in ant colony systems, it can indirectly exploit the past experiences of other ants by following an existing pheromone trail to reach previously discovered food sources. This process is referred to as stigmergy. The environment is changed by the individual agents via the chemically pheromones that they deposit [2]. The changing environment then guides the ants to the food source. The ants use the simple rule of following the direction with the highest pheromone intensity. This stigmergic behaviour where ants react to and follow the path with the highest intensity of pheromones leads to the emergence of the shortest path to the food source hence, acquiring food quickly and efficiently.

2.5.4 Positive and negative feedback

A single ant moves at random in the ant colony system looking for food, and when it finds some scent trails, there is a high probability that the ants will start to follow the previously discovered path to the food source. When the food source is found, the ants follow the route they have traversed from the nest to the food source thereby reinforcing it and other ants are also attracted to routes that have got higher pheromone levels [75][74]. This reinforcement of the frequently used paths from source to the destination (that is nest to the food source) or bee dance in bee colony systems is called positive feedback. This cooperative interaction of ants has often resulted in the emergence of the shortest path from the nest to the food source.

Negative feedback counterbalances the positive feedback. The former is also known as pheromone evaporation, that is the decrease in pheromone intensity which occurs when a route does not have many ants to add more trails, for example, longer routes or either there is exhaustion of food sources or there is competition for food at the food source. Evaporation of pheromones can be viewed as exploration mechanism that allows for other routes to be discovered. This evaporation is critical because errors or poor choices that might have been selected in the past will be eliminated as other new routes which might be better will be explored.

2.5.5 Motivation for swarm-based routing methods

The behaviour of agent in swarm intelligence makes them fit to solve routing optimisation problems in MANET networks. In swarm intelligence, a problem is solved through the interaction on different agents which result in the emergence of global behaviour [35], [67]. The decentralisation and self-organisation features associated with social insects make them ideal for solving problems associated with MANET networks such as; dynamism and limited energy. Following short routes to food sources in the ant colony systems is positively influenced by the heuristics information such as, levels of pheromone that has been deposited by the previous ants. This is the same behaviour with ad hoc networks where choosing transient routes depends on the nodes remaining battery life and congestion levels of the links.

The high levels of pheromones show the desirability of using a particular route in ant colony systems. If pheromone levels decay, indicating the previously found route become undesirable, maybe due to food exhaustion the ants explore other paths. This feature found in natural social insects systems is also useful in routing data packets in ad hoc network when congestion is encountered on the link and alternative paths can be explored. Thus, multiple paths routes are also available in ad hoc network. The characteristics of natural swarm-based routing approaches makes them ideal for solving routing challenges in MANET networks which are non-deterministic polynomial (NP) hard problems.

Scalability and faulty tolerance or robustness to failure of swarm intelligence agents also make it easy to mimic these same techniques in routing data packets in wireless ad hoc networks. This fits well with the spatially distributed limited computational power of the wireless MANET network [34]. In swarm intelligence, agents quickly adapt to changes in environment in a robust way to topological changes and traffic changes and as component changes. The adaptability of agents in relation to topological changes suits perfectly the changes that occur in MANET network when nodes join and leave arbitrarily and the topology of the ad hoc network changes to reflect the status of the network. Local interaction of agents influenced by stigmergy only locally available information results using in the sophisticated global behaviour and the local interaction to through exchange of Hello messages to determine next-hop neighbours that can be easily imitated by agents.

Examples of swarm intelligence approaches that have been presented in the literature include: ant colony optimisation, particle swarm optimisation, bacterial foraging optimisation, genetic-based optimisation, artificial bee colony optimisation and hybrid optimisation techniques.

2.6 POPULAR NATURE INSPIRED ROUTING TECHNIQUES IN MANETS

The popular routing protocols that are an inspiration of social insects and animals include: ant colony optimisation, particle swarm optimisation, bacterial foraging optimisation, genetic-based optimisation, artificial bee colony optimisation and hybrid optimisation techniques.

2.6.1 Bacterial foraging optimisation

Bacterial foraging optimisation (BFO) is a bio-inspired technique that has been developed by Kevin M. Passino in 2002 [48]. BFO is based on the bacterial searching activity that happens inside the human body stomach. BFO mimics the foraging behaviour of *Escherichia Coli* which is shortened to E. coli bacteria that reside in the human intestines. BFO is based on the concept of natural selection whereby animals with poor foraging strategies are eliminated in favour of those animals whose genes are more favourable for foraging strategies [76]. Animals with good foraging strategies are favoured and tend to enjoy better reproductive success in comparison with those that have weak foraging strategies. After several generations, poor foraging strategies are eliminated. This way of bacterial foraging led researchers to use it as an optimisation method. The E. coli bacteria that experienced the foraging strategy dictates how the foraging process should go. The foraging mechanism is divided into three steps being:

Chemotaxis- in chemotaxis the E. coli bacteria move in two different ways. It can either swim or it may tumble and usually alternative between these two different states at any time. The E. coli bacteria swim when the conditions are favourable, that is usually when the bacteria approach the a nutrient gradient, and they tumble when the environment is unfavourable that is when bacteria move away from food source to search for more [69].

Swarming- in swarm, the cells produce an attractant aspartate when it has been stimulated by high level of succinate. The attractant aspartate helps the bacteria to gather in several subgroups and ultimately, resulting in them moving together as a group of high bacterial density [68].

Reproduction- the strong bacteria produce offspring whilst the weak bacteria die. This naturally balances the swarm size.

Elimination and dispersal- in a natural habitat, the population of bacteria can either increase or decrease, maybe due to some other factors. In BFO, this is counterbalanced by removing some bacteria at random, though with small probability whilst new bacteria replacements are initialised randomly over the search space. BFO pseudo code is shown below [69].

Pseudo code 2.1 : BFO Protocol

Step 1: Initialisation of parameters n, S, N_c, N_s, N_{re}, N_{ed}, $C(i)$ $[for\ i = 1,2, \ldots, S]$,$\theta^j$

n: dimension of the search pace

S: the number of bacteria in the colony

N_c:chemotactic steps

N_s : swim steps

N_{re} : reproductive steps

N_{ed} : elimination and dispersal steps

P_{ed} : probability of elimination

C(i): run time length which is the size of step taken to swim or tumble

Step 2: Elimination dispersal loop: $l = l + 1$

Step 3: Reproduction loop: k= $k + 1$

Step 4: Chemotaxis loop: j= $j + 1$

for i= $1,2, \ldots S$ take a chemotactic step for bacterium i as follows

let $J_{last} = J(i, j, k, l)$ to save this value since a better value can be found in another run

tumble: generate a random vector Δ(i)∈R^n with each element $\Delta_m(i)$, $m = 1,2, \ldots, n$

a random on [-1, +1]

move let $\theta^i(j + 1, k, l) = \theta^i(j, k, l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$ //this results in step of size $C(i)$

in the direction of the tumble for bacterium i

compute $J(i, j + 1, k, l)$ with $\theta^i(j + 1, k, l)$

swim

let m=0 // initialisation of swim counter

let m=m+1

if $J(i, j + 1, k, l) < J_{last}$ then $J_{last} = J(i, j + 1, k, l)$ and use $\theta^i(j + 1, k, l)$ to compute new $J(i, j + 1, k, l)$

else $m = N_s$

go to next bacterium $(i + 1)$ if $i \neq S$

Step 5: if $j < N_c$ go to step 3

Step 6: Reproduction: for given values of k and l where $i = 1,2, \ldots, S$, compute the health of bacteria using the equation

$$J_{health}^{i} = \sum_{j=1}^{N_c+1} J(i, j, k, l)$$

and sort the bacteria in ascending values according to J_{health}

Step 7: if $k < N_{re}$, go to step 2 // the number of reproduction steps not yet reached

Step 8: Elimination and dispersal: for $i = 1,2, \ldots, S$ with probability P_{ed} eliminate and disperse each bacterium,

if $l < N_{ed}$ then go to step 2

otherwise end

2.6.2 Artificial bee colony optimisation

Artificial bee colony (ABC) is also another bio-inspired optimisation technique which is modelled around the behaviour of honey bees. The ABC optimisation technique was invented by Karabogin Erciyes in 2005 to solve numerical optimisation problems [55][77]. ABC is simple to implement because it has few control parameters and a number of studies carried out shows that the extended ABC optimisation approaches produces better results in comparisons with particle swarm optimisation and differential evolution techniques. There are three different types of bees in ABC systems. These are the employed bees, scouts and onlooker bees. Each type of bee has different roles in the scouting for food sources. An employed bee explores the food source visited by itself previously [78]. Onlooker bees wait in the dance area waiting to make decisions to select a better food source. The scout bees do random search. The process of wandering for food sources by bees is the process of finding the optimal path with each solution of optimisation problem being treated as a food source in the search space. The fitness of each solution represents the probability of the food source. The pseudo code 2.2 for ABC is shown below [76].

Pseudo code 2.2 : ABC Protocol

Step 1: Randomly generate initial solutions of the population, $\Theta_i = (1,2, \ldots, SN)$ //vector of dimension and SN is solution number which is equal to number of employed bees

Step 2: Employed bees start to wander around looking for food source

select randomly dimension j using of bee i using equation

$\lambda_{i,j}(t) = \sigma_{i,j}(\Theta_{i,j}(t) - \Theta_{k,j}(t))$

where k ∈ {1, 2,…,SN and j∈{1,2,….,D} are randomly chosen indexes, $\sigma_{i,j}$ is a

random

number between [-1,+1]

candidate position is found by using equation $\lambda_{i,j}(t) = (\Theta_{i,j}(t) - \lambda_{i,j}(t)$

Step 3: The position of new sources replaces the old sources if it is better than the previous one

otherwise keep the position of the previous one

Step 4: When all employed bees complete search process, share nectar information with onlooker bees

Step 5: Onlooker evaluate the quality of nectar information provided and select the food source with higher fitness of the solution using equation

$P_i = Fitness_i / \sum_{j=1}^{SN} Fitness_j$

solutions with high values of P_i are selected //P_i is fitness of the i^th solution

Step 6: Onlookers carry out exploitation as in Step 2 until solution is found or until a number of cycles or iterations has been reached

2.6.3 Genetic based optimisation

Genetic based optimisation is an adaptive evolutionary heuristic search method that was first proposed by Hollard in 1970. It is based on the principles of natural selection and genetics that mimic natural biological evolution [46]. Genetic based methods are basically made up of two processes; being selection of individuals that are involved in reproducing the next future generation and the changing of selected individuals parents by the process of mutation and crossover to form the next generation. Genetic based methods maintain a list of potential solutions where each potential solution is termed a chromosome. The chromosomes are made up of positive numbers that show the node's identity numbers that consist of a route path towards the destination.

Chromosomes make up the population, and each chromosome is evaluated for fitness [79]. Evaluation of fitness for each chromosome is important in routing path evaluation because high fitness value indicates the goodness of each candidate's solution. The evolution from the next generation involves fitness evaluation, selection and reproduction. The initial population is evaluated for fitness and then the parents are ranked based on their respective fitness values. Then the second selected parents with better fitness values are chosen for producing the next generation of offspring using crossover or mutation operators. Crossover involves random exchanges of bits and mutation operator is associated with altering the randomly selected bits by the crossover operator [46]. The genetic based method terminates when an acceptable solution has been found. The pseudo code 2.3 shows the genetic based protocol.

Pseudo code 2.3 : Genetic based protocol

Step 1: Initialisation : Generate random population of n chromosomes
Step 2: while stopping criterion is not satisfied do
Step 3: Evaluate the fitness g(x) of each chromosome x in the population
while the new population is not complete do
Step 4: Selection : select two parent chromosomes from the population according to fitness
Step 5: Crossover: with crossover probability, crossover the parents to form the new offspring
Mutation: with probability mutate new offspring
Step 6: Insert the new offspring in the new population
end
Step 7: Replace: Use the new offspring to generate future generations
end
Step 8: Return: Save the best solution found so far

2.6.4 Hybrid based optimisation

Hybrid based optimisation involves utilising more than the optimisation approach which enables efficient routing of data packets in networks. Simulation results from various hybridised optimisation techniques have shown that the performance of hybrid optimisation is better relative to using one optimisation technique. A hybrid Genetic based and Artificial Immune System called IGA was proposed by [80]. Negative selection associated with artificial immune system was adopted to determine input variables from the population whilst genetic-based method was used to select regions in which global optimum exists. Hopfield neural network combined with particle swarm optimisation is another hybrid optimisation routing method which was presented by [81][82] to improve the network lifetime of the network. Genetic based method with Particle Swarm Optimisation (GA_PSO) is a hybrid optimisation routing method proposed by [29].

GA_PSO partitions the wireless network into logical clusters to minimise overall transmission distance between source and destination node(s).

Zone-based routing with Parallel Collision Guided Broadcasting Protocol (ZCG) is another hybrid routing method proposed by [10]. ZCG partitions a network into clusters similar to GA_PSO, but ZCG uses intelligent broadcasting which reduces bandwidth consumption by reducing re-broadcasting and the chances of message collision by using a parallel and distributed broadcasting technique. Particle Swarm Optimisation and local search routing method was proposed by [83] to reduce energy consumption of nodes on the network. The power transmission levels were used to determine a particle's position after each iteration. Cuckoo Search with Ad hoc On-Demand Distance Vector (CS-AODV) is another hybrid routing method proposed by [84].

2.6.5 Ant colony optimisation

Ant colony optimisation (ACO) is a metaheuristic optimisation strategy based on the behaviour of ants whose successful foraging behaviour is based on stigmergy [20][85][86] [87][88]. Ant Colony System (ACS) is a metaheuristic bio-inspired approach of finding the path from the source node to the destination node. ACS method can be used to solve many combinatorial optimisation problems. It has been observed that in the natural environment setting, ants tend to perform simple autonomous tasks and cooperate with each other to solve a problem which a single ant would not be able to solve alone. Ants start searching for food by moving around to different locations. During movement, the ants lay an odorous chemical substance known as pheromone along the path from the food source to the nest, which in turn influences the behaviour of other future ants [89][87]. It has been observed that over time, many ants will tend to follow the path that has the highest level of pheromone trail and abandon those that have less pheromone levels (longest routes). This is shown in Figure 2.4.

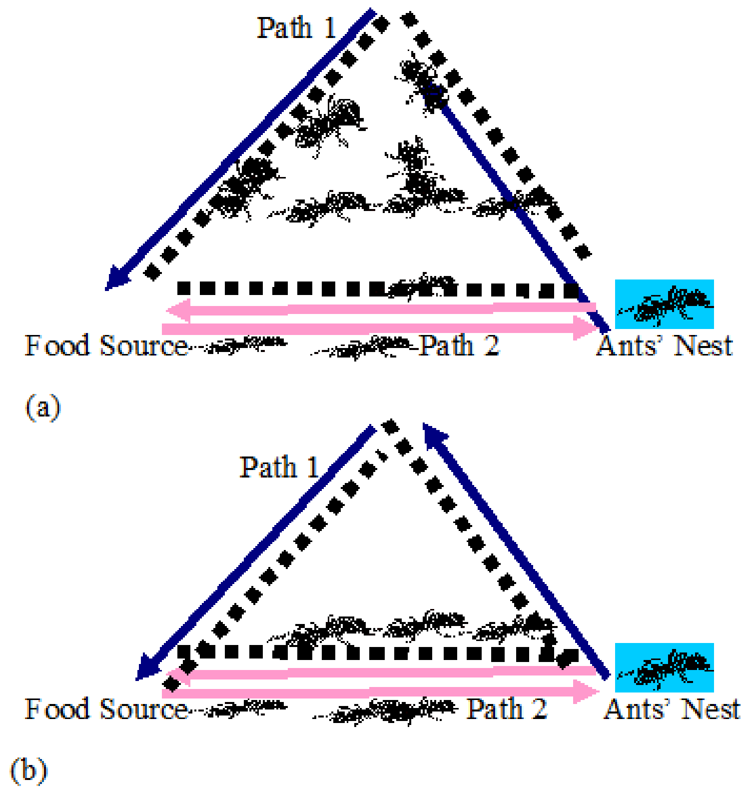

Figure 2.4 a and **b** Double bridge experiments for ants foraging for food adopted from [87], [90]

When ants reinforce the trails left by previous ants, they indirectly inform other future ants on the existence of the route that future ants will follow as well. This indirect communication by ants is called stigmergy. When ants reinforce the trails left by the previous ants, a process called positive feedback it results in many other ants following it, as shown on the results from the double bridge experiment in Figure 2.4b. Unattractive routes result in pheromone evaporation as shown by the longest side of the bridge, that is, path 1, in Figure 2.4b. The following are the characteristics of ACS routing protocols [67]:

- Local estimates by ants should not influence a global impact directly
- The ants rely solely on passive and active information monitoring and gathering
- Ensures that ants provide traffic-adaptive and multipath routing
- Makes stochastic decision based on the pheromone intensity

The pheromone tables (routing tables) in MANET, resemble the pheromone in the natural world setting [88]. The artificial ants (mobile agents) in MANETs are routed on a hop-by-hop basis from the source to the destination. The pheromone update relaying information from node to the destination is given by the following equations (2.1) and (2.2) [11].

$$t_{\ ij} = t_{ij} + \Delta^{k} t_{ij} \tag{2.1}$$

t_{ij} *is the amount of pheromone deposited on the link i to j at a given point in time denoted by t*

The local pheromone update is done by the node

$$t_{ij} = (1 - p) * t_{ij} + p * tr^{0} \quad where\ r^{0}\ is\ initial\ pheromene\ for\ edges \tag{2.2}$$

$$r^{0}\ \ is\ calculated\ as\ = \frac{1}{no.of\ nodes * number\ of\ nodes\ from\ source\ to\ destination}$$

$and\ p\ is\ evaporation\ factor\ and\ \ 0 < p < 1$

This gives rise to the following properties of MANET

For any edge in the MANET, there exists an edge (i, j) at time denoted by t if 0< $t_{ij}(t) + p * r^{0} <$ 1 *holds true* then 0< ((*1*-*p*) * $t_{ij}(t) + p * r^{0}) < 1$

In the absence of a global pheromone from source to the destination node in the MANET, for every edge (i, j) if $t_{ij}(t) > r^{0}\ then\ t_{ij}(t + 1) < t_{ij}(t)$, however in the absence of the global pheromone update for every edge (i, j) $\lim_{t \to \infty} t_{ij}(t) = r_{0}$ holds true.

Once ants finish searching for the path from source to destination and the best path has been found, a global pheromone update is done. The evaluation which consists of all paths found from the source $s \in S$ to the destination $\in D$ is computed. The global pheromone update is given by equation (2.3) [11].

$$t_{ij}(t + 1) = (1 - \lambda) * t_{ij}(t) + \Delta\lambda t_{ij}(t) \tag{2.3}$$

where $\lambda(0 < \lambda < 1) is\ the\ global\ decaying\ factor\ from\ source\ to\ the\ destination$

There are two types of ants. They are forward ants (FANTs) and backward ants (BANTs). The data structure of FANTS and BANTS is shown in Figure 2.5.

Source address	Sequence number	Destination address	Intermediate stack	Intermediate stack pointer	Ant type

Figure 2.5 Ant data structure

2.6.6 Particle swarm optimisation

Particle swarm optimisation (PSO) is a population based stochastic optimisation technique that was developed by Eberhert and Kennedy in 1995 [91], [92]. PSO is an inspiration from social behaviour of organisms such as fish schooling and birds flocking [93][94][47]. In a computing environment, PSO is a computational method that tries to find the shortest best possible path from a list of candidate solutions through iteratively trying to improve the chosen solution which meets the given set of quality constraints. PSO's fundamental objective is to find the maximum or minimum values that suit the objective set of quality constraints.

In PSO, a swarm is any potential candidate solution to the problem that needs to be solved. The main objective of PSO is to find the particle position that gives evaluation to the fitness factors. Each individual agent is viewed as a particle that has no volume in a multidimensional space and again flying at a certain speed. The following definitions are crucial for PSO:

$$X_i = (X_1, X_2, X_3, , \ldots, X_{im}), where\ i\ is\ the\ i^{th}\ particle$$

$$V_i = (V_1, V_2, V_3, \ldots, V_{im}) current\ flying\ speed\ of\ the\ \ i^{th}\ particle$$

$$P_i = (P_1, P_2, P_3, \ldots, P_{im}), the\ best\ position\ based\ on\ experience\ of\ the\ i^{th}\ particle$$

This therefore means that if a particle at time $t + 1$ has a better position, the best position for particle i will be updated, otherwise the previously observed optimal value in the experience remains unchanged. During the initialisation stage, each particle (agent) is assigned randomly some initial parameters and the particle flies at certain speed in multidimensional space. During the process of flying each particle utilises information about its best individual position (P_{id}) and the global best solution (P_{id}) to increase its chances of getting towards the global best position which ultimately leads to a better fitness. When an agent finds a new fitness that is better than the fitness it already has, it replaces its individual best fitness and updates its possible solution to the problem using the following equation 2.4.

$$V_{id}(t) = w * V_{id}(t-1) + c_1 \Phi 1(P_{id} - X_{id}(t-1)) + c_2 \Phi 2(P_{gd}(t-1)) \qquad (2.4)$$

The particle's position is updated using equation 2.5.

$$X_{id} = X_{id}(t-1) + V_{id} \qquad (2.5)$$

Table 2.5 shows the variables that are used in PSO protocol;

Table 2.5 List of variables used in PSO

Parameter	Description
V	Particle velocity
X	The particle (agent) position
t	time
c_1, c_2	Learning factor
Φ1,Φ2	Random numbers between 0 and 1 inclusive
P_{id}	Particle's best position
P_{gb}	Global best position
w	Inertia weight, it controls velocity of particles

The good choice of w controls the convergence behaviour of PSO [35]. A good value for w gives a rationale of balance between local and global explorations. If w is greater than 1, the PSO diverges because of increase in velocities. If w is between 0 and 1, PSO converges depending on the values of c_1, and c_2, and particles velocities decelerates. Inertia weight w is given by the equation 2.6. The impact of inertia affects the convergence of the PSO protocol, and its purpose is to provide the balance between the local and global search capabilities of the swarm which can be birds flocking, swarm of insects or schools of fish.

$$w = w_{max} - \frac{w_{max} - w_{min}}{\max iter} * iter \qquad (2.6)$$

where w_{max} is the maximum inertia, w_{min} is minimum inertia value and current iteration is represented by being $iter$.

The local optimum value is the minimum fitness value of each particle in PSO. When a particle in a new iteration gets a new value, it compares it with the previous iteration. If the new value is better than the previous update is done using equations 2.4 and 2.5, otherwise the previous value remains as the best local value. After particles have their local optimum values, each individual particle explores the solution space for other particles that have a better solution than it. If there are better particles with solution to it, then that will be updated as the global best optimum value.

PSO is ideal for solving NP hard problems because it can explore a wider solution space to come up with the best solution on given constraints [95]. In each iteration, particles adjust its route based on local optimum value and global best value of the entire swarm population. It has been observed that the PSO responds quickly to global minima within a reasonable time as compared to genetic-based methods [96].

The flow chart, Figure 2.6 shows the steps involved in PSO.

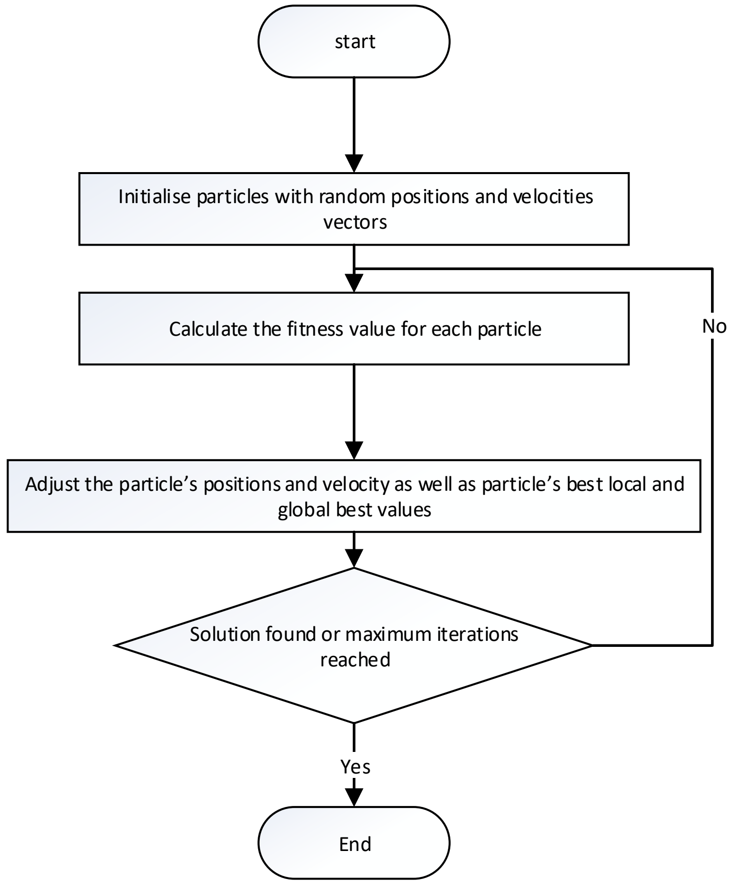

Figure 2.6 PSO protocol flow chart

The idea behind PSO can be summarised as follows:

1. Adaptability whereby the population of swarm should have the aptitude to adjust to behaviour made when consumption of energy and resources worth.
2. Quality principle is whereby the swarms should have the capability of making own adjustment based on the defined quality factors in the area that they operate.
3. Stability idea is when the swarm should maintain stable status even though there maybe some changes in the environment they operate.
4. Proximity principle whereby the swarms should have the ability to make some simple computations based on the environment they are in.

2.7 BACTERIAL FORAGING OPTIMISATION

This section presents bacterial foraging optimisation background, swarm-based routing methods that utilises bacterial foraging optimisation (BFO) approaches. This will be followed by challenges that are associated with BFO routing methods and lastly, the comparison of BFO routing methods.

2.7.1 Bacterial foraging optimisation routing background

BFO has been introduced after other swarm-based routing optimisation techniques as discussed by [62][89][90][99] . BFO is a new swarm intelligent routing method which is computationally efficient in solving complex numerical problems, continuous optimisation problems as indicated by [100], [101]. BFO searches for food sources in a way that enables them to maximise the energy expended to foraging. BFO generally consists of four processes: chemotaxis, swarming, reproduction and lastly, elimination and dispersal. Chemotaxis process is done by employed and onlooker bees. BFO has been used to solve optimisation problems because of its easy implementation. The parameters used in it can be fine-tuned according to the need of the application to be solved, hence its applicability in solving routing challenges associated with the dynamic MANET network.

2.7.2 Bacterial foraging optimisation methods

2.7.2.1 Hybrid artificial bee colony with bacterial foraging optimisation routing

A hybrid artificial bee colony with bacterial foraging optimisation (HABC)was presented by [76]. The bacterial foraging optimisation was employed to perform local search because of its good exploration which resulted in quality solutions generated. Bacterial foraging optimisation was used to improve the performance of artificial bee colony optimisation within the employed and onlooker bees phases to improve on search conditions. This local search approach is made possible because BFO bacteria tend to move in groups and then move as a pattern with high bacterial density. Once the bacteria reach the food source as a group, they let other bacteria move towards that same direction and hence, the destination can be reached quicker in comparison to other optimisation methods.

2.7.2.2 Cooperative bacterial foraging optimisation routing

Cooperative bacterial foraging optimisation (CBFO) was presented by [69] to improve on the convergence, speed and accuracy of the original BFO in solving complex optimisation problem.

Two variants being serial heterogenous on implicit space decomposition level and serial heterogenous cooperation on the hybrid decomposition level were infused into the traditional BFO. The cooperative BFO relies on splitting the n-dimensional search space into $n/2$ subspaces with each subspace optimised by a separate bacteria colony. The overall solution is found by combining the vector containing the best bacterium of the colony.

2.7.2.3 Bacterial foraging optimisation with the dynamic source routing

Bacterial foraging optimisation was hybridised with the dynamic source routing to improve on the network lifetime of the MANET network by [102]. BFO was used to identify the path by focussing on fitness levels for each node that has the route towards the destination node. The simulation results show that combing dynamic source routing with BFO improves packet throughput and reduces bit error rate in MANET networks.

2.7.2.4 Bacterial foraging optimisation with genetic method

Improvement of network lifetime durability is dependent on the existence of energy aware routing protocols. Energy aware routing based on BFO, combined with a genetic method was proposed by [103]. The routing protocol was termed transmission-based energy aware routing, which identifies energy efficient optimal paths when routing data packets in wireless networks.

2.7.2.5 Bacterial foraging optimisation with particle swarm optimisation

A proposed hybrid routing model that was based on bacterial foraging optimisation and particle swarm optimisation was developed by [104][105]. A PSO approach was used in clustering the network into logical groups (k optimal clusters) and the cluster head for each logical group was selected. The BFO technique was utilised in selecting the node in each cluster that had a greater residual battery life than the average energy of other nodes in the group.

2.7.3 Bacterial foraging optimisation routing methods challenges

Bacterial foraging optimisation has been used to solve problems such as: machine learning, routing in wireless networks and energy conservation because they provide high optimised solutions. BFO approaches are associated with high convergence rate as compared to other nature-inspired routing approaches. BFO approaches have shown from literature [68], [105] that if a problem becomes more complex, the performance of BFO becomes poor. Hence, some efficient optimisation strategies that decrease chemotaxis are required which assist in solving poor premature convergence rate. The performance of BFO routing method also suffers from increased growth of search space because of its stochastic nature.

2.7.4 Comparisons of bacterial foraging optimisation routing methods

From the five BFO routing methods that have been presented on the BFO routing methods section, they were focusing on extending the lifetime of wireless MANET network. The routing methods were hybridised with other nature approaches such as: genetic-based methods, PSO, ABC and non-nature approaches such as, dynamic source routing. It has been observed in the routing methods that utilising BFO alone is prone to premature convergence. Hybridising BFO with other approaches tends to produce better results even when the dimension search space is increased. Using BFO methods hybridised with other approaches can help in reducing congestion and multipath routing, unfortunately this has not been explored before.

2.8 ARTIFICIAL BEE COLONY OPTIMISATION

This section presents artificial bee colony optimisation (ABC) background, swarm-based routing methods that utilise artificial bee colony optimisation approaches. This will be followed by challenges that are associated with ABC routing methods and lastly the comparison of the various ABC based routing methods.

2.8.1 Artificial bee colony optimisation routing background

ABC is an optimisation for mimicking the behaviour exhibited by bees. ABC is a swarm-based meta-heuristic method that can be used in solving complex multivariable numerical optimisation problems. It is inspired from the foraging behaviour of honeybees. ABC is made up of employed bees whose job is to explore food sources and measure the food quality; onlooker bees which communicate with the employed bees to select the food sources and lastly, scout bees whose role is to explore new possible food sources when previously established food sources are deemed to be of low quality as presented by [76], [106]. ABC has been widely used in solving problems in MANETs, wireless sensor networks, image processing and civil engineering domains because of its excellent global optimisation [68], [69].

2.8.2 Artificial bee colony optimisation routing methods

2.8.2.1 Bee-inspired protocol method

A Bee-Inspired Protocol (BeeIP) routing protocol which reactively discovers multiple paths between source and destination nodes has been proposed by [5] an inspiration from honeybee adaptive behaviour which is characterised by collaboration behaviour of bees. There are three types of agents in this routing protocols namely: the scout, ack scout and foragers. The scouts discover the paths from the source to the destination node. Scouts are transmitted via broadcasting and they carry information about the state of the source node. The acknowledgement scout which is termed ack scout is generated once a scout reaches the destination node. It traverses back the path that has been used by the scout to the source node. The foragers carry information such as payload from the source to the destination node and foragers update neighbours nodes state, link information and monitor the paths they traverse for any improvements [106]. BeeIP is adaptable to MANET because it makes routing decisions when the route is needed to be established between source and destination.

2.8.2.2 Clustered artificial bee colony optimisation routing

The efficiency of wireless networks is dependent on a robust energy saving mechanism that is associated with a routing protocol. A clustering based wireless sensor network routing using artificial bee colony protocol has been proposed by [107]. Clustering the wireless network was done using artificial bee colony protocol and this involves the computation of fitness function of energy levels and remaining nodes' residual battery power when selecting the route to relay data to the destination nodes.

2.8.2.3 Beesensor-C routing protocol

BEESENSOR-C routing protocol is a multipath routing strategy that minimises routing overhead in dynamic clusters in wireless sensor networks using artificial bee colony optimisation approaches [108]. The BEESENSOR-C protocol focussed on reducing energy consumption on the network. To achieve reduced overall energy consumption when routing data packets on the network, it uses AODV routing strategy where the route is only explored only when there is data to be sent. The proposed BEESENSOR-C routing protocol reduces overhead by stopping the recruitment of forager swarms into heavily congested routes and the scouts are released to explore other possible routes that have been previously identified in multipath routing which are less congested.

2.8.2.4 Fuzzy bee ad hoc routing

Fuzzy BeeAdHoc is a reactive routing proposed by [3] to conserve the scarce battery life for MANET network thereby prolonging its lifetime. The security threat that occurs in conventional BeeAdHoc routing protocol decreases the network lifetime of a wireless ad hoc network. When fake routes are established, they disrupt the usual routing behaviour thereby decreasing the lifetime of the wireless network since all nodes in the network are battery powered. Foraging attacks, scout attacks and foraging routing information related attacks are common in traditional BeeAdHoc routing protocols [3].

The secure framework for BeeAdHoc based on fuzzy set theory was developed based on the trust values of the nodes in the network. The route that has the ultimate high route trust levels is used for routing of data packets. Experimental results from the simulations studies carried by [3] indicated that the secure FBeeAdHoc routing protocol has low end-to-end delay and high packet delivery ratio in comparison with the original BeeAdHoc and AODV routing protocols.

2.8.2.5 Ant colony optimisation with bee foraging optimisation

Ant colony optimisation with bee foraging optimisation routing method was proposed by [109] and it combines ant colony optimisation with bee foraging optimisation called ant-bee routing (ABR). The ants in the ABR routing are involved in foraging for food sources that is determining the destinations in the network. Once the destination node is found, an artificial bee is assigned to one of the destinations to check on the quality food source [109].

2.8.2.6 Artificial bee-colony-inspired interest-based forwarding

Artificial bee-colony-inspired Interest-based Forwarding (BEEINFO) is an interest-based forwarding scheme that uses artificial bee colony [110] which adapts to the changing environment through exploiting swarm intelligence. BEEINFO adapts to the foraging behaviour of the employed and onlooker bees to detect any changes in the environment when they scavenge for the food sources. BEEINFO optimises the forwarding procedure by doing message scheduling and buffer management to improve on the data forwarding process.

2.8.3 Artificial bee colony optimisation routing methods challenges

Artificial bee colony optimisation has also been used in solving problems in MANET network routing, image processing and civil engineering domains because of its excellent globalisation optimisation. The search pattern of bees is excellent, but the exploitation is poor. Exploitation is the process of applying knowledge of the previous good solutions to find better solutions, but the ABC tend to focus more on exploration of the food sources than exploitation of previously found food source. ABC is also associated with slow convergence rate when solving complex unimodal problems and can easily get trapped in local optima, especially when solving complex multimodal problems. The ABC routing protocol that seeks to balance exploration and exploitation is required to improve the performance of the ABC routing method. Therefore, coming up with ABC based routing methods that speed up the convergence rate as well as trying to avoid being trapped in local optima, are some of the issues that future ABC-based routing methods should focus on.

2.8.4 Comparisons of artificial bee colony optimisation routing methods

The six artificial bee colony optimisation methods presented on ABC routing methods section focussed on extending network lifetime of the MANET network. Shortest path to the quality food source results in onlookers using the shortest path that has been found by foragers to the food source. The ABC-inspired routing methods focussed on conserving network lifetime to improve its lifetime. ABC routing methods tend to perform poorly on exploitation of the previously found solutions only the fuzzy BeeAdHoc focussed on extending network lifetime by also exploring the security of nodes that join the network because malicious users can join the network results in denial of service attacks and establishment of fake routes with the ultimate objective of diverting messages sent across the network. Using ABC methods hybridised with other approaches can help in reducing congestion and multipath routing, unfortunately this has not been explored before.

2.9 ANT COLONY OPTIMISATION

This section presents ACO background, swarm-based routing methods that utilise ant colony optimisation approaches. This will be followed by challenges that are associated with ACO routing methods and lastly the comparison of ACO routing methods.

2.9.1 Ant colony optimisation routing background

ACO is a meta-heuristic method based on the foraging behaviour of ant species. In ant colony systems, if there exist multiple paths to the food source, ants start by random walks to various food sources. During route exploration to the food source and back to the nest they lay pheromones which influence the behaviour of future ants [20], [35], [67], [73], [87]. The routes that have high pheromone values are subsequently followed by many ants, hence become regular paths and those that have less pheromone values become obsolete routes. As a result of these autocatalytic effects, there is emergency of global behaviour rapidly.

2.9.2 Ant colony optimisation routing methods

There are ant-based optimisation techniques that have been proposed by various scholars ranging from: Ant Based Control, AntNet, Probabilistic Ant Routing, Automatic Clustering Inspired Ant Dynamics, Ant Colony-based Routing protocol, Probabilistic Emergent Routing method, Ant

Dynamic Source Routing [72], [111]–[113] among other ant-based outing protocols are going to be discussed.

2.9.2.1 Ant based control (ABC) routing

In this method every node that makes up the wireless network has a routing table which is referred to pheromone table. The learning strategy of exploratory ants is based on pheromone laid down by previous ants and information that has been gained because of past experiences of the network which is stored in the memory of the systems [72] to assist future ants in making decisions. The pheromone tables have an entry for each of its neighbour nodes (within the communication radio link radius) together with probabilities for choosing the next route from its next-hop neighbours. Ants are generated from any node in the network. The ants move from the source to the destination through multi-hopping and intermediate nodes are selected according to probabilities in the pheromone tables of their destinations [111]. On heavily congested routes, the ants get delayed and [111] suggested that noise can be introduced to avoid freezing of the pheromones. When an ant reaches a particular node on its way to the destination, it updates the probabilities of that node's pheromone using the equation 2.7.

$$p = \frac{p_{old}+\Delta p}{1+\Delta p} \tag{2.7}$$

Where p is the new probability and Δp is the probability increase emanating from the ants arriving at the node. Aging (number of trips that passes since the launch of the exploratory ant) is also introduced to ensure that heavily congested routes are avoided. Delay where there is congestion depends on the spare capacity(s) of the node, which is given by equation 2.8 [111].

$$delay = 80 * e^{-0.075s} \tag{2.8}$$

The delay in releasing the forward ant means reduced flow of agents to the neighbours, thus ultimately results in preventing positive reinforcement of the pheromone towards the congested nodes. The challenge with ABC is that the best route can get congested easily, hence increase end-to-end delay on the network.

2.9.2.2 Antnet routing

The AntNet is also a proactive ant routing protocol [87][111]. It uses delay for each hop as a metric for routing. The way the AntNet operates is basically similar to ABC routing in the sense that forward ants are generated to explore the route from the source node to the destination. The selection of the next hop to send data packets is a function of the queue from the source to the current node and the corresponding pheromone tables. There is also an introduction of a weight α with values ranging between 0.2 and 0.5 [111]. These weights show the significance given to the local queue. When a node has been selected, the forward ant checks whether the node has been previously visited or not. If the node has been visited before, this shows that it is a closed loop and therefore the forward ant is terminated [112].

If the node has not been visited earlier on, then the forward ant will save the node ID of the current node and a timestamp at which the node was visited. If the current node is the destination, then a backward ant will be generated. The information that has been recorded before for the forward ant will be retraced by the backward ant until it reaches the source node and information like congestion and underlying network dynamics and the number of hops traversed will be recorded. The challenge with AntNet is that there are long delays in propagating routing information.

2.9.2.3 Probabilistic ant routing (PAR)

The probabilistic ant routing method uses two agents i.e. forward and backward ants like the other proactive routing protocols. The forward ants which are generated by the source nodes at regular intervals are unicasted or broadcasted to the network and they explore the network to find the route for sending the data packets. If the route from the source node to the destination is available, then a unicast ant is generated, otherwise a broadcast ant will be generated if there is no route to the destination. When the forward ant arrives at the destination, a backward ant is generated, and this ant will be sent deterministically on a high priority queue unlike the forward ant which is sent on the normal queue [111]. Hello single hop packets are generated to find the nodes which are one hop neighbours to the current node, thus enabling the node to build its neighbour list at regular interval. Its challenge (PAR) is that of congestion.

2.9.2.4 Automatic clustering inspired ant dynamics (ACAD)

ACAD identifies clusters by identifying available ones using *pseudo* ants. These traverse nodes that are close to their proximity and when they come back to their original source where they were generated from, they die and the nodes that would have been visited form a cluster. When individual clusters have been formed, they are removed from their population. The issue to do with generation of pseudo ants in parameter estimation is an area that has been presented by [111] for further research.

2.9.2.5 Ant colony- based routing method (ARA)

The network agents are sent on demand and they are flooded (ants setting multiple paths between source node and the destination at the commencement of a data session) on the wireless network just as in AODV. The routing table in this scenario does not contain probabilities but they store pheromone levels which will ultimately be turned on to probabilities [112]. ARA is made up of three phases which are route discovery, route maintenance and route failure handling. During route discovery forward ants are generated to establish the route and at the receiver's side backward ants are generated to trace back the path traversed by the forward ant back to the source. The forward ants are broadcasted to all their neighbours and they have a unique sequence number that assist in avoiding replication. The forward ants will have information on the destination ID address, address of previous hops and computation of the pheromone levels which are directly dependent on the number of hops that the forward ant needs to reach the node [112].

In route maintenance, once a link is established between a source and a destination node, future data packets will increase the pheromone value for that link because when a neighbour node relays a data packet towards the destination node, pheromone levels accumulate and likewise, if the route is being visited by few ants, pheromone levels tend to decrease because of the evaporation process. Missing acknowledgements on the MAC layer is an indication of route failure on the network. Route error messages are sent to the source node to request to explore an alternative route to route the data packets. The main weakness of ARA is that it does not have the built-in mechanism to adapt to changes in a dynamic network like a MANET.

2.9.2.6 Probabilistic emergent routing protocol (PERA)

PERA is a multipath routing method in wireless network. This routing method works in an on-demand situation and it broadcasts the ants towards a particular destination. Multiple paths are setup and it is only the path that has the highest pheromone level that will be selected, and the other paths will be used as backup in case there is a failure on the other main route on the network [113]. Neighbour nodes are discovered using HELLO messages, but they will only be update in the pheromone table after they receive the backward ants. Sequence numbers are used to avoid duplication of data packets. The forward ants that possess the greatest sequence numbers are taken into consideration and those forward ants with lower sequence numbers are dropped [113]. The weakness about this routing method is that at each node, both forward and backward ants are created which leads to high duplicated ants in the network.

2.9.2.7 Ant dynamic source routing (ADSR)

This method takes into consideration the quality of service performance metrics which are delay, jitter and energy [111]. Nodes in the MANET have route caches and these route caches are updated depending on the status of the network at a given point in time. The process of operation of ADSR is made up of two components which are route discovery and route maintenance. During route discovery, the route cache is checked to see if there is a route entry to the destination [34]. If the route is not available, then broadcasting is done to determine the path to the destination. Route maintenance is accomplished through route error packets and acknowledgements. Its problem is that it requires some additional control packets to monitor the network status regularly on those paths that would have been identified before.

2.9.2.8 Improvised ant colony optimisation (PACONET)

This on demand ant routing protocol makes use of two ants that are the forward and backward ants just like other ant routing methods. Forward ants are broadcasted to find new route to the destination node from the source [87]. Backward ants retrace the route back from the destination to the source, updating information like the link status which include the number of hops passed. Forward ants travel along unvisited paths on the network and naturally, they choose the paths with the highest amount of pheromone. Each node in PACONET maintains its own routing pheromone, hence there is increased overhead.

2.9.2.9 Nature inspired scalable routing protocol for MANETs (NISR)

This on-demand ant routing protocol is modelled around the Temporally Ordered Routing Protocol (TORA) which means it is a multipath routing protocol. Multiple routes are discovered but at the end, it is only the shortest route that will be chosen based on the number of hops to be traversed from the source to the destination. NISR protocol was developed through an inspiration of ants and bee colonies [111], [113].

2.9.2.10 AntHocNet

AntHocNet is a multipath routing method for MANETs that combine both the features of reactive and proactive ant routing strategies [72]. AntHocNet is reactive in the sense that it only maintains route for the open data session, that is, when communication session between the source and destination nodes is ongoing. The proactive strategy is evident in the sense that the routing protocol tries to maintain, improve and extend route, when there is an open data session [111]. Proactive method is used to update the quality of the route and this is achieved through regular broadcasting information on the best pheromone levels.

Reactive route setup is achieved when reactive forward ants are sent across the network to find multiple paths towards the destination node. Loops are prevented in AntHocNet through the use of a sequence identification mechanism and link errors are also detected by Hello messages not received from the neighbours after a defined time period [111]. The AntHocNet uses a random probability approach to routing data packets in a wireless network. Routes are found when there is a data packet that needs to be sent, but once the route has been established, it will be proactively maintained. This approach of using AntHocNet has got challenges in the sense that it fails to reduce overheads on heavily used network when traffic load increases.

2.9.2.11 Ant routing protocol for MANETs based on adaptive improvement (ARAAI)

This routing approach also takes both the feature of proactive and reactive ant routing approaches. ARAAI makes use of two tables, that is, routing table that has a heuristic value (local node energy information), initial node and last node [111]. The second routing table consists of neighbour information. The similar approach of release of forward and backward ant is also visible in the ARAAI method.

2.9.2.12 Multi agent-based routing protocol (MAARA)

MAARA works the same as the AntHocNet in the sense that the routes are established and maintained when there is an ongoing communication session. MAARA method consists of five phases which are route discovery, route update, data routing, route maintenance and route failure handling [111].

2.9.2.13 Hopnet

This is a hybrid ant routing protocol modelled around the ZRP routing protocol for MANETs. The ants hop from one zone to the other zone. The network in Hopnet is divided into some sections which are referred to as zones, and these zones are node's local neighbours within a defined radius of the radio link communication [59], [114]. Each node has two routing tables namely; the intrazone routing and the interzone routing. Proactive approach is done to find the path from the source done to the destination node through intra routing approach. Forward ants are generated to find the path and likewise, when they reach the destination, backward ants are generated just as with the other ant routing protocols.

The inter zone routing stores the information beyond the node's zone. Hopnet routing method consists of route discovery process which is done proactively observing the node's neighbourhood and there is reactive communication between local neighbours [111]. The weakness of Hopnet is that it is not scalable for large networks.

2.9.2.14 Ant AODV

This is a multipath ant hybrid routing protocol which decreases end-to-end delay on a network through its route discovery process and maintains the route that has been discovered hence reducing latency rate. Ant AODV makes use of route error mechanism to inform the sending node of any link failure that will be occurring on the route to their destination [111].

2.9.2.15 Aleep with ACO

Autonomous Location based Energy Efficient routing Protocol with ant colony optimisation (ALEEP with ACO) by [86] is a hybrid routing optimisation method. It factors in the remaining residual energy and received signal strength indicator factors in choosing the path to send the data on the network. Next hop nodes that are below a given threshold are not used in relaying data packets, thereby conserving the node(s) remaining battery life. This improves the network lifetime because periodically, the threshold is computed for all next hop neighbours to determine if the nodes are still usable as relay nodes.

2.9.3 Ant colony optimisation routing methods challenges

Ant colony optimisation assumes that ants always live a mark also known as pheromone that can be exploited by future ants, when they explore for food from the nest. The pheromone levels are kept up to date by other ants ensuring load balancing in the network. However, using ACO-based methods have a challenge of poor exploitation, especially when there is a quick change in routes. The other challenge is that of not factoring in congestion of links when exploring the best shortest path in the network. The best shortest possible path that has many data packets relayed through it can ultimately result in high average end-to-end delay which is detrimental to the overall performance of the network.

2.9.4 Comparisons of ant colony optimisation routing methods

Table 2.6 provides a summary of ant colony optimisation routing methods for establishing the best shortest path in MANET networks including the similarities and differences that exist among the various ant colony optimisation routing methods. Approaches in routing data packets such as: route discovery, the type of ants used, and local route repair techniques have been used for comparing the routing approaches using ACO techniques. Using ACO methods hybridised with other approaches can help in reducing congestion and exploring multipath routing, unfortunately this has not been explored before.

Table 2.6 Summary of major ant colony optimisation routing methods

Routing Protocol	ABC	AntNet	PAR	ACAD	ARA	PERA	PACONET	AntHocNet	MAARA	Ant-AODV
Route discovery	Flooding	Flooding	Flooding	Flooding	Flooding	Flooding	Flooding	Flooding	Flooding	Flooding
Approach to loop prevention	not available	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used	sequence numbers are used
Type of ants in use	exploratory ants	forward and backward ants	forward and backward ants	pseudo ants	forward and backward ants	forward and backward ants	forward and backward ants	proactive forward and backward ants	Forward and backward ants and local route repair ants	forward and backward ants
Detecting route failure approach	not available	not available	backtrack	not defined	backtrack	missing Hello packets	backtrack	local repair error message	local repair error message	local repair error message
Type of route created	single path	single path	single path	single path	multipath	multipath	single path	multipath	multipath	single path
Problem with the routing method	congestion on best path resulting in more packets being dropped	There is a huge overhead when propagating data control packets	high overhead leading to congestion	use of pseudo ants in parameter estimation not clear	no built-in feature to detect network topology changes	high duplication of ants ultimately leading to congestion	high overhead since each node maintain its own routing table	overhead problems	overhead in route update	overhead in route error and repair

2.10 PARTICLE SWARM OPTIMISATION

This section presents particle swarm optimisation background, swarm-based routing methods that utilise particle swarm optimisation approaches. This will be followed by challenges that are associated with PSO routing methods and lastly the comparison of PSO routing methods

2.10.1 Particle swarm optimisation routing background

Particle Swarm Optimisation (PSO) is a population based stochastic optimisation technique. PSO is an inspiration from social behaviour of organisms such as fish schooling and birds flocking [47], [91], [94]. In a computing environment, PSO is a computational method that tries to find the best solution from a list of candidate solutions through iteratively trying to improve the chosen solution which meets the given set of quality constraints. The main objective of PSO is to find the particle position that gives best evaluation of results to the fitness factors [91].

Each individual agent is viewed as a particle that has no volume in a multidimensional space and again flying at a certain speed. During the initialisation stage, each particle (agent) is assigned randomly some initial parameters and the particle fly at certain speed in multidimensional space. During the process of flying, each particle utilises information about its best individual position (P_{id}) and the global best solution (P_{gd}) to increase its chances of getting towards the global best position which ultimately leads to a better fitness [115]. When an agent finds a new fitness that is better than the fitness it already has, it replaces its individual best fitness and update the particle velocity ($V_{id}(t)$) at time t using the following equation 2.4. The particle's position (X_{id}) is updated using equation 2.5.

The good choice of inertia weight (w) which is found using equation 2.6, controls the convergence behaviour of PSO [116]. A good value for w gives a rationale of balance between local and global explorations. If w is greater than 1, the PSO diverges because of increase in velocities. If w is between 0 and 1, PSO converges depending on the values of c_1, and c_2, and particles velocities decelerate [116].

The principles behind PSO in nature as presented by [91] are as follows:

- Quality principle - this is a principle whereby the population should have an ability to make some adjustments depending on the criterion of the quality factors in the environment
- Diverse response principle - population should not restrict itself to extremely narrow environment
- Proximity principle - individual agents should have the capability of making simple computations
- Stability principle - even in changes in the environment, the population should retain stability.

2.10.2 Particle swarm optimisation routing methods

2.10.2.1 Genetic protocol with particle swarm optimisation

Genetic protocol hybridised with particle swarm optimisation (GA_PSO) routing method was presented by [29] to optimise on the battery life of nodes in the ad hoc network. In this routing method, genetic protocol was combined with particle swarm optimisation. Genetic protocol is an evolutionary method to optimise energy dissipation in ad hoc networks [29]. The first phase of GA_PSO involves dividing the wireless network into clusters to minimise the overall transmission distance between the destination and source nodes.

Dividing the network reduces the overall energy consumption because it will only be the cluster heads in the cluster which will be tasked with communicating and the regular nodes will be in sleep state, hence they (regular nodes) will not be consuming much battery life in sleep state. The regular nodes which want to communicate will do so through the cluster head. The process of selecting the cluster heads is done using the genetic protocol. The second phase of the GA_PSO involving fitness function evaluating the distance-number of heads rules [29]. The fitness is done using equation 2.9.

$$Fitness = w * (D - Distance_i) + (1 - w) * (N - nH_i \qquad (2.9)$$

where D is the total distance from source node to the destination, and $Distance_i$ is sum of distance from the regular nodes to the cluster head nodes plus the sum of distance from cluster heads to the destination [29], N is the total number of the nodes in the wireless network and w is predefined weight and nH_i is the number of cluster heads in the network. Few nodes are selected as cluster heads, therefore, there is less energy consumption because there would be few nodes that will be communicating whilst others (regular nodes) will be in sleep state. The second step in GA_PSO involves managing the distance in the wireless network using the particle swarm optimisation (PSO). In PSO each potential solution is termed a swarm and the particles positions are initialised randomly. Each particle's position, after each iteration is evaluated using the evaluation function toward optimality using equation 2.9**.** The pseudo code 2.4 for GA_PSO ABC is shown below.

Pseudo code 2.4 : Particle swarm optimisation using GA_PSO adopted from [29]

```
Step 1:  particle swarm initialisation , i.e. position and velocity of each swarm
Step 2: while maximum iteration is not reached, or optimal solution not found do
Step 3:  Invoke the  evaluation function using equation 2.9
Step 4:  if current fitness is  better than that particle's previous fitness value then
Step 5:  Assign the previous particle position to the current position
Step 6:  Assign the current particle's position to global best position
         End if
```

Step 7: Update particle and velocities positions

End while

When best positions and velocities have been updated, the total energy loss is computed using equation 2.10.

$$Total\ loss\ due\ to\ distance = \sum_{j=1}^{k}\sum_{i=1}^{n_j}(d_{(ij)}^2 + \frac{D_j^2}{n_j}) \tag{2.10}$$

where k is the iteration number, D is total distance of all nodes to destination and d is the total distance from node i to node j from regular nodes to cluster heads plus distance from cluster head to the destination. The GA_PSO routing data packets on the network use cluster heads, but it does not factor the load of each node and the time frame when the cluster head nodes will be regular node.

2.10.2.2 Ant colony optimisation with particle swarm optimisation

Hybridisation of particle swarm optimisation with ant colony optimisation (ACO_PSO) was proposed by [1] to conserve battery life in MANET thereby extending the network lifetime of the wireless network. The ACO approach was used to identify the most feasible and best path in the network whilst the PSO was used to find the particle's best solution based on the particle's velocity and position that minimises power consumption and average end-to-end delay by the nodes. The steps that are involved in intelligent ACO-PSO are highlight in the ACO-PSO protocol below.

Pseudo code 2.5 : ACO_PSO Protocol

Step 1: initialising the number of particles and generation of particles values randomly

Step 2: Initialisation of ACO parameters

Step 3: Generation of solutions from each ant's random walk

Step 4: Updating of pheromone values using equation $T_x = (1-p)T_x + \sum_k \Delta^k T_x$

$where\ p\ is\ pheromone\ evaporation\ and\ k\ is\ the\ ant\ that\ deposit\ the\ pheromene$

Step 5: if solution is not the best, introduce swarm with random positions and velocities

Step 6: Select each particle's individual best for each generation

Step 7: Select the particle's best global value

Step 8: Select the particles' worst value

Step 9: Update velocities and position of each particle Step 10: Terminate process if maximum iterations have been reached or if optimum value has been obtained

Comparisons of PSO_ACO were done with Genetic protocol and the power consumption of PSO_ACO is less as compared to GA. The PSO_ACO has a lesser number of iterations to find the optimal values relative to GA method. However, the hybrid PSO_ACO does not consider the node's data buffer to check on the data being processed and the packets waiting in the queue to be relayed to the next nodes before the destination. It only evaluates the time it takes to reach optimum value in comparison to other swarm-based routing methods. Increasing network life through conserving node's battery life has not been included in [1][20].

2.10.2.3 Binary particle swarm optimisation based temporally ordered routing protocol

Binary Particle Swarm Optimisation (BPSO) based Temporally Ordered Routing Protocol (TORA) is reactive routing protocol that adds energy awareness feature on TORA [9]. BPSO considers the route length, routing path energy levels when selecting the shortest path to route data packets on an ad hoc network. BPSO chooses a route that maximises on a weighted function of the route length and remaining energy levels of the nodes from the source to the destination on multiple routes that might have been discovered during route exploration phase. The BPSO-TORA protocol 's main strength is that of distributing load across intermediate nodes during data packets transfer, thereby reducing congestion on some links on the network and helps in prolonging the network lifetime of an ad hoc network.

2.10.2.4 Bacterial foraging optimisation combined with particle swarm optimisation

This is a hybrid routing model based on bacterial foraging optimisation and particle swarm optimisation [105]. A PSO approach was used to cluster the network into logical groups (k optimal clusters) and the cluster head for each logical group was selected. The BFO technique was utilised in selecting the node in each cluster that had a greatest residual battery life than the average energy of other nodes in the group to be elected as the cluster head. The technique has a limitation in receiving feedback on update local and global positions during PSO clustering routing. There is also a challenge of low signal strength which is associated with nodes that are far away from each other as presented in [117].

2.10.2.5 Clustering using particle swarm optimisation

Using PSO approach to cluster the network was proposed by [118] for routing data in wireless network. Once clustering is done, the cluster heads are selected based on the nodes remaining battery life. Other nodes that have not been selected as cluster head nodes become member nodes. Member nodes within the cluster enter '*sleep*' mode to conserve the battery power. This is possible because the communication within the cluster is handled by the cluster head node. Periodically, the cluster heads are rotated based on remaining battery life. This approach prolongs the network lifetime more as compared to genetic based and the traditional PSO protocol.

2.10.2.6 Hierarchical cell relaying scheme based on particle swarm optimisation

A hierarchical cell relaying (HCR) scheme based on particle swarm optimisation (PSO) was presented by [116] for MANET networks. Hierarchical cell relay uses the global positioning system (GPS) to locate the mobile node position. The HCR-PSO save the battery life for nodes that participate in routing of data packets on the MANET network by exploring the most feasible transmission radius for all the nodes in the network since mobile nodes can have different communication ranges. The PSO was used to find the suitable transmission radius for each node that conserves the total energy consumption on the network [116].

2.10.3 Particle swarm optimisation routing challenges

PSO evolves particles until the desirable solution is found and solution can be found quicker as compared to the optimisation approaches. PSO has been used to solve routing-related problems in MANET network because of its simplicity and high-quality solutions that it produces. However, there are challenges associated with PSO, such as; huge memory resources required and the iterative nature of the PSO approach which makes it less favourable for the solutions that require high speed real-time transactions where optimisation is frequently required. The solution searching strategy depends on the selection of PSO parameters such as; inertia weight and this affects the convergence rate of the PSO method.

2.10.4 Comparison of particle swarm optimisation routing methods

The particle swarm optimisation all focussed on making the network lifetime longer. In extending the network lifetime, approaches to conserve battery power were adopted. The approaches adopted by six PSO related routing methods all focussed on partitioning the network into logical groups called clusters. Cell splitting as presented by [116] enables the nodes to communicate to the cells whose radius is close to them. The communication has been assigned to the cluster head to handle communication on behalf of the other member nodes. The cluster heads are rotated based on the remaining nodes residual energy. The metrics that have been used for partitioning the network into clusters were remaining residual power only. The other focus was on transmission radius to reach the next node for relaying data packets when deciding on the path for routing data packets. Authors [9] only added load balancing apart from remaining residual battery life, when selecting the best path from the source node to the destination node. Using PSO methods hybridised with other approaches that can help in reducing congestion and exploring multipath routing, unfortunately this has not been explored before.

2.11 QUEUING THEORY

Queuing system consists of a data network where packets arrive, wait in various queues to be served, receive the service at various points in the systems and finally exit the system after some time. Queuing system comprises of one or more servers that will be providing some services to the customers. Customers in real world arrive and find that the servers are busy, and they have to wait for their turn to be served after the customers they found already in the systems have been served. Examples of queuing system include: communication systems, bank-teller service and computer systems amongst others. Figure 2.7 shows the queue, where customer arrives at the queue, gets serviced and departs the system.

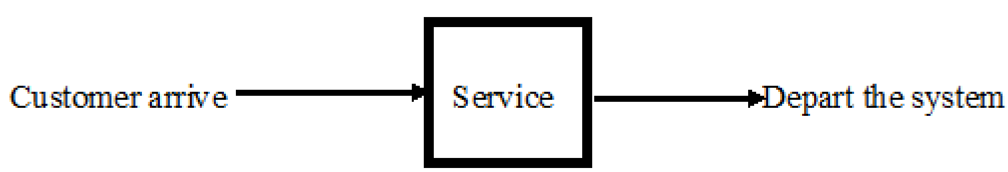

Figure 2.7 Example of queuing system

Queuing theory has been applied to a number of areas ranging from planning, air traffic control and communication networks. Kendall classified systems has been adopted as $X/Y/m/D/L$, where X is the probability distribution of interarrival times, Y is probability distribution of service times, m is number of servers, D is the queuing discipline being followed, L is for maximum number of customers in the system. X and Y , can be Markovian, general distribution, deterministic or Erlang distribution [119], [120][121].

In the queuing theory system, an input and output process and queuing discipline need to be specified. The following is a brief description of each component that makes up the queuing system;

a) Arrival process (input process)-arrivals originated from various sources from the calling population. The population from which the input originates can be finite or infinite depending on the nature of the problem to be solved. An example of an arrival process in the queue system is that of arrivals of customers in a bank. The inter-arrival time between $n^{th}-1$ and n^{th} customer is λ. The Poisson distribution is assumed in this case. The assumption for this process is;

   The probability of arrivals in an interval of Δt seconds, from $(t, t+\Delta t)$ is $\lambda\Delta t$ and is independent of arrivals at any time.

   The probability of no arrivals in Δt seconds, is thus $1-\Delta t$. The probability of n jobs arriving during an interval time of t can be given by the following Poisson distribution law using equation 2.11.

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad where\ n \geq 0, t > 0 \tag{2.11}$$

b) Service process (output process)-the service process depends on the service time distribution and in most cases, it is assumed that the service process is independent of the number of customers present in the system. The service process also depends on the arrangement of server. Servers can be arranged in parallel or in series. Servers are in parallel if they are providing the same type of service and thus the customers only need to pass through one server to complete the service.

   An example of such a service distribution being done in parallel is found in the groceries shop where tills are arranged in parallel. The customer needs to be serviced by only one till operator and any till operator can thus perform the same function. Servers are in series if a customer has to pass through several servers before completing the service. The process of how a customer is served in a shop resembles the operation of a mobile ad hoc network. In MANET network data has to be relayed through multiple nodes before reaching the intended destination. The service process is determined by the number of servers and the mean service time is denoted by μ.

c) Queue discipline-queuing discipline describes the manner in which customers are served. It is a rule that server chooses the next customer from the queue if it exists, when the server completes the service of the current job in the queue. The following are examples of queuing disciplines:
   - First In First Out (FIFO)-under FIFO customers are served according to their arrival times, i.e., those that arrived earlier are served first.
   - Last In First Out (LIFO)-in LIFO systems, the most recent arrivals are the first to be served.
   - Service in Random Order (SIRO) - in SIRO discipline, customer arrivals have no bearing on the order in which they are served. The next customer to enter the service is chosen randomly from the customers waiting to be served.
   - Priority Queuing- customers are served in their order of importance usually based on their service requirements. They are usually found in computer time-sharing systems where priority is given to jobs with shorter processing time.

Queuing theory is help in providing solutions to questions such as; cost and performance that arise throughout the lifetime of the systems. In queuing system, there can either be single server or multiple servers.

In single server centre model, customers (which in computing terms are the data packets) arrive at the server, that is, receive the service and depart the system. The utilisation factor (proportion of time the server is busy), denoted by p is computed using equation 2.12 [121].

$$Utilisation\ factor(p) = \lambda/\mu \tag{2.12}$$

with λ being arrival rate, and μ service rate

if the utilisation factor is less than 1, then there is no queue since customers arrive and get service quickly, that is, the service rate is higher than the customers arrival rate. However, if the customer arrival rate is higher than the service rate, queues start to emerge with customers waiting to be served. The probability of finding n customers in the system is computed using equation 2.13 [121].

$$Probability\ of\ n\ customers = p^n(1-p) \tag{2.13}$$

The average waiting time that the customer wait to be served is computed using equation 2.14 [121].

$$Average\ waiting\ time = \frac{p}{\mu-\lambda} \tag{2.14}$$

The average time a customer spends in the system is computed using equation 2.15 [121].

$$Average\ time\ spend\ in\ the\ system = \frac{1}{\mu-\lambda} \tag{2.15}$$

The average number of customers in the queue is computed using equation 2.16 [121].

$$Average\ number\ of\ customers\ in\ the\ queue = \frac{p^2}{1-p} \tag{2.16}$$

In multiple servers also known as multiple service centres, there are multiple servers that the customer can choose to be served and once the customer is served, the results can be an input to the other servers until the customer exits the system.

The average time the customer spends in the systems using multiple servers is computed using equation 2.17 [121].

$$Average\ time\ spend\ in\ the\ system = \frac{Number\ of\ customers\ in\ the\ system}{\sum_{i=1}^{n} \lambda_i} \tag{2.17}$$

The utilisation factor (p) is computed using equation 2.18 with X being average service rate.

$$p = \lambda X \tag{2.18}$$

The probability of finding m customers in the systems where there are multiple servers is computed using equation 2.19 [121].

$$Probability\ of\ m\ customers = P_0 * \left(\frac{\lambda}{\mu}\right)^n * \frac{1}{n!} \tag{2.19}$$

; $where\ n = 1,2, \dots m$ and P_0 is computed using equation 2.20.

$$P_0 = \left[\sum_{n=0}^{m} \left(\frac{\lambda}{\mu}\right)^n * \frac{1}{n!}\right]^{-1} \tag{2.20}$$

2.12 CHAPTER SUMMARY

Routing in MANETs has been explored on extending the network lifetime. The definition of MANETs and its architecture adopted from OSI model was presented. It compressed the original seven layers of the OSI into five layers by combining the top three layers of the OSI model into one. Characteristics of MANET networks ranging from dynamic topology, multi-hopping routing, limited transmission range, limited processing capabilities, limited energy and short lifetime have been presented as characteristics of the MANET. Benefits that emanate from using MANETs such as enhanced user mobility, quick installations and flexibility were also articulated. Areas of application of the wireless ad hoc networks ranging from battlefield communication, emergency medical rescue operations and other hostile environment where it is impossible to lay down telecommunication infrastructure for communication are all environments which can benefit from using the ad hoc networks for sharing information quickly.

The traditional routing approaches in MANET has also been presented. Classification of ad hoc routing protocols based on flat, hierarchical and geographical positioning- based have been presented. Further classification based on how routing tables are updated being: proactive, reactive and hybrid has also been presented. The various types of routing methods that fall under the proactive, reactive and hybrid routing protocols together with each protocol advantages and disadvantages were presented. Challenges in routing of data packets which include network lifetime, energy conservation, quality of service and security need to be addressed to enable routing of data packet to be done efficiently and thereby improving the performance of the ad hoc network.

Swarm intelligence is a subfield of computational intelligence that seeks to solve problems that are usually difficult to solve using the conventional approaches. Through simple interaction of agents, results in the emergence of a global behaviour. In ant colony systems, pheromone and stigmergy plays a pivotal role in determining the shortest path to the food source. Motivations for using swarm-based techniques were presented such as decentralisation and self-organisation feature; scalability and robustness to failure of swarm intelligence which makes it suitable to solve routing problems in MANET environment.

A number of state-of-the-art swarm-based routing techniques have been presented and some comparisons among them was done. Popular nature-inspired techniques such as: genetic protocols, artificial bee colony optimisation, ant colony optimisation, particle swarm optimisation and bacterial foraging optimisation were presented. Routing protocols that follows ABC, BFO,PSO and ACO were presented together with challenges associated with each of these nature-inspired routing methods. Comparisons of different nature-inspired approaches were done, and it was found that the approach used to extend the network lifetime and finding shortest path from source to destination nodes slightly vary from one technique to the other. Lastly, queuing theory together with approaches to find average customer waiting time, average number of customers in the system on both single and multiple servers were presented. The literature review has helped in identifying approaches that have been used by previous researches to address routing issue in MANET networks. However, the current approaches in solving routing issues in MANET networks did not considers queuing theory aspect in routing data packets.

CHAPTER 3. SWARM INTELLIGENT BASED ROUTING FRAMEWORK AND ROUTING PROTOCOLS DEVELOPMENT

3.1 INTRODUCTION

This chapter focuses on queuing adaptation to MANET battery life and the effect of implementing queuing theory in both single path and multipath routing scenarios. Some computations will be done to show the relative superiority of multipath routing in relation to single path routing. In multipath routing, more than one route is established between source and destination nodes whereas in single path routing, only one path is identified. A framework that is nature-inspired and coupled with queuing theory will be presented. From this framework comes two sub-frameworks, and later on routing methods based on ant colony and particle swarm optimisation hybridised with queuing theory will be presented.

An approach for enabling quick communication of MANET network in emergency medical rescue operation termed QUACS will also be presented, QUACS is a hybrid approach where ant colony optimisation and queuing theory were merged together to form a new routing protocol which computes stability of nodes before choosing the nodes to relay data to in the ad hoc network environment. Another routing method called Q-PSO will be presented and it is based on PSO and queuing theory. Metrics which are used to measure performance of routing protocols namely: packet delivery ratio, average end-to-end delay, average jitter, throughput, network lifetime and routing overhead will be presented, and this will be followed by the summary of the chapter.

3.2 QUEUING ADAPTATION TO MANET BATTERY LIFE

Queuing provides a model for providing forecasting behaviour of systems subject to random demand. In a queue a customer arrives in the system and waits for to be serviced and then departs the system to another server until they reach the end. Queuing theory has been applied to a number of areas ranging from planning, air traffic control and communication networks. Kendall classified system has been adopted as $X/Y/m/D/L$, where X is the probability distribution of interarrival times, Y is probability distribution of service times, m is number of servers, D is the queuing discipline being followed, L is for maximum number of customers in the system. X and Y, can be Markovian, general distribution, deterministic or Erlang distribution [119], [120].

The Jackson open network Markovian queuing system is applicable to MANETs because data packets are passed to multiple relay nodes before reaching their intended destinations. The characteristics associated with Jacksonian networks are as follows:

- Any arrivals to nodes in the network follow a Poisson distribution [122].
- The service distribution time is exponentially distributed
- Queuing discipline is First Come First Serve (FCFS)
- The utilisation at all queues is less than 1 , that is, arrival rate is always less than the service rate
- A customer completing the service at queue i,will move to another relay node j towards the destination and enter queue, or if the next node is the destination node, it leaves the system with probability $1-\sum_{i=1}^{n} P_{ij}$, where P_{ij} is the probability of a packet moving from node i to node j.

Queuing system is an open Jacksonian network and comprises of one or more servers that relays data packets from source node to the destination node(s). MANET uses multi-hopping technique whereby the data packets are relayed to other next-hop nodes on their way to the destination node(s). Equilibrium state probability distribution for states $(k_1, k_2, \ldots, k_n)$ in $M/M/1$ queues, when utilisation factor is less than 1, is the product of individual node's equilibrium distribution given by $л(k_1, k_2, \ldots, k_n) = \prod_{i=1}^{n} K_i = \prod_{i=1}^{n} P_i^{ki}(1-P_i)$. Figure 3.1 shows the structure of the node buffer. One of the salient features of MANET is limited node storage space and limited processing capabilities [120]. So, any data packets which come when there are some data packets being processed at the server are placed in the finite buffer waiting for their turn to access the server. Data comes from different nodes that are one-hop away from the current node and they are placed in a queue when there are data packets being processed. The multiplexing (MUX) converts data packets coming from different nodes into one data stream and the demultiplexing (DEMUX) splits the data packets directing the data packets to various destinations.

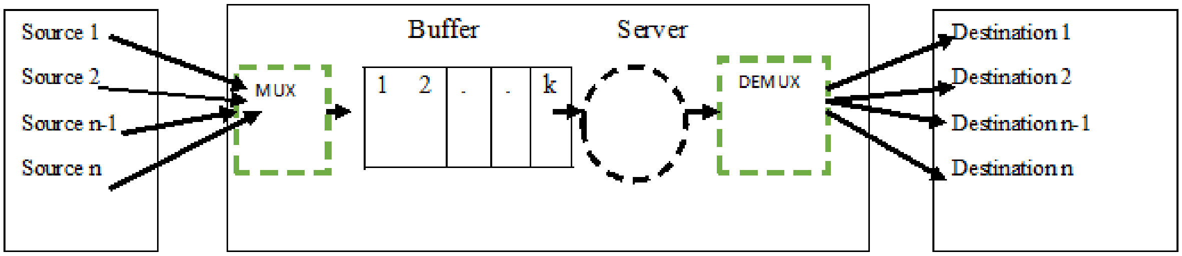

Figure 3.1 Structure of a node queue in MANET

The following is a brief description of each component that makes up the queuing system:

- Arrival process denoted by λ. The arrival process is Poisson in nature. The assumption for this process is that the probability of arrivals in intervals of Δt seconds, from (t, $t+\Delta$t) is $\lambda\Delta t$ and is independent of arrivals at any time.
- Service process-the service process denoted by μ depends on the service time distribution and in most cases, it is assumed that the service process is independent of the number of data packets at the node.
- Queue discipline-queuing discipline describes the way customers are served. The queue disciplines explain how data packets are served in case there are some data packets waiting to be sent to the next-hop neighbours. In MANETs, First Come First Serve (FCFS) queuing discipline is followed, whereby data packets are served according to their arrival times. Data packets that arrive earlier are given precedence over the data packets which come last.

Table 3.1 shows the symbols and the description of notations used in single path and multipath routing (to be discussed in section 3.3 and section 3.4) approaches.

Table 3.1 MANET queuing notations

Symbol	Description
μ	Node processing capability
λ	Node-to-node transmission rate
N	Number of nodes that can be reached from node i
r	Distance from the current node i from radius R
Qlength	Buffer size capacity of the node
λ(r)	Data traffic by a node r from centre of the node communication range
M	Total number of nodes in the MANET networks
$\lambda^{'}(r)$	Effective arrival rate of data at node r distance from centre
L_m	Average route length (number of hops) in multipath

M/M/1/Qlength indicate a finite queue in wireless ad hoc networks. The nodes have maximum buffer size, defined by $Qlength$. The following section discusses the various queuing approaches in single and multipath routing techniques.

3.3 SINGLE PATH SCENARIO QUEUING

With single path scenario, the best path from source to the destination is explored. Probability of k packets in the queue can be computed using equation 3.1 [119].

$$P_k(r) = \begin{cases} \frac{1-\frac{\lambda(r)}{\mu}}{1-(\frac{\lambda(r)}{\mu})^{Qlength+1}} \cdot (\frac{\lambda(r)}{\mu})^k & if\ 0 \le k \le Qlength \\ 0 & otherwise \end{cases} \qquad (3.1)$$

The probability of packet loss due to buffer node being full (congestion), a scenario where the value of *k=Qlength*, on a wireless sensor network is given by the equation 3.2 [119].

$$P(loss\ due\ to\ full\ buffer) = \left\{ \frac{1-\frac{\lambda(r)}{\mu}}{1-\left(\frac{\lambda(r)}{\mu}\right)^{Qlength+1}} * (\lambda(r)/\mu)^{Qlength}) \right. \qquad (3.2)$$

Any data packets which arrive when the buffer is full are dropped. Ultimately, congestion on a network can be due to packet overflow when packets are being sent to nodes whose buffer is *k=Qlength*. Packet loss overflow is given by the equation 3.3 [119].

$$P(loss\ overflow) = \begin{cases} \frac{\mu-\lambda(r)}{1-\left(\frac{\lambda(r)}{\mu}\right)^{Qlength+1}} * (\lambda(r)/\mu)^{Qlength+1}) \end{cases} \quad (3.3)$$

The average end-to-end delay is the summation of delays which the data packets experience on each hop to the destination. It is dependent on the congestion status of the relay nodes to the destination node(s) waiting for transmission and also on the arrival rate of data packets from other nodes. Single path average end-to-end delay is computed using equation 3.4 [119].

$$Average\ delay = \frac{\sum_{k=1}^{Qlength} \quad k* \quad \frac{1-\frac{\lambda(r)}{\mu}}{1-\left(\frac{\lambda(r)}{\mu}\right)^{Qlength+1}} * (\lambda(r)/\mu)^{k})}{\lambda(r)(1- \quad \frac{1-\frac{\lambda(r)}{\mu}}{1-\left(\frac{\lambda(r)}{\mu}\right)^{Qlength+1}} * (\lambda(r)/\mu)^{Qlength})} \quad (3.4)$$

3.4 MULTIPATH SCENARIO QUEUING

In multipath approach, multiple routes are established from source to the destination. Utilising multipath, the load balancing is achieved since a number of routes established from source to the destination(s) are potential paths to be used in the event of high congestion levels on routes that were previously regarded as shortest paths. There are multipaths involved in routing data packets as there is no single path from source to destination. In the event of one route being congested, then other routes can be used to send data packets.

The probability of packet loss due to buffer being full in multipath using the same M/M/1/Qlength, is given by equation 3.5.

$$P(\ packet\ loss\ due\ to\ full\ buffer) = \frac{1-(N-1)\lambda L_m/\mu}{1-((N-1)\lambda L_m/\mu)^{Qlength+1}} * \left(\frac{(N-1)\lambda L_m}{\mu}\right)^{Qlength} \quad (3.5)$$

The average route length (L_m) is computed using equation 3.6.

$$L_m = \frac{1}{2*\left(\frac{\beta}{2\pi} - \sqrt{\frac{\beta}{2N\pi}}\, arctan\left(\sqrt{\frac{\beta N}{2\pi}}\right)\right)} \quad (3.6)$$

The probability of packet loss at a given node as a relay node during multi-hopping process is given by equation 3.7.

$$P(\ packet\ loss\ due\ to\ buffer\ overflow) = \frac{\mu-(N-1)\lambda L_m}{1-\left(\frac{(N-1)\lambda L_m}{\mu}\right)^{Qlength+1}} \cdot \left(\frac{(N-1)\lambda L_m}{\mu}\right)^{Qlength+1} \quad (3.7)$$

The probability of k packets in queue is given by equation 3.8 [119].

$$P_k(r) = \begin{cases} \frac{1-\frac{\lambda'(r)}{\mu}}{1-(\frac{\lambda'(r)}{\mu})^{Qlength+1}}.(\frac{\lambda'(r)}{\mu})^k & if\ 0 \le k \le Qlength \\ 0 & otherwise \end{cases} \tag{3.8}$$

Similarly, average-end-to-end delay for data packet can be computed using equation 3.9 [119].

$$Average\ delay = \frac{\sum_{k=1}^{Qlength} k.\frac{1-\lambda'(r)/\mu}{1-(\frac{\lambda'(r)}{\mu})^{Qlength+1}}.(\frac{\lambda'(r)}{\mu})^k}{\lambda'(r)} \tag{3.9}$$

3.5 NUMERICAL COMPUTATIONS FOR SINGLE PATH ROUTING QUEUING

A MANET network comprises N nodes (100 nodes in this example) with node processing rate (μ) of 500 and node density (σ) of 0.01, where node density is the number of nodes in a unit area, $Qlength$(buffer size)=20 packets, and each data packet is of size 512 bytes, $\beta = \pi/16$, Radius (R) of 100m and r value of 20m and λ =0.5, then λ(r) can be computed as:

$\lambda(r) = \lambda(N-1) + \frac{\pi(R^2-r^2)^2.\lambda.\sigma^2.\beta}{2}$; which gives the $\lambda(r) = 1470\ bytes\ of\ data.$ Then probability of packet loss due to congestion of buffer being full is found using equation 3.2 is computed as follows:

$$Packet\ loss\ due\ to\ congestion = \frac{1-1470/500}{1-(1470/500)^{21}} * \left(\frac{1470}{500}\right)^{20} \text{which gives 0.6599}$$

$$Packets\ lost\ due\ to\ overflow = \begin{cases} \frac{1470-500}{1-\left(\frac{1470}{500}\right)^{21}} * (1470/500)^{21}) \end{cases} = 970\ bytes$$

Packet lost due to overflow is 970 bytes using equation 3.3. The expected packets to be delivered to the destination node(s), if there is no packet lost due to overflow is computed by multiplying the number of data packets and node buffer holding capacity (20*512=10240bytes). Therefore, the lost rate in single path routing is 970/10240, which is 0.095 (9.5%).

The average delay for a data packet in single path scenario, when the node buffer is full i.e. when k=Qlength is computed using equation 3.4.

$$Average\ delay = k * \frac{\frac{1-1470/500}{1-(\frac{1470}{500})^{21}} * \left(\frac{1470}{500}\right)^{20}}{1470\left(1 - \frac{1-\frac{1470}{500}}{1-\left(\frac{1470}{500}\right)^{21}} * (1470/500)^{20}\right)}$$

The average delay experienced by the data packet in single path routing is 0.0136 (1.36%).

3.6 NUMERICAL COMPUTATIONS FOR MULTIPATH ROUTING QUEUING

The numerical computation and analysis are done using the same parameters as those of single path with the exception that the number of hops, L_m are computed using the equation 3.6.

$$L_m = \frac{1}{2*\left(\frac{\pi/16}{2\pi} - \sqrt{\frac{\pi/16}{2*100*\pi}}\, arctan\left(\sqrt{\frac{100*\pi/16}{2\pi}}\right)\right)}$$, which gives $L_m \approx 17$ hops.

The probability of packet lost due to buffer being full is computed using equation 3.5 as:

$$Packet\ loss\ due\ to\ buffer\ being\ full = \frac{1-(100-1)*0.5*17/500}{1-((100.1)0.5*17/500)^{21}} * \left(\frac{(100-1)*0.5*17}{500}\right)^{20}$$ which gives 0.4058.

Number of packets lost due to overflow is computed using equation 3.7 as:

$$Packets\ lost\ due\ to\ overflow = \frac{500-(100-1)*0.5*17}{1-\left(\frac{(100-1)*0.5*17}{500}\right)^{21}} * \left(\frac{(100-1)*0.5*17}{500}\right)^{21}$$ =342 bytes

Packet lost due to overflow is 342 bytes. Therefore, the lost rate is 342/10240, which is 0.033 (3.33%).

In computation of the average delay experienced by the data packet in multipath, there is load balancing where multiple paths are established based on the nodes traffic conditions, thus effective arrival rate needs to be computed, since when buffers are full some packets arriving end up being dropped. Effective arrival rate $\lambda'(r)$ is computed using equation 3.10.

$$\lambda'(r) = \lambda(r) - packet\ lost\ rate\ in\ multipath\ route \qquad (3.10)$$

$$\lambda'(r) = 1470 - 342\ ; which\ give\ 1128\ bytes$$

The average delay experienced by the data packet when the buffer is full is computed using equation 3.9.

$$Average\ delay = \frac{\sum_{k=20}^{20} 20*\frac{1-1128/500}{1-(\frac{1128}{500})^{21}}.(\frac{1128}{500})^{20}}{342}$$ = 0.00987 (0.987%)

3.7 ANALYSIS OF SINGLE PATH AND MULTIPATH ROUTING

From the computation of single path routing and multipath routing, better routing results come from multipath routing approach as compared to single path routing mainly due to load balancing scheme in multipath. The numerical results show that the probability of data packets being dropped, when the node buffer is full for single path is 0.6599 and for multipath it is 0.4058. The lost rate is 9.5% and 3.33% for single path and multipath routing respectively. The average delay experienced by the data packets for single path routing is 1.36% and 0.987% in multipath routing. The numerical results favour multipath routing as compared to single path routing in MANET wireless network due to data traffic being shared with the nodes on the network rather than overloading certain nodes across the network.

3.8 QUEUING SWARM OPTIMISATION ROUTING FRAMEWORK FOR MANETS

A main framework based on swarm-based and queuing theory help in improving the survivability of MANET network. Integrating swarm-based routing with queuing theory help in determining the best path to route data packets across the network. Figure 3.2 shows the main framework for optimisation that combines queuing theory and swarm-based optimisation.

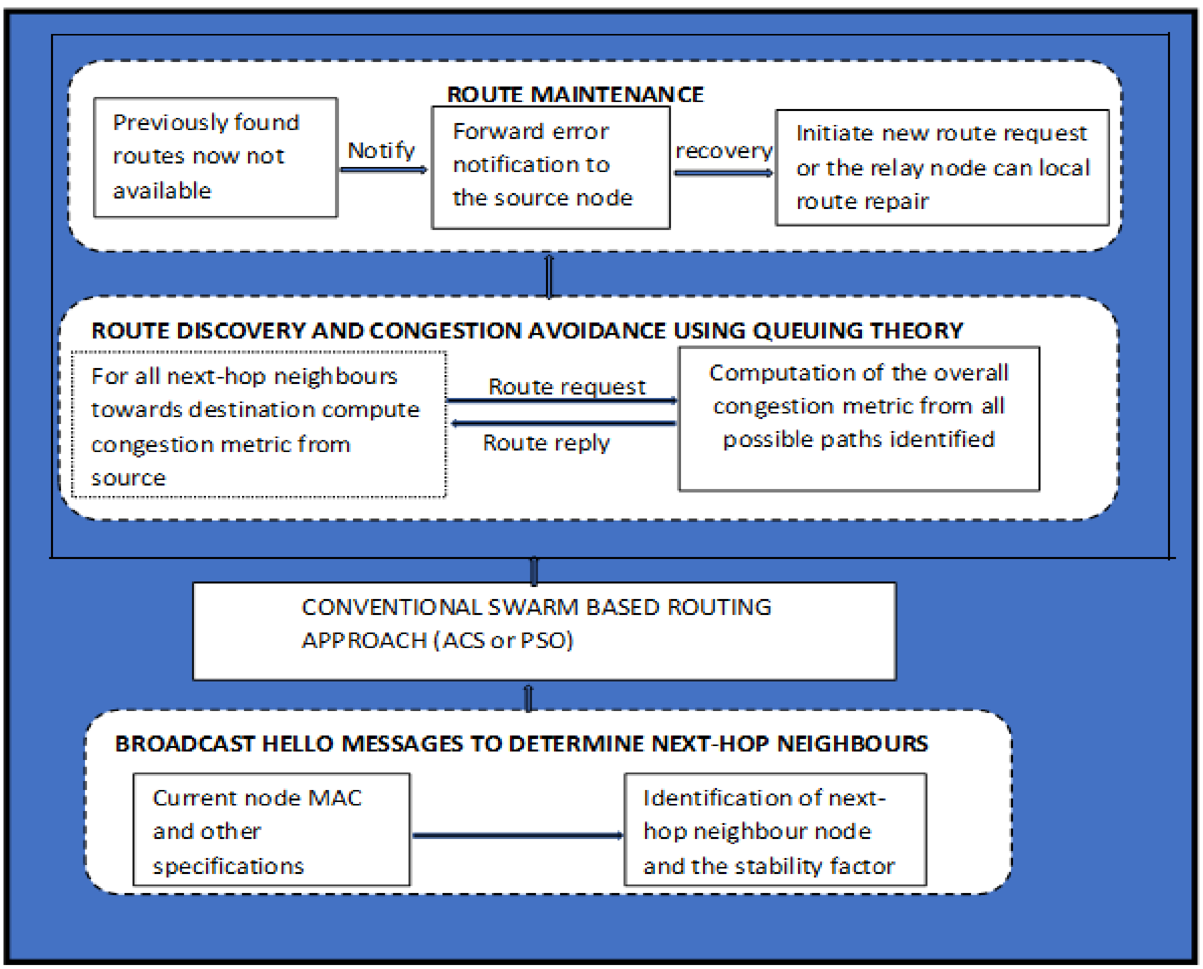

Figure 3.2 Queuing swarm optimisation routing for MANETs

From the main framework in Figure 3.2, two frameworks were developed. The first framework was based on particle swarm optimisation and queuing theory termed Q-PSO (see section 3.9.4). In Q-PSO routing framework, queuing theory was hybridised with particle swarm optimisation. The components that make up the Q-PSO routing framework include determination on nodes positions and route discover. Once nodes had identified each other, particle swarm optimisation approach is applied in clustering the network into logical groups and in each group, a cluster head node is chosen based on the node's remaining battery life.

The second framework has been termed QUACS. It is underpinned on the idea of ant colony optimisation and queuing theory (see section 3.10.4). QUACS routing framework consists of determining nodes positions and stability factor of the relay nodes. The stability factor of nodes is computed so that relaying of data packets is done on those nodes which are relatively stable hence improving chances of quicker receiving of data packets. Queuing theory was applied in determining the best path to route data packets based on the congestion status of next-hop neighbours. Reactive route maintenance approach is followed in QUACS routing protocol so that the nodes limited buffers are only utilised when there are data packets to be sent.

3.9 Q-PSO: QUEUING PARTICLE SWARM OPTIMISATION

3.9.1 Problem formulation

A MANET is an undirected graph where each node within a given radius denoted by, R can directly communicate with each other. MANET can be represented as $G = (V, E)$, where V is the set of vertices and E is the set of links also known as edges. A link exists between node i and j, shown as $E(i, j) \in E$, where the distance between $D_{ij} \leq R$ indicates that there is direct link between node i and node j [118]. Nodes in MANET use multi-hop approach to route data packets to other nodes till destination node(s) is reached. Intermediate nodes that are used to relay data packets can have their battery life depleted, if they are heavily used and hence, communication with far away nodes ceases to be operational. Strategies to ensure higher network lifetime for nodes in the MANET network which can aid in enabling communication to take place for a longer time need to be explored in an environment where it is impossible to replenish the nodes battery power.

3.9.2 Objective function

Routing plays a pivotal role in determining and choosing the next node and transmitting data packets across the network from source node to destination node. One of the objectives of this research was to increase network lifetime. This was done through exploring congestion levels before choosing routes to relay data packets. Using particle swarm optimisation coupled with queuing theory under a limited buffer-constrained MANET. Using particle swarm optimisation (PSO) with queuing theory which we call, Q-PSO, can be beneficial in routing data packets in a battery-constrained MANET. There are $SW,$ swarm particles, which are possible solutions and each particle has a position vector and velocity vector denoted by x_i and v_i respectively. The objective is to optimise the combined congestion metric residual and residual battery power when data packets are routed under a MANET with constrained battery power. The objective function of i^{th} particle at time t, denoted by $f\big(x_i(t)\big)$ of finding least congestion path in single and multipath in the wireless network is given by the equation 3.11.

$$f\big(x_i(t)\big) = optimise\ (w_1\beta_1 + w_2\beta_2) \tag{3.11}$$

$where\ w_1$and w_2 are weights between 0 and 1 exclusively showing the relative importance of each parameter in routing decisions. The total weights add up to one (1). β_1 represent residual energy and β_2 is congestion metric. The weights are chosen relative to the importance of each metric. Varying the weights shows the metric that has a higher priority relative to other metrics. In this study, congestion metric and residual energy have all been assigned values of 0.5 each (that is equal weighting), as they are all equally important in extending the network lifetime of MANET).

3.9.3 Particle swarm optimisation theory

Particle Swarm Optimisation (PSO) is a population based stochastic optimisation technique which is derived from social behaviour of organisms such as; schools of fish and flock of birds [88][89]. The main objective of PSO is to find the particle position that gives the best evaluation of results to the fitness factors [32]. During the initialisation stage, each particle is assigned randomly some initial parameters. Each particle utilises information about its best individual position denoted by, (P_{id}), and the global best solution denoted by, (P_{gd}) to increase its chances of getting towards the global best position, which ultimately leads to a better fitness [115]. When a particle finds a new fitness value that is better than the fitness it already has, it replaces its individual best fitness and updates the particle velocity ($V_{id}(t)$) at time t using the following equation 3.12.

$$V_{id}(t) = w * V_{id}(t-1) + c_1 \Phi 1(P_{id} - X_{id}(t-1)) + c_2 \Phi 2(P_{gd}(t-1)) \quad (3.12)$$

where, Φ1, Φ2 are random numbers between 0 and 1; c_1, c_2 are learning factors

The particle's position (X_{id}) is updated using equation 3.13.

$$X_{id} = X_{id}(t-1) + V_{id} \quad (3.13)$$

The good choice of inertia weight (w) controls the convergence behaviour of PSO [116]. Inertia weight w is given by the equation 3.14.

$$w = w_{max} - \frac{w_{max} - w_{min}}{\max iter} * iter \quad (3.14)$$

where w_{max} is the maximum inertia, w_{min} is minimum inertia value and current iteration is represented by $iter$. PSO is ideal for solving NP hard problems because it can explore a wider solution space, to come up with the best solution on given constraints and responds quickly to global minima within a reasonable time [90][101].

3.9.4 Proposed Q-PSO routing protocol framework

This section proposes a new framework for routing called Queuing with Particle Swarm Optimisation (Q-PSO) as shown in Figure 3.3. This is a hybrid routing process which is comprised of particle swarm optimisation and queuing theory.

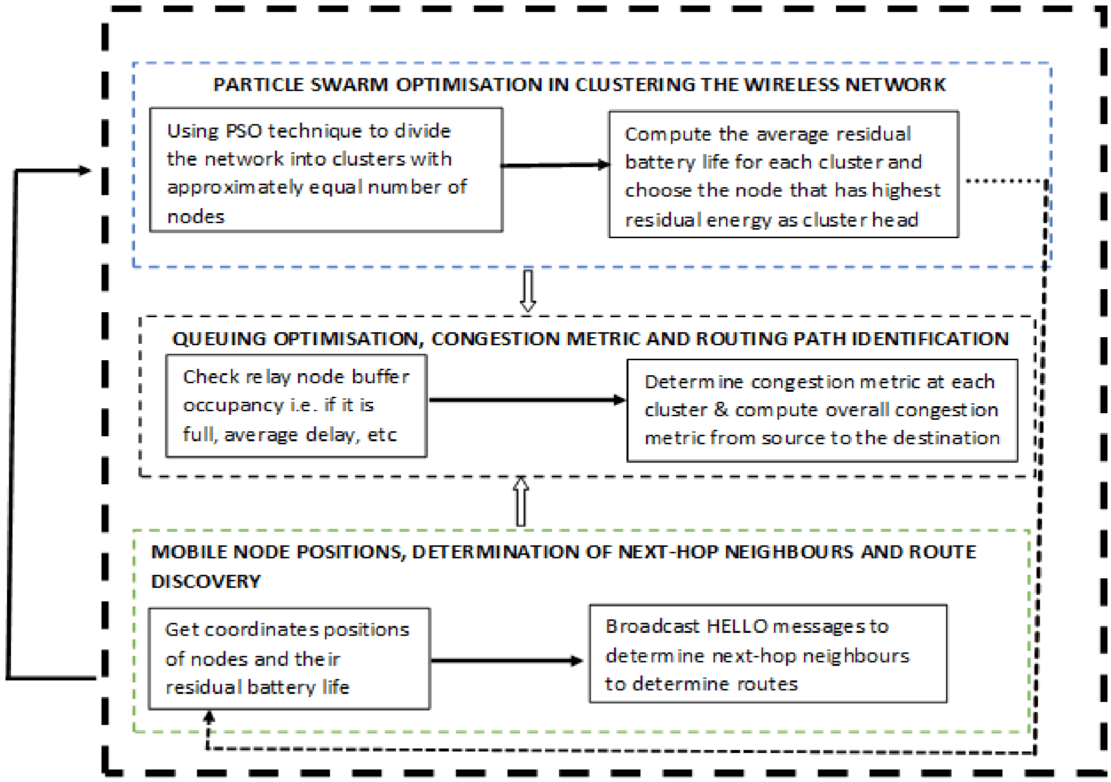

Figure 3.3 Q-PSO routing framework

The following is a detailed description of what happens at each layer of the Q-PSO routing framework.

3.9.5 Mobile nodes position and route discovery

All mobile nodes in the MANET broadcast their status information on their location and residual energy level status. Almost all wireless devices nowadays are equipped with Global Positioning System (GPS) systems which enable them to know their geographical positions. Neighbours are nodes that are directly connected to one another. The identification of next-hop neighbours is done with the Neighbour Discovery Protocol (NDP) at Medium Access Control (MAC) level. The mobile nodes periodically broadcast Hello packets which are exchanged by nodes that are one-hop away from each other. Hello packets help in determining whether the nodes are still available or not. If the node(s) are no longer available maybe due to battery depletion or node moving away from the cluster, the routing tables are updated to reflect on those changes by removing those nodes from the routing tables.

3.9.6 Particle swarm optimisation in clustering a wireless network

Particle swarm optimisation clustering is a nature inspired problem-solving technique [94][95]. Once particles' positions and neighbours are identified, then particle swarm optimisation technique follows in clustering the network into logical groups. The process of clustering the networks involves the following steps:

Step 1: The first process involves random initialisation of particles (x-y coordinates) together with their velocities.

Step 2: The second step involves estimating the fitness value using equations 3.15 and 3.16.

$$F = \sum_{i=1}^{n} \alpha * \frac{dist(nid, member\ of\ i)}{no.of\ members\ in\ cluster} + \beta * \frac{Avg\ energy\ of\ member\ nodes}{Residual\ energy\ of\ cid} + \gamma * \frac{1}{No.of\ members\ in\ nid} \quad (3.15)$$

$$\alpha + \beta + \gamma = 1;\ \text{where}\ \beta\ and\ \gamma\ are\ weights \quad (3.16)$$

and $dist(nid, member\ of\ i)$ is the average distance of the current node (nid) to all the nodes that it can reach directly, $Avg\ energy\ of\ member\ nodes$ is the average residual energy for nodes nid can reach directly.

Step 3: The particle's new (both the x and y values) positions are updated using equation 3.17.

$$\left.\begin{aligned} X_{xid}(t+1) = X_{xid}(t) + V_{xid}(t) \\ X_{yid}(t+1) = X_{yid}(t) + V_{yid}(t) \end{aligned}\right\} \quad (3.17)$$

Computation of local best and global best particle positions is performed. The new velocities of the particles are updated as well using equation 3.18.

$$\left.\begin{aligned} V_{xid}(t+1) = \omega V_{xid}(t) + c_1 * \Phi 1 * [p_{id}(t) - X_{xid}(t)] + c_2 * \Phi 2 * [p_{gd}(t) - X_{xid}(t)] \\ V_{yid}(t+1) = \omega V_{yid}(t) + c_1 * \Phi 1 * [p_{id}(t) - X_{yid}(t)] + c_2 * \Phi 2 * [p_{gd}(t) - X_{yid}(t)] \end{aligned}\right\} \quad (3.18)$$

Step 4: Computation of fitness of new particles is undertaken and a comparison of old and new particle positions performed for the iteration and particle best local and global positions

if new position value > old fitness value then

replace the old particle position with the new particle position and save it

else

old particle position is forwarded to the next iteration

Step 5: The new particle values positions and velocities are obtained and then return to Step 3 until fitness of particles converge to the minimal value or the required number of clusters is reached (square root of number of nodes in the MANET network minus 1).

After clustering the network, then cluster head selection process follows. A node that has the highest remaining residual battery life in the cluster is selected as the cluster head. Member nodes join only one cluster closest to them based on geographical location relative to the cluster head nodes. Figure 3.4 shows the combined clustering and selection of cluster heads flow diagram.

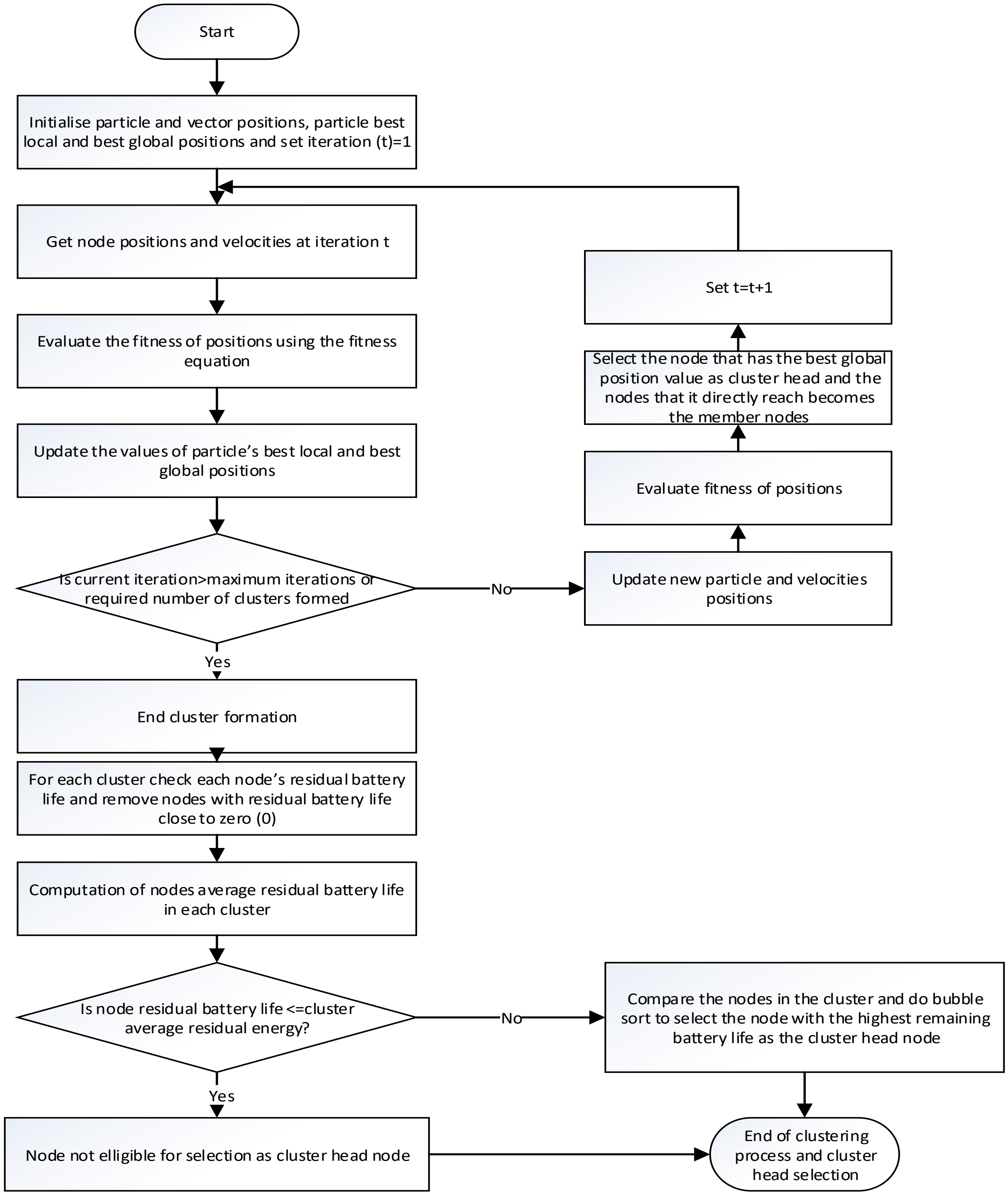

Figure 3.4 Clustering and selection of cluster heads paradigm flow chart

At each time, Ω, the cluster head is selected because the node that might have been selected as a cluster head might run out of power yet there might be other member nodes whose residual battery power maybe greater than the residual battery power of the current cluster head. At every, Ω seconds, a new cluster head is determined using equation 3.19.

$$\Omega = \frac{1.5*R}{V} \tag{3.19}$$

The value R is the cluster head communication radius and V is the velocity of the current cluster head. A new cluster head is selected every Ω seconds because of the dynamism of the wireless network where some nodes join, and others leave. Mobile nodes choose to relay data to nodes whose signal strength is higher. Periodically mobile nodes choose the zone they should belong based on their proximity to the cluster head node.

3.9.7 Congestion metric and routing path identification

The buffer occupancy of all the clusters is checked prior to sending data packets across the network. Congestion is a critical metric to be checked when routing data packet in wireless network because of the following [123]:

- A path that has high congestion tends to suffer from high packet delay
- Chances of packet loss is high, especially if the buffer is full
- Increase in communication overhead when the cluster head buffer is full

If the destination node is not the cluster head (CH) of the cluster where it belongs, its cluster head handles the communication on its behalf. Other member nodes will be in '*sleep*' state and the cluster heads are the only active nodes. The member nodes only change from '*sleep'* to '*active*' state only when it is receiving data or if it is sending data packets. This ensures that all the nodes will not drain battery at the same time, thereby prolonging the lifetime of the MANET network.

For example, Intracluster routing is done by nodes which belong to the same cluster, such nodes are (CH_1, 2, 3, 4), (CH_2, 5, 6,7, 8), (CH_6, 23, 24, 25) as shown in Figure 3.5. For example, any member node (2, 3, 4) in cluster 1 led by CH_1 node which wants to communicate could do so via the cluster head CH_1. This is done to control redundant information from being sent across the network. Member nodes which will not be sending any information enter into '*sleep*' state thereby conserving the scarce battery. It only enters '*active*' state if it receives data or during selection of the new cluster head.

In Intercluster routing, the source and destination nodes are in different clusters. Multi-hopping technique, whereby data packets are relayed from one intermediate cluster head to the destination cluster head is practised. The arrow from one cluster to the other cluster (Figure 3.5) shows that the cluster heads that can communicate directly with each other, for example if CH_1 is the source node and wants to send data to CH_7 possible paths are:

- Path 1.......................... $CH_1 - CH_2 - CH_4 - CH_7$
- Path 2.......................... $CH_1 - CH_2 - CH_4 - CH_6 - CH_7$
- Path 3.......................... $CH_1 - CH_2 - CH_4 - CH_3 - CH_6 - CH_7$

The path $CH_1 - CH_2 - CH_5$ is discarded because CH_1 cluster head cannot communicate further to reach cluster head node CH_7 and if the data packet bounces to CH_2 , it is still going to be discarded because the node (CH_2) is identified as the cluster head node that has been visited before. The mode of communication in wireless ad hoc network is bidirectional for next-hop neighbours.

Only one routing table maintained, that is, Intercluster routing table. For communication within the cluster, that is Intracluster, communication is handled by the cluster head node of that particular group. This is not costly in terms of battery drain/ lost because nodes that act as cluster head nodes are rotated at regular time interval and other cluster head nodes are chosen based on the remaining battery life.

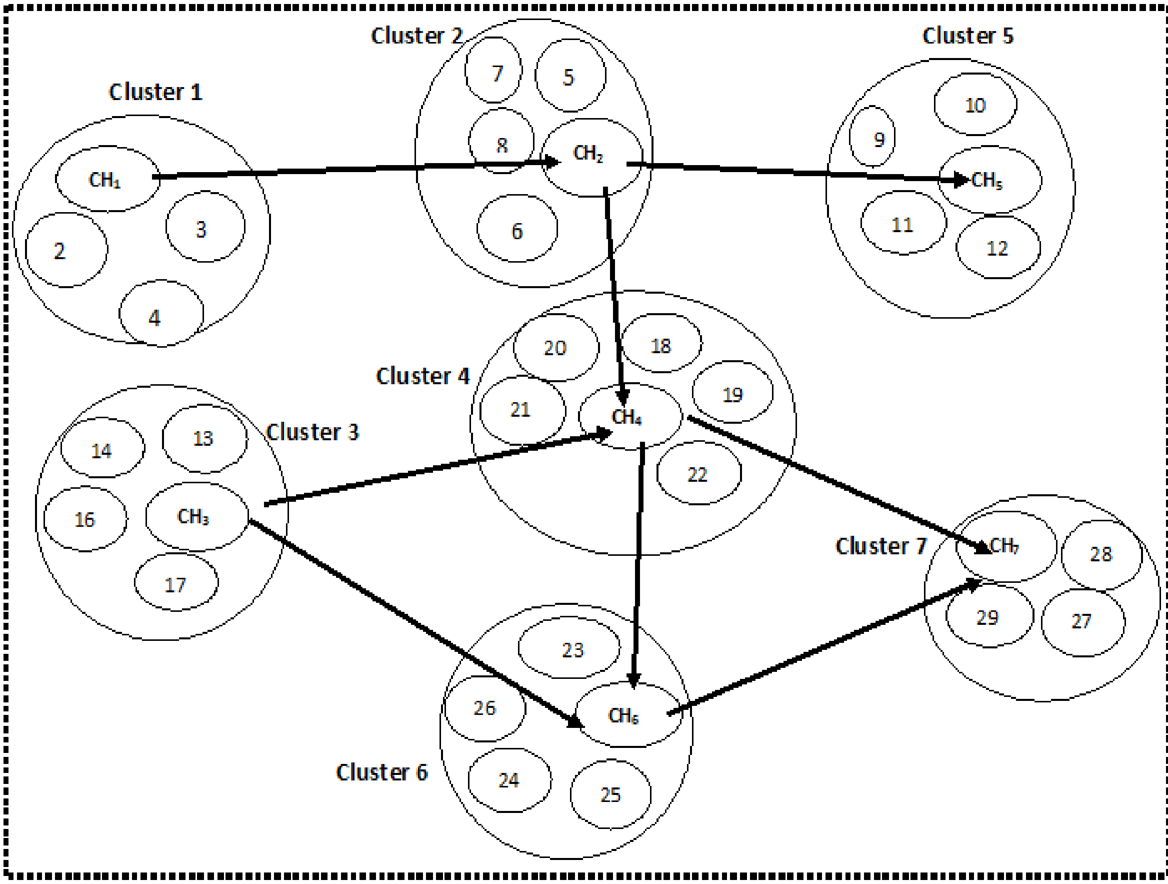

Figure 3.5 Intracluster and intercluster routing

If hop count metric was to be used to determine the best route from $CH_1$to CH_7 , the route that has the lowest number of hops is chosen in this case, route $CH_1 - CH_2 - CH_4 - CH_7$, is chosen for sending data packets from CH_1 to CH_7. However, in our proposed approach, the overall congestion metric is taken into consideration because a route can have fewer hops but may have high overall congestion compared to other alternative routes. This will result in high average end-to-end delay and reduced packet delivery ratio of the network, even though the number of hops will be few.

Each cluster head maintains a routing table for Intercluster routing. In Intracluster routing, member nodes just save their cluster head information, since their communication is handled by the cluster head node. The communication is controlled by the cluster head. In Intercluster routing, that is, routing outside the node's cluster zone, information on next-hop cluster head node is maintained. This InterCluster routing table consists of the next-hop cluster head nodes, congestion metric following that particular link, number of hops from source node and overall congestion metric

(OCM) from source cluster head node to the current relay cluster head node, which is computed using equation 3.2. The cluster heads that do not have a valid route to the destination node, thus cluster head node CH_5 is left in the routing table.

At each intermediate cluster head computation, the probability of the cluster head node buffer being full in single path routing is done using equation 3.2 [119].

At each intermediate cluster head computation of the probability of the cluster head node buffer being full in multipath routing is done using equation 3.7.

The value of $P(loss\ due\ to\ congestion)$ at each cluster head is the congestion metric value at the given cluster head. The congestion metric for all cluster heads is computed. On each route from the source node to the destination node, possible paths are identified via multi-hopping technique. At each intermediate cluster head node, the congestion metric (CM) at that cluster head is multiplied with the previous congestion metric values of previous cluster heads from the source node. At the destination node, the overall congestion metric from source node to the destination node is computed using the equation 3.20.

$$Overall\ Congestion\ \ metric\ on\ Path_i = 1 * CM_1 * CM_2 * \dots \dots \dots .. * CM_n \tag{3.20}$$

In single path routing scenario, there are a number of routes from source node to the destination nodes, but the path that has the lowest overall congestion metric value is chosen as the best path to route the data packets across the network. The cluster head(s) that have lowest overall congestion metric is stored in the routing table at each node as the best path.

During route discovery process, cluster heads that result in a loop are omitted since the cluster head node would have been visited before (see Pseudo code 3.1, step 11). During route request information broadcasting to find next-hop neighbours, congestion metric is computed using equation 3.2 or equation 3.7 depending on whether it is single path or multipath routing.

Routing table for cluster head nodes CH_1, CH_2, CH_3, CH_4, and CH_6 are shown in Tables 3.2-3.6 as these are tables that matter most for routing from CH_1 to CH_7. For example, computation of overall congestion metric (OCM) for the routing table at CH_2 from source node CH_1 is done using equation 3.20 as follows:

0.65*0.4=**0.26,** if CH_4 is chosen as the next-hop neighbour, the OCM will be computed as **0.6175**, which is found by multiplying 0.65*0.95 when CH_5 is chosen as next-hop neighbour.

Table 3.2 Routing table at $\mathbf{CH_1}$

Source & Destination		Next-hop neighbours cluster heads		
		CH_2		
S	D	CM	OCM	Hop count
CH_1	CH_7	0.65	0.65	1

Table 3.3 Routing table at CH_2

Source & Destination		Next-hop neighbours cluster heads					
		CH_4			CH_5		
S	D	CM	OCM	Hop count	CM	OCM	Hop count
CH_1	CH_7	0.4	0.26	2	0.95	0.6175	2

Table 3.4 Routing table at CH_3

Source & Destination		Next-hop neighbours cluster heads					
		CH_6			CH_4		
S	D	CM	OCM	Hop count	CM	OCM	Hop count
CH_1	CH_7	0.75	0.04875	4	0.4	0.026	(previously visited)- therefore discard

Table 3.5 Routing table at CH_4

Source & Destination		Next-hop neighbours cluster heads								
		CH_3			CH_6			CH_7		
S	D	CM	OCM	Hop count	CM	OCM	Hop count	CM	OCM	Hop count
CH_1	CH_7	0.25	0.065	3	0.75	0.195	3	0.8	0.208	3

Table 3.6 Routing table at CH_6

Source & Destination		Next-hop neighbours cluster heads					
		CH_7			CH_4		
S	D	CM	OCM	Hop count	CM	OCM	Hop count
CH_1	CH_7	0.8	0.039	5	0.75	0.195	(previously visited)-therefore discard
CH_1	CH_7	0.8	0.156	4	0.75	0.195	(previously visited)-therefore discard

There are three (3) possible paths of routing the data from the source node, CH_1, to the destination node, CH_7. The overall congestion metrics and number of hops for possible routes as from the routing tables in Tables 3.2-3.6 is as shown in Table 3.7.

Table 3.7 Possible paths from source node $\mathbf{CH_1}$ to destination node $\mathbf{CH_7}$

Possible path from CH1-CH7	Overall congestion metric	Hop Count
CH1-CH2-CH4-CH7	0.208	3
CH1-CH2-CH4-CH3-CH6-CH7	0.039	5
CH1-CH2-CH4-CH6-CH7	0.156	4

From Table 3.7, if number of hops was the sole determination of the best route in single path, route $CH_1 - CH_2 - CH_4 - CH_7$, with 3 hops was going to be chosen ahead of the other two routes. However, if overall congestion metric is taken into consideration path, $CH_1 - CH_2 - CH_4 - CH_3 - CH_6 - CH_7$ with the least overall congestion metric value is chosen ahead of path, $CH_1 - CH_2 - CH_4 - CH_7$.The chances of high packet delivery are high if congestion is taken into consideration as the path chosen will have checked the likelihood of packet being dropped due to buffer being full.

In multipath routing table, the best path $(CH_1 - CH_2 - CH_4 - CH_7)$ and other possible paths, that is, $(CH_1 - CH_2 - CH_4 - CH_6 - CH_7)$ and $(CH_1 - CH_2 - CH_4 - CH_3 - CH_6 - CH_7)$ are stored. If the best path has cluster heads whose buffers are full or nearly full, other alternative paths can be chosen based on overall congestion status identified during route discovery stage.

3.9.8 Development of the Q-PSO routing protocol

The Q-PSO routing protocol involves a number of processes in determining the least congested free path on the network. The PSO routing technique is applied to determine the possible clusters on the network. After clustering has been done, the cluster head nodes are selected based on the average residual battery lives for nodes in the particular cluster. If a node has battery life that is less than the average residual battery life, it is not eligible for selection. The node with battery life greater than average cluster heads are ranked. After ranking, it is the member node that has the highest residual battery life that will be selected using bubble sorting method as the cluster head. Bubble sorting was chosen ahead of other sorting methods such as linear sorting because it is simple to implement especially in MANET environment where there is high volatility due to nodes joining and leaving the network arbitrarily.

When route request packets are initiated by the source node to establish the possible paths to the destination node, along the way they compute and save the probability of loss due to buffer being full which is termed congestion metric (CM) value. CM is computed using equation 3.2 or equation 3.7, depending on whether it is single path or multipath routing at each cluster head towards the destination node. If the source node is within the same cluster as the destination node, proactive routing approach called Intracluster routing is utilised. If the clusters are different, then reactive routing approach called Intercluster routing is adopted. The choice of the best path in single path and multipath routing is not determined by the number of hops traversed from source node to the destination node. It is influenced by the overall congestion metric (OCM) factor. The path with the lowest OCM is chosen as the best path for sending data packets. Pseudo code 3.1 shows the stages involved in Q-PSO routing technique.

Pseudo code 3.1: Q-PSO routing protocol

INPUT: Nodes on the network β= $\{n_1,n_2,n_3,\ldots,n_m\}$, Set of cluster heads γ=$\{Ch_1,Ch_2,Ch_3,\ldots.Ch_m\}$, Source node (S), Destination node (D), hop count (H), Predefined swarm size SW_n, Node Residual Energy α= $\{E_1,E_2,E_3,\ldots,E_m\}$, Iteration (t) **OUTPUT**: LocalBest_t, Globalbest, Congestion Metric(CM) at each cluster head $\{a_1,a_2,a_3,\ldots.a_n\}$, Overall congestion metric (OCM) value for each path //values range from 0 to 1
Procedure **Step 1**: initialisation particles SW_i , $\forall i, 1 \le i \le SW_n$ initialisation particles velocities V_i , $\forall i, 1 \le i \le V_n$

hop count :=0
CM of S cluster head:= 1
OCM:=1
t=0

Step 2: **for** i=1 to SW_n **do**
compute fitness value for each particle SW_i using equation 3.15-3.16
$LocalBest_t$:=SW_i
end

Step 3: $Globalbest$ =minimum (Fitness ($LocalBest_t$) , $\forall i, 1 \leq i \leq SW_n$

Step 4: **repeat**
for i=1 to SW_n **do**
Update position of SW_i using equation 3.17
Update particle velocity of SW_i using equation 3.18
Compute fitness of SW_i
if fitness (SW_i)<Fitness ($Localbest_t$) **then**
$LocalBest_t$=SW_i
else
no change in the current local position //remain with the previous $LocalBest_t$
end if
if fitness($LocalBest_t$)<Fitness ($Globalbest$) **then**
$Globalbest = LocalBest_t$
else
previous global best position remains unchanged
end if
t=t+1
remove the node that has the particle that has the global best position together with nodes that are one-hop away from it //a new cluster that has been formed
until number of clusters has been reached or maximum iteration (t) reached
//end of cluster head

Step 5: for each cluster $i = 1 \; to \; Ch_m$
if $E_i \leq 0$ **then**
battery exhausted purge from the network
else //Node still has battery and can communicate on the network
for i=1 to Ch_m
compute average residual energy for cluster i nodes using the formula

$$Average\ residual\ \ energy_{cluster\ m} = \frac{\sum_{i=1}^{m} Residul\ Energy_m}{m}$$

end for
end if

Step 6: **if** Residual Energy of node $n_m <$ Average residual energy$_{\text{cluster i}}$ then node n_m not eligible for cluster head

else

use bubble sort and select the node with the highest remaining residual battery life as the cluster head

end if

end for // end of selecting cluster heads

Step 7: Generating the source node and destination nodes

S=rand(n_i) //choose source node

D=rand(n_j), $where n_i \neq n_j$ //choose destination node and it cannot be the same as source node

Step 8: S broadcast RREQ // new route request (RREQ) to determine the path to destination node

if D can be reached within the cluster i

Intracluster routing coordinated by the cluster head

else //Intercluster routing

Step 9: while S!=D and H<255 //maximum hop count is 254 else the packet is dropped

do

broadcast HELLO message packet to check on the cluster heads one hop away

Step 10: **for** next-hop cluster head nodes are found //all cluster heads neighbours of Ch_i node cluster head

Compute CM value for the cluster head node using equation 3.2 for single path routing

Compute CM value for the cluster head using equation 3.7 for multipath routing

Step 11: At each intermediate cluster head towards D cluster head **do**

if cluster head node visited before **then**

drop the RREQ packet i.e. cluster head node visited before

else

for k=1 to $path_m$ //for saving all the new routes found

H=H+1

Compute OCM at intermediate cluster head node using equation 3.20

end if

end for

end while

Step 12: until D is reached

Step 13: At D generate the route reply packet to S to reinforce the paths found and overall congestion on path found previously by the request data packets

Step 14: Generate the route reply packet (RREP) from D to S

Step 15: At cluster head node S **do**

if single routing **then**

Bubble sort the OCMs found from paths $path_m$ and choose path k with the least OCM

else // multipath routing scenario

Rank paths $path_m$ based on overall congestion metric values ascending order

as all possible paths from S to D and prioritise the ones with least congestion
end if
end procedure

3.9.9 Route discovery and maintenance

A route can be invalidated by node(s) movement in a wireless network or maybe due to battery depletion and new possible paths need to be explored. When a node does not get Hello packets from its neighbours after a defined period of time, it is assumed that the neighbour node is no longer available. The routing tables need to be updated to reflect on the new status of the network. Local route repair process is initiated by the cluster head node that detects the broken link. This is done by trying to explore other alternative paths towards the destination. If a new route is not found, an error message is sent back to the source cluster head node to find the new path. Q-PSO provides multipath to the destination node but only the best path with the least overall congestion metric value is chosen.

Each mobile node in the MANET that is awake broadcast Hello message from time to time to check the available next-hop neighbours. All the next-hop neighbour nodes that respond with an acknowledgement (ACK) to the requesting node indicates their presence. The node’s next-hop neighbours are thus updated periodically by requesting node. If the requesting node broadcast the message and does not receive the response from the next-hop neighbours nodes, it discards these nodes from its list of next-hop neighbours. The flow chart Figure 3.6 shows the Hello message processing.

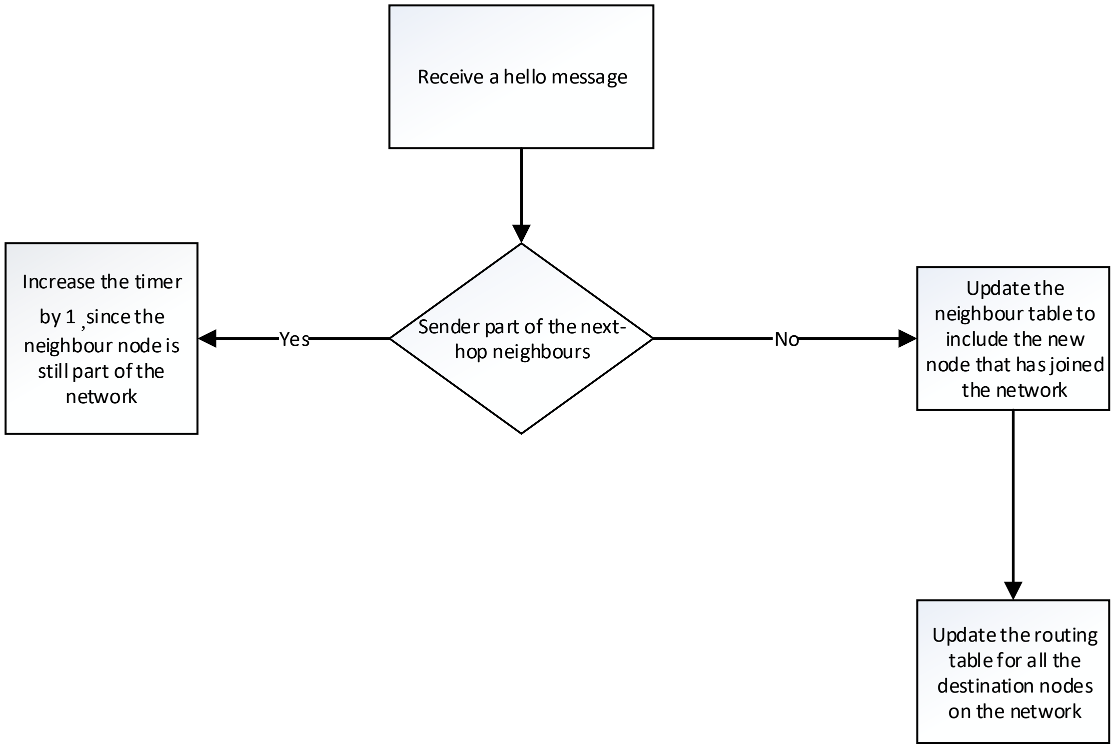

Figure 3.6 Hello message processing in the MANET network

In Figure 3.6 when the node is already in the neighbour table the expiration time increases since the node is still part of the network.

3.10 QUACS: QUEUING ANT COLONY SYSTEM

3.10.1 Problem formulation

In a MANET, each mobile node performs two duties, namely as the source node or destination node. Secondly, mobile node acts as a router where it relays data packets to the next nodes destined for a destination node in the network. The radio link type of communication in MANET is bidirectional. The MANET can be represented as an undirected graph with edges between each node being able to communicate directly. This can be presented as $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ where *V* shows the set of vertices, that is, number of nodes in the MANET network, whilst *E* represents the set of edges, that is, radio links that exist between nodes that can directly communication with each other, they are one-hop away from the current node. All these individual links that connect nodes in the network, are bi-directional such that if

$$(\boldsymbol{v}_i, \boldsymbol{v}_{i+1}) \rightarrow \boldsymbol{E}, \boldsymbol{then}\ (\boldsymbol{v}_{i+1}, \boldsymbol{v}_i) \rightarrow \boldsymbol{E}\ also\ exist$$

Each node V_n has its maximum radio communication range defined by radius R. The nodes in the network are only capable of communicating directly with those nodes that are one-hop away from it. Nodes *i* and *j* are neighbours if $D_{(i,j)} \leq R,$ that is, if the distance between node *i* and *j* are within each other's communication radius. However, due to mobility the set of *E* keeps on changing in MANETs. At any time, some nodes join, and others leave the MANET. At time *t*, the MANET can be represented as $\boldsymbol{G_t = (V_t, E_t)}$**.** In wireless networks, the capacity of the link to deliver data packets to the intended destination depends on the signal strength, which is negatively correlated to distance between two nodes. If nodes are too close to each other, then the chances of high signal strength is likely and vice versa. Using the IEEE 802.11 standard a multi-hop MANET can be created, and the ad hoc network can span several distances through multi-hopping. The bandwidth capacity of the link between node *i* and node *j* at time *t*, that is, $L_{ij}(t)$ in bits per second can be calculated using equation 3.21 [124].

$$L_{ij}(t) = [1 + e^{10*(D_{ij}(t)^{-0.5}}]^{-1} \qquad (3.21)$$

$where\ D_{ij}(t)\ is\ the\ Euclidean\ distance\ between\ node\ i\ and\ node\ j\ at\ time\ t$

Notations

$G_0 = (V_0, E_0)$ MANET at the beginning

$G_t = (V_t, E_t)$MANET at time *t*

$E_{ij}(t)$=1 if there is a bidirectional link between node *i* and *j* at time *t*, otherwise it is 0

$(X_{ij}(t), Y_{ij}(t))$= the *x* and *y* coordinates values of the i^{th} MANET node at time *t*

$R_{ij}(t)$=wireless radio connection range of the i^{th} node at time t

$D_{ij}(t)$=Euclidean distance between node *i* and *j* at time *t* and this is calculated using the formula;

$$D_{ij}(t) = \sqrt{(X_i(t) - X_j(t))^2 + \ (Y_i(t) - Y_j(t))^2}$$

3.10.2 Objective function

The main objective of this research is to find the shortest path routing method of sending data packets under a buffer limited constrained network. Sending of data packets in a limited capacity storage space constrained environment is critical for developing countries, Africa included. Routing of data packets needs to be relayed using routes that minimise average end-to-end delay. Information must be relayed through several hops in a short period of time to reach the intended recipient(s). It is thus the purpose of this study to identify the shortest route for routing data packet in a MANET networks, such as during emergency situations. ACS hybridised with Queuing theory techniques have been proposed.

Finding the shortest path is an NP hard problem. We therefore propose a QUACS routing protocol that can be used to convey information in a MANET in a short period of time. The proposed QUACS routing protocol is an integration of ant colony optimisation technique with queuing theory. Since the mobile nodes in a MANET have limited storage capabilities and bandwidth, there is need to hybridise the two techniques to come up with a better solution (QUACS routing method). The hybridised method can lead to increase in throughput and minimises average end-to-end delay among other routing protocols performance metrics. The proposed QUACS routing method can be used to solve the optimisation problem which can be defined as follows:

$Q_{\text{shortest best path under buffer constrained storage space}} = \text{argmax}(P_k)(\,TP_k | \forall k \in K\,)$, where k is ant generated by the source node and TP_k is the pheromone level on each path identified by ant k. P_k is the route evaluation function.

$D_{sd}^{k} \leq D_T\ ; \forall k \in K, \forall\ s \in S\ and\ \forall d \in D$

$P_{loss} \leq P_T;\ \forall k \in K, \forall\ s \in S\ and\ \forall d \in D$

D_{sd}^{k} and P_{loss} are end-to-end delay and packet loss respectively, and D_T and are constraints on delay and packet loss set for by the user.

3.10.3 Ant colony optimisation theory

An Ant Colony System (ACS) is a metaheuristic bio-inspired approach of finding the optimal path from the source to the destination [53]. ACS methods can be used to solve many combinatorial optimisation problems. It has been observed that in the natural environment, setting ants to perform simple autonomous tasks and cooperate with each other to solve a problem which a single ant would not be able to solve alone. Ants start searching for food by moving around to different locations in search of food. During movement, the ants lay an odorous chemical substance known as pheromone along the path from the food source to the nest. This pheromone in turn influences the behaviour of other future ants. It has been observed that over some time, many ants will tend to follow the path that has the highest level of pheromone trail and abandon those that have less pheromone levels (longest routes) [66], [90].

3.10.4 Proposed QUACS routing protocol framework

Figure 3.7 is the proposed QUACS framework. QUACS method is a combination of ant colony system (ACS) and Queuing theory. It is basically made up of three interrelated layers: node configuration and mobility prediction layer, congestion avoidance, dynamic route discovery layer, and lastly, reactive route maintenance layer. Two types of ants are used: forward ant (FANTs) and backward ants (BANTs). Exploring of new routes is done by FANTs through a process called route request (RREQ) and reinforcing of the found routes is done by BANTs using route reply (RREP) process.

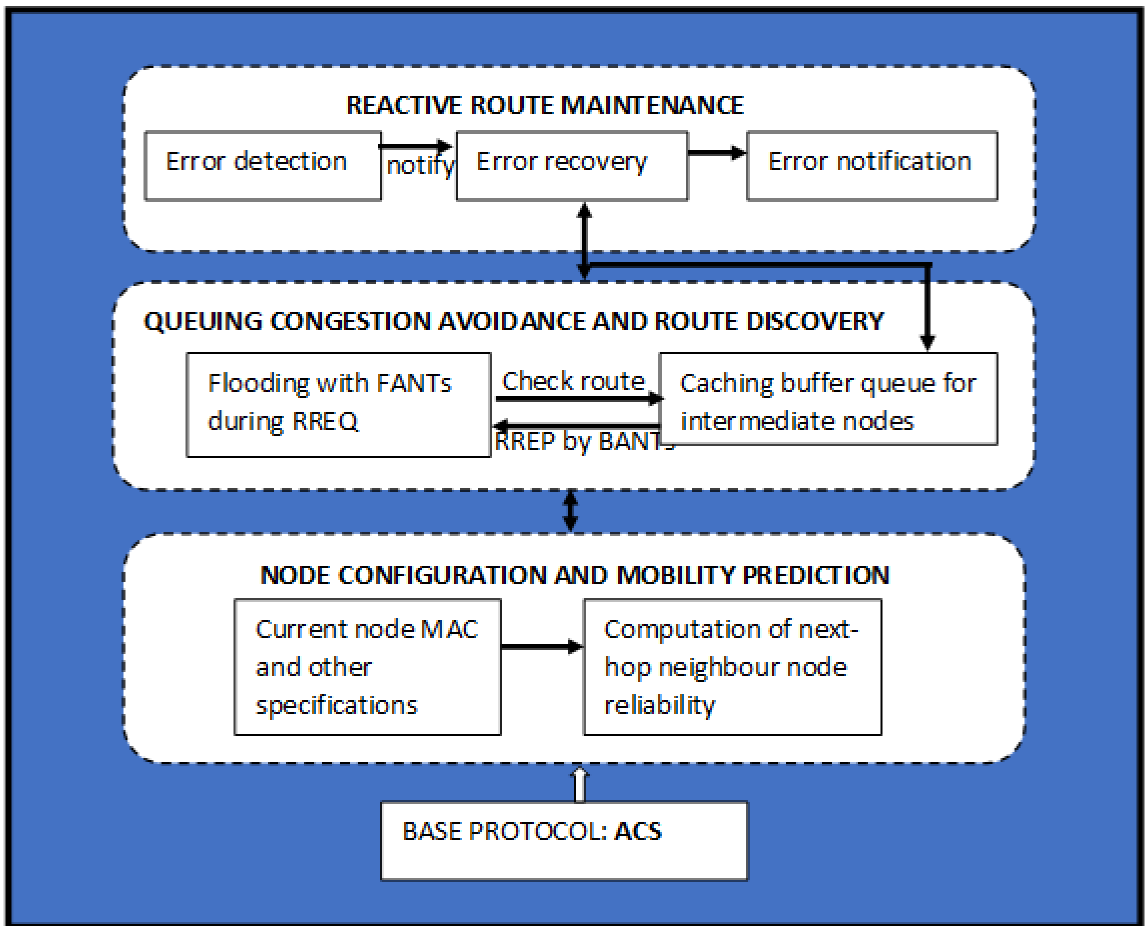

Figure 3.7 Proposed QUACS routing method architecture

The base routing protocol is ACS. The proposed routing method builds from the conventional ACS system operation, whereby mobile ants are released, is also found in ACS. The other sections of the QUACS routing method are explained in the following sections.

3.10.5 Mobile nodes configuration and node mobility prediction

Mobile nodes in MANET devices communicate using radio signals with nodes that are within each other's communication range. Mobile nodes perform two-fold duties; first as source or destination node, and then secondly as routers. Most of the wireless devices nowadays are equipped with a Global Positioning System (GPS), where each mobile node's position can be determined. The position of the nodes is assumed to be the *x-y* Cartesian coordination plane. Each node's time is synchronised to a GPS clock. Mobile devices will be assigned the same clock time at any moment. Mobile nodes that have greater link reliability (with reliability ranging from 0 to 1) close to one are those that are one-hop away from each other and can communicate directly. Nodes close to each other are assumed to have greater link reliability than those that are a further distance away from each other.

The process of calculating mobility involves calculating reliability of each one-hop neighbour from the source node. Assume the initial positions of node i and j having *x-y* coordinates (x_1, y_1) and (x_2, y_2) and the nodes move with random velocities in a direction with angles ϕ and Ω with respect to the *x*-axis. Then, the amount of time the link denoted by $T_{ij}(t)$ between node *i* and j can stay connected (also known as neighbour reachability time) at time *i* is calculated using equation 3.22.

$$T_{ij}(t) = \frac{-(ab+cd)+\sqrt{|(a^2+c^2)*R^2-(ad-bc)^2|}}{a^2+c^2} \tag{3.22}$$

$$a = v_i\,(t)Cos\Theta\phi(\mathrm{t}) - v_j\,(t)Cos\Theta\Omega(\mathrm{t})$$

$$b = x_i\,(t) - x_j(t)$$

$$c = v_i\,(t)Sin\Theta\phi(\mathrm{t}) - v_j\,(t)Sin\Theta\Omega(\mathrm{t})$$

$$b = y_i\,(t) - y_j(t)$$

$R\ is\ the\ maximum\ transmission\ range\ between\ node\ i\ and\ j.$

The importance of knowing neighbour reachability time, is to determine which next-hop neighbours will be stable for a reasonable window period. This helps to minimise sending data packet on the nodes which are not stable, and hence resulting in increasing average end-to-end delay and decreased throughput. Pseudo code 3.2 is for determining link stability factor in a MANET.

Pseudo code 3.2: Link stability factor computation

```
INPUT:    Number of nodes {n_1,n_2,n_3, ..... n_m}, FANT and BANT set {a_1,a_2,a_3, ..... a_n},
          Simulation time (T), Source node (S), Destination node (D)
OUTPUT: Vertices of nodes with and their respective stability factors
--------------------------------------------------------------------------------
procedure
while t≤ T || i ∈ G(t)                  //G(t) MANET at time t do
Step 1: if S! =D || initialisation memory = {} then
        configure GPS on to get the x-y coordinates of each mobile node in the network
        S broadcast HELLO message to determine one-hop neighbours with its MAC address
Step 2:   for each next-hop neighbour from current node
          computes T_ij(t) using equation 3.22
          save each T_ij(t) value for next-hop neighbours in memory i.e. push (M, node)
Step 3:   at each intermediate node do
          if visited node in pheromone table! = null then
            drop the packet i.e. node visited before since T_ij(t) is known
              else
Step 4:   for each node within R of i
          compute T_ij(t) using equation 3.22
          save in cache memory the T_ij(t) values for each next-hop
          end for
         end if
Step 5:  until D is reached
        end if
  end while
end procedure
```

3.10.6 Queuing congestion avoidance and route discovery

Congestion avoidance using queuing theory from co-operating nodes on the network is vital for the survivability of MANET. Every node in the MANET calculates congestion values considering the buffer occupancy using equation 3.2. The buffer occupancy congestion metric ranges from 0 to 1 [18]. The congestion value of 1 indicates that the buffer is full and any data packets that continue to come will be dropped using equation 3.3. A buffer congestion metric value of 0 indicates that the buffer is empty. The FANTs generated by the source node capture the information on the number of hops passed from source node to the destination node. FANTs capture information like congestion status on each intermediate node that it passes through. There is checking of the buffer congestion metrics for each next-hop neighbour. When the FANT reaches the destination, it calculates overall congestion metric (OCM) using equation 3.20.

The congestion metric is computed per hop. Assuming a MANET (see Figure 3.8) where some FANTs have been generated by the source node N_1 to destination N_5, the FANTs can choose different routes. If the hop count is the only metric to be considered the data packet will be relayed through (N_1, N_3, N_5) instead of (N_1, N_2, N_4, N_5). However, the shortest route in accordance with hop count might experience some challenges due to congestion on the links. Some data packets that might be waiting for some time to be processed due to limited buffer storage being full, may end up being dropped. Therefore, it is important to consider the congestion on the routes found from the source to the destination, before choosing the optimum shortest path. A good routing protocol should ensure high throughput, and less end-to-end delay, among other metrics for comparison of routing methods.

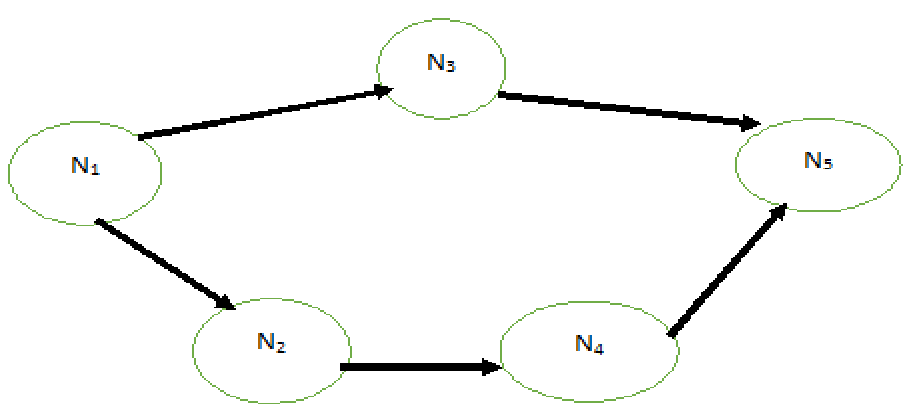

Figure 3.8 MANET multi-hopping and determination of congestion links

The *CM* from each node needs to be calculated, that is, congestion metric from $N_1 - N_3$ and $N_3 - N_5$ and likewise the congestion metric from $N_1 - N_2$, then $N_2 - N_4$ and finally $N_4 - N_5$. The overall congestion metric for any route chosen will be the one that has the minimum OCM level and is computed again using the formula:

OCM= $N_1 - N_3 - N_5$5 is =*min [CM (*$N_1 - N_3$*), (*$N_3 - N_5$*)]* and similarly the congestion level for route ($N_1 - N_2 - N_4 - N_5$)=*min [CM (*$N_1 - N_2$*), (*$N_2 - N_4$*), (*$N_4 - N_5$*)*]. A route that has the lowest OCM is chosen over the other paths that have higher overall OCM.

Once the congestion metric of the path has been identified and the FANT has reached the destination, the BANTs are generated at the destination node. BANTs inherit the data metrics that would have been captured by the FANT and retraces the route from the destination node towards the source node. When the BANT retraces the path from the source, it updates the pheromone on the path using equation 3.23.

$$P(i) = P(i) + r^0(1 - P(i)) + (r^0)^2) * Th/C \tag{3.23}$$

And unused routes pheromone is decreased using equation 3.24.

$$P(i) = P(i) - r^0 * P(i) - (r^0)^2) * Th/(C(|Neighbours| - 1)) \tag{3.24}$$

where *P(i)* is the current pheromone on the node prior to update, r^0 is reinforcement factor, Th is the highest pheromone value in all the neighbours at the current node. *C* is a constant set to 1000 since simulations were done in milliseconds (ms).

The pheromone updating is done by the BANT for each hop from the destination back to the source. Using Figure 3.8, the pheromone will be updated for path 1 from $N_5 - N_3$ and $N_3 - N_1$ and similarly for path 2 from $N_5 - N_4$, then $N_4 - N_2$ and lastly $N_2 - N_1$. The route that has a higher probability of being chosen for routing of data packets will be one that has the lowest overall congestion metric. Alternative paths are kept in a BANT memory stack, in case, the chosen shortest route nodes become overloaded with data packets.

3.10.7 Development of the QUACS routing protocol

Pseudo code 3.3 is for the proposed congestion avoidance routing from a queuing theory perspective. The pseudo code involves checking if the link from the source to the destination has been found before, which means the route exists. Previous routes can be used provided there has been no changes on the network. If there are some changes on the network, pheromone values are equally distributed on the next-hop neighbours from the current node (Step 3 of the Pseudo code

3.3). The next step involves checking the stability factor [stability factor ∈ (0,1)] of next-hop neighbours as proposed in Pseudo code 3.2 and the nodes with greater than 0.6 stability have an equal chance of being selected. Nodes with stability factor less than 0.6 are considered unstable and they are purged from the network in favour of more stable routes. Otherwise, FANTS are released towards the destination node. Congestion metrics at each relay node towards the destination node is computed. The route with the lowest overall congestion metric is chosen as the best route for sending data packets from source node to the destination node, as shown by the Pseudo code 3.3.

Pseudo code 3.3: Congestion avoidance from queuing theory perspective

INPUT: Number of nodes $\{n_1, n_2, n_3, \ldots. n_m\}$, FANT and BANT set $\{a_1, a_2, a_3, \ldots. a_n\}$,
Simulation time (T), Source node (S), Destination node (D), Stack counter (N)= {},
TTL: =0

OUTPUT: Vertices of nodes with highest pheromone count, Congestion metric of each node,
Shortest Path

procedure

Step 1: randomly generate S and D from the domain of nodes in G(t)

Step 2: is path S to D previously found

if no **then**

go to Step 4

else

Step 3: Are there new nodes or any nodes that have left the previous identified next-hop neighbours?

if yes **then**

use Pseudo code 3.2 to computer next-hop nodes stability and Step 4 to purge some nodes

probabilistically reassign pheromone values equally as $\frac{1}{n}$ // where n is number of next-hop neighbours after checking on the stability of next-hop neighbours

else // no changes in the network since the establishment of the previous shortest path

go to Step 8

end if

end if

Step 4: check on the next-hop neighbours stability using Pseudo code 3.2

if all next-hop neighbour nodes have stability factor > 0.6 **then**

any of the nodes can be chosen in routing of data packets // the nodes are assumed to be stable

else

if next-hop neighbours have other nodes with stability>0.6 and other next-hop nodes with stability factor less than 0.6 **then**

purge the nodes whose stability factor is less than 0.6 the nodes are less stable and can move out of the network //most scenario found in wireless networks

else **//** a rare case where all nodes have stability factor less than 0.6

all nodes are eligible for selection though chances of nodes moving out of the network is high

end if

Step 5: with the remaining nodes **do** // after pruning/purging of nodes

Step 6: initialise pheromone values on all vertices // pheromone of all one hop neighbours must add to 1

Step 7: FANTS are generated // FANTs are control packets generated to find route from S to D

for each FANT in queue

if current time==time of sending FANT ^TTL<128 **then**

check buffer size and availability of next-hop nodes neighbour using equation 3.1

else

Step 8: Computation of buffer space availability

//periodically compute buffer space availability every 2 seconds

for every 2 seconds **do**

if node buffer storage space=full // equal to 1 **then**

notify S that the route congestion is high on the node

else // buffer storage space is available on next-hop node

use equation 3.2 to computer to compute CM

end for

compute next-hop neighbour overall congestion metric at each intermediate node for each path using the formula path $i=1*CM_1*CM_2*......*CM_n$ // where n is current node

push (N, current node) // increment the stack counter by 1

TTL←TTL+1 //increment TTL by 1

if TTL>128 //reached maximum limit on the number of hops **then**

drop the FANT

else

until D is reached

end if

end if

end if

end for

Step 9: **if** current node= D //arrived at destination node **then**

bubble sort the overall congestion metric found on paths from S to D

select $path\ k$ that has the lowest overall congestion metric value as shortest path

terminate FANT and its content are copied to the newly to be created ant called BANT

create BANT

else

if current node= visited before //prevent looping

clear ant's memory contents

empty the contents of the N

else

current node is assigned as the next-hop node towards S

end if

end if

Step 10: **while** TTL>0

N←N-1 //decrement N by 1

if current node=S **then**

exit

else

pop (N, current node)

// update pheromone on the next-hop that has greatest amount of pheromone and decrease pheromone concentration on other next-hop neighbours that have lower pheromone values

if current node was in the path of FANT **then**

// reinforce the path that has the least overall congestion metric value

update pheromone using equation 3.23

else //reduce pheromone levels on other next-hop neighbours

update pheromone using equation 3.24

end if

end if

end while

Step 11: **for** i=1 to number of next-hop neighbours //until D node is reached

Compute the pheromone from S to D after BANT visit

Save the pheromone route with the highest value of and it will be in the shortest path

Return path with the highest pheromone values

end for

end procedure

3.10.8 Route discovery and maintenance

A broken link between nodes results in route failure on the network. If an intermediary node does not receive periodic Hello message packets from neighbours in its routing table, it is assumed that there has been a link failure. New routes should be established. The nodes that have encountered broken links update their pheromone tables for that missing neighbour node to 0. The new data packets coming in are buffered in a queue waiting for the new routes to be established at the relay node. When the queue is full upcoming data packets probability of being lost is computed using equation 3.3.

Notification ants are sent to the source node regarding changes in the route(s). When the local repair process fails to find the route, an error message will be sent to the source node to start the whole route discovery process. New FANTs will be released by the source node to initiate the new shortest route discovery process. The proposed QUACS routing method checks for pheromone values for all the neighbour nodes. However, only the one with the greatest pheromone will be used for communication after checking its limited buffer space occupancy position.

3.11 ROUTING PROTOCOL PERFORMANCE METRICS

New routing methods are usually compared to the already existing routing protocols for performance. Performance metrics can be used to gauge if the proposed protocols are better in relation to other routing protocols that have been devised before. A variety of performance metrics exists to measure the performance of proposed routing protocols in MANET networks relative to other routing protocols. The performance of routing protocols is evaluated against a number of metrics such as: packet delivery ratio, average end-to-end delay, average jitter, network lifetime, routing overhead and throughput amongst other routing metrics.

3.11.1 Packet delivery ratio

Packet Delivery Ratio (PDR) is the ratio of the number of data packets successfully received by the destination node to the number of data packets sent by the source node. PDR measures how effective the routing protocol delivers the data packets to the destination node. PDR routing metric does not take into consideration the number of control packets that are needed to establish the route from source node to the destination node. PDR only focusses on the actual data packet sent and data packets received on the wireless MANET network. It is computed using equation 3.25.

$$PDR = \sum_i \frac{Number\ of\ data\ packets\ delivered}{Number\ of\ data\ packets\ sent} * 100 \tag{3.25}$$

where i, is the i^{th} data packet

A good routing protocol should have a high value of PDR. New routing protocols endeavour to have a high PDR relative to the other routing protocols that have been developed before from literature. A high PDR value is required for any routing protocol [5]. PDR is measured in percentage terms or decimal values.

3.11.2 Average end-to-end delay

Average end-to-end delay is the total delay the data packets encounters from the source node to the destination node. It is the difference between times from when the data packet was sent to the time the data packet was received by the destination node. The average end-to-end delay includes delay encountered on the network due to queuing or congestion on intermediate links during multi-hopping, processing and propagation delays. Average end-to-end delay is computed using equation 3.26.

$$\text{Average end} - \text{to} - \text{end delay} = \sum(Packet\ i\ arrival\ time - Packet\ i\ sent\ time) \quad (3.26)$$

A lower value of average end-to-end delay indicates that the data transmission on the network is fast. So, a low value of average end-to-end delay indicates that the MANET routing protocol is better. A new routing protocol should also strive to have a low average end-to-end delay. Average end-to-end delay is measured in seconds, milliseconds or microseconds

3.11.3 Average jitter

Average jitter is the delay that occurs when a data packet does not reach the destination node on expected time. According to [84], average jitter is reference clock source. Jitter is present in all communication on wireless network and it can be observed in characteristics such as signal amplitude, frequency of successive pulses. Average jitter is measured in seconds, milliseconds or microseconds. Average jitter is computed using equation 3.27.

$$Average\ jitter = \sum_{i=0}^{m}(Delay_i - Average\ delay)^2\ /N \quad (3.27)$$

;where N is number of node and i is i^{th} data packet. A good routing protocol is associated with a low average jitter as data packets are delivered to the destination nodes as per the expected delay along the links.

3.11.4 Network lifetime

Network lifetime is the time when the network is functional with all the nodes being active and can be chosen for relaying data to other nodes on the MANET network up to the time when at least one node drains its energy completely [125]. The time when a network is considered non-functional is usually application specific [48]. The time when the first node ceases to be part of the network as a result of battery power depletion or the percentage of mobile nodes that ceases to be part of the network over a given period of time, measures the network lifetime of the MANET network.

When a node ceases to be part of the wireless network, there is reconfiguration of the nodes and new routes have to be established between source and destination nodes and this affects the performance of the whole network. It is worth noting that with nodes in the network with high battery power, chances of high network lifetime is increased depending on dynamism of the MANET network.

3.11.5 Routing overhead

Routing overhead or control overhead is the number of control packets that are sent between the source and destination node, to establish the path or route and maintain the routes that the data packet can be send through. Routing overhead is thus the ratio of non-data packets (control packets) to the total number of data packets received during the simulation time. A good routing protocol should use less control packets to establish the routes between source and destination node. Routing overhead is computed using equation 3.28.

$$Routing\ overhead = \frac{Number\ of\ control\ packets\ sent}{Number\ of\ data\ packet\ received} \tag{3.28}$$

Routing overhead is thus the measure of amount of effort that is expended by the wireless MANET in order to maintain the routes between source and destination node(s).

3.11.6 Throughput

Throughput is the amount of data packets that are successfully transmitted from the source node to the destination node over a given period of time. A high throughput is desirable for a wireless ad hoc network routing protocol since many data packets can be transmitted in a short period of time between the sending and receiving node(s). Throughput can be computed using the formula,

$$Throughput = \sum_{t=0}^{n}\left(\frac{Number\ of\ packets\ delivered}{Time_n - Time_0}\right) \tag{3.29}$$

Thus, throughput is the number of bits that has been successfully delivered to the destination node for the duration of a session.

3.12 EXPERIMENTAL TOOLS USED

The two newly developed routing protocols that are queuing theory hybridised with ant colony system and particle swarm optimisation respectively has been embedded in the Network Simulator 2 (NS-2). Simulations are run using NS-2 to determine the performance of swarm-based routing methods relative to other nature-inspired based routing methods. NS-2 is an open source simulation tool originated from Lawrence Berkeley National Laboratory [17], [51]. It is targeted at networking research and based on discrete events simulations. The simulator is written in C++

programming language and it uses OTcl as a command and configuration interface. This means OTcl scripts are used to setup simulation scenarios in the simulator. One great benefit of this is that there is no need to recompile the simulator between different simulations since one will be capable of setting up topology, link bandwidth and traffic sources from the OTcl scripts [17].

NS-2 simulator provides substantial support for simulation of routing and multicast protocols over wired and wireless networks. It has an advanced 802.11 module, which is applied and verified extensively in the network community [17]. Events are inserted into a scheduling list upon request, together with their expiration time. The scheduler is responsible for going through the list and performing the necessary actions. Simulations in NS-2 can be logged to trace files, which include detailed information about received and transmitted packets and allow for post-run processing with some analysis tools. The simulation parameters that have been used with their justification is shown on Table 3.8 below.

Table 3.8 Simulation parameter values and their justification

Simulation parameter	Parameter justification
Simulation duration	The time that is required for nodes to be able to communicate with one another during the information exchange session. The simulation time is measured in seconds
Area of simulation	MANETs are confined to a small geographical area. The simulation area has been set to 1 000m* 500m
Mobility model	The mobility model is designed to describe the movement pattern of mobile users, and how their location, velocity and acceleration change over time. Mobility patterns has a critical role in determining the protocol performance. Mobility models should usually emulate the movement pattern of targeted real-life applications. Random Way Point mobility model has been used in simulation because of its spatial distribution of nodes which move randomly in the network. The Random Way Point is simple and widely used in simulation MANETs
Medium Access Protocol used	IEEE 802.11 Distributed Coordination Function was used because it is a popular protocol that is used for physical and medium access control (MAC) layers in MANETs
Data packet size	Data packets are divided into chunks for routing across the MANET. Small chunks of 512KB were used.
Node maximum buffer size	MANET nodes have limited storage memory. The amount of data that can be accommodated by a node has been set to 25600KB (that is a maximum of 50 data packets). Any data that comes after the queue is full will be lost.
Radio transmission range	Radio waves are used to communicate. Nodes have a range that they can reach to other nodes that are one-hop away. The maximum radio range has been set to 100 metres for one-hop neighbours.
Channel bandwidth	Limited bandwidth is shared among nodes that communicate in MANET for effective quality of service in MANETs. The bandwidth to be shared has been set to 2MB.
Maximum node mobility speed	Since Random Way Point is used, nodes are not stationary. The maximum mobility speed they can move has been set to 30m/s in this study.
Traffic model	Nodes send data packets to one-hop neighbours over the wireless channel at a deterministic data rate hence the Constant Bit Rate was used.

3.13 CHAPTER SUMMARY

In this chapter, queuing adaptation to MANET battery life has been presented. Two new routing protocols based on the swarm intelligence have been presented. These swarm-based routing methods have been termed Q-PSO and QUACS. They are both hybridised with queuing theory. Q-PSO is based on particle swarm optimisation technique whilst QUACS is based on ant colony optimisation.

The developed routing protocols which are all swarm-based are based on the concept of queuing theory. Nodes' limited buffer is explored before choosing the next-hop neighbour as the possible route towards the destination node(s). Numerical computations involving single path and multipath routing were done and the results showed that multipath routing approach is better relative to single path routing. The superiority of multipath routing can be attributed to fault tolerance, reduced delay in case of route failure because there are multiple redundant paths as well as load balancing which is not the case with in single path routing. NS-2 simulator tool was presented. Newly developed protocols for ad hoc network are usually measured for performance in relation to other established routing methods. The metrics that are generally used to measure performance of new routing protocol include: packet delivery ratio, average end-to-end delay, average jitter, routing overhead, network lifetime and throughput. Tools used in simulation together with justification of the simulation parameters concluded this chapter.

CHAPTER 4. Q-PSO EXPERIMENTAL EVALUATIONS AND RESULTS

4.1 OVERALL EXPERIMENTAL SETUP

Network Simulator 2 (NS-2) is an open source simulation tool that runs on Linux operating system which has been used in this study to evaluate the performance of the newly developed routing protocols [52], [126], [127] . NS-2 is an open source simulation tool originated from Lawrence Berkeley National Laboratory. It is targeted at networking research and based on discrete events simulations. NS-2 simulator provides a lot of information particularly on simulation of routing and queuing, multicasting in both wired and wireless networking environments. NS-2 also supports Transmission Control Protocol (TCP), User Datagram Protocol (UDP), Realtime Transport Protocol (RTP) and Scalable Reliable Multicast (SRM) which make it possible to simulate all types of data traffic. Various versions of NS simulators are available, and these include NS-1, NS-2 and NS-3. NS-2 runs on various operating systems such as Linux, Sun Solaris, MacOS X, FreeBSD and Windows operating systems once a package called Cygwin has been installed.

The NS-2 simulator is written in C++ and it uses object-oriented Tool Command language (OTcl) which is an extension of Tool Command Language (TCL) as a command and configuration interface. TCL is a dynamic programming language that is compatible with C programming language widely used in networking, administration and desktop application. This means that OTcl scripts are used to setup simulation scenarios in the simulator. One great benefit of this is that there is no need to recompile the simulator between different simulations since one will be capable of setting up topology, link bandwidth, traffic sources etc, from the OTcl scripts.

The idea of a discrete event scheduler is that actions may only be started as a result of an event. In NS-2, this is taken care of by a scheduler and a scheduling list. Events are inserted into a scheduling list upon request, together with their expiration time. The scheduler is responsible for going through the list and performing the necessary actions.

Simulations in NS-2 can be logged to trace files, which include detailed information about received and transmitted packets and allow for post-run processing with some analysis tools. Network Animator (NAM) is a TCL based simulation which emulates the behaviour of the real network. It is capable of collecting and visualising patterns and trends of communication among various nodes on the network. The NAM collects the NAM file which has been generated by the NS in simulation run of the network and a trace file (graphical output of the input data after simulation). Trace file consists of 12 fields namely: event, time, from node, to node, packet type, packet size, flags, fid (flow id), source address, destination address, sequence number and lastly packet id. This is depicted in Figure 4.1.

Event	Time	From node	To node	Packet type	Packet size	Flags	Fid	Source add	Dest add	Seq. no.	Packet id

Figure 4.1 Components of a trace file

The event field can take four symbols which are $\boldsymbol{r}$ for receive, $+$ for enqueued, $-$ for dequeued, and $\boldsymbol{d}$ for dropped. The time field shows the unit time when the event occurred. The $\boldsymbol{from\ node}$ and $\boldsymbol{to\ node}$, represents the input and output node where the event takes place. Then a packet type can be a Constant Bit Rate (CBR) or TCP. Packet size is the size of data packets that are being sent. Flow id (Fid) represents flow indemnities which can be used for analysis of data traffic patterns. Source add (source address) and dest add (destination address) are source and destination address of the nodes where data originates and where they will be finally received respectively. Each data packet sent across the network should be unique and this is achieved through the use of different sequence numbers.

Trace graphs which can either be statistical or graphical results are generated from trace files described above. Trace files generated during simulations can be used to produce graph using MATLAB. Figure 4.2 shows how one can run NS-2.

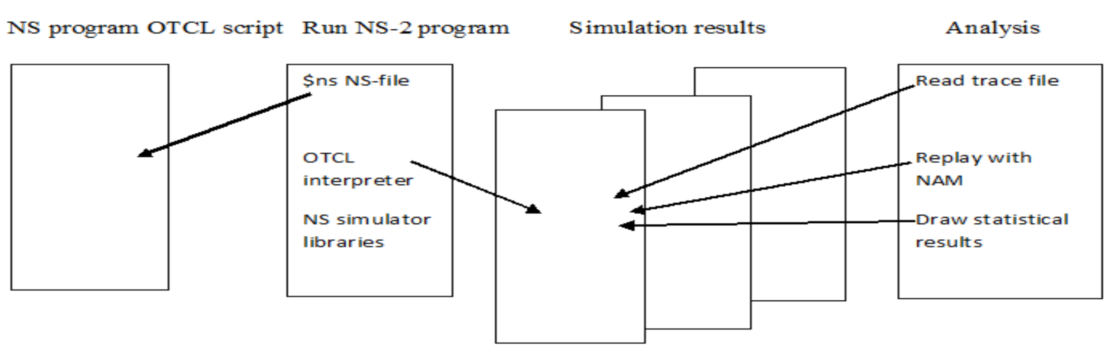

Figure 4.2 Running NS-2 programme

The experimental design of simulations was conducted. The following assumptions of NS-2 simulator were taken into consideration during the design of the experiment;

- All nodes which make up part of the MANET are homogeneous. This means that the nodes all have the capabilities of acting as source or destinations nodes. Again, they can perform the function of routers where they relay data packets to the next node if data packets are not destined for itself
- All nodes in MANET networks have the same data transmission range. In this study the transmission range has been varied with the maximum transmission range set to 100 metres.
- There is bidirectional transmission (communication can take place in either direction) of data packets. The use of sequence number enables checking if the node route has been saved as a potential route before to avoid looping.
- The number of nodes were also varied with the maximum nodes in the MANET network being 150 nodes.

4.2 EXPERIMENT 1: EVALUATION AND VALIDATION OF Q-PSO IN SINGLE PATH SCENARIO

4.2.1 Introduction and experimental setup

Network Simulator version 2.35 has been used to validate the results of the proposed Q-PSO routing method in single path routing scenario. NS2.35 is an open source simulation tool that is targeted for use in networking research and is based on discrete event simulations [52], [126]. Table 4.1 shows the simulation parameters used in the experiment.

Table 4.1 Simulation Parameters used

Simulation parameter	Values used
Simulation duration	240seconds
Area of simulation	1000m*500m
Mobility model	Random Way Point
Medium Access Protocol used	IEEE 802.11 Distributed Coordination Function
Data packet size	512KB
Node maximum buffer size	25600KB (that is a maximum of 50 data packets)
Radio transmission range	100metres
Channel bandwidth	2MB
Maximum node mobility speed	30m/s
Traffic model	Constant Bit Rate
Maximum number of nodes	150

The Q-PSO routing method is benchmarked against other energy-aware routing methods to check if the performance of the proposed routing method is better than those of the existing routing methods. The node mobility was varied from 10m/s being the lowest, to a maximum mobility of 30m/s. Simulations have been run for more than once to ascertain the validity of the results.

For the purposes of showing the performance of the proposed Q-PSO routing method, it is going to be compared against other PSO-based routing methods such as: Ant Colony Optimisation with Endocrine Co-operative Particle Swarm Optimisation (ACO with ECPSOA) [128] [129], Improved Multi-Objective Particle Swarm Optimisation (IMOPSO) [130] [131] and the popular AODV routing methods. The simulation results of the propose Q-PSO routing method is going to be evaluated in terms of the following performance metrics:

- **Average End-to-end delay -** is the average time that data packet takes to be transmitted from the source node to the destination node.
- **Communication/Routing overhead** - is the amount of required information of control packets which should be embedded in the data packets so that the data packets reach their

intended destination(s). Routing overhead is ratio of number of control packets sent to number of data packets received.

- **Average Jitter -** is the variation in time between the arriving of data packets caused by congestion on the links between the intermediary nodes between the source node and the destination node.
- **Network lifetime -** evaluates the time when the first member node's battery power gets depleted.
- **Packet delivery ratio (PDR)-** is the ratio of the amount of data packets sent to the actual number of data packets that are received by the destination node(s).

Q-PSO routing method is going to be compared against other PSO-based routing methods such as: IMOPSO, ACO with ECPSOA and the popular AODV routing methods using under same conditions and similar seeds (initial parameters). All data traffic sessions were generated in parallel routed to different destinations in order to test whether the newly developed routing protocols were efficient on route discovery and maintenance relative to the other routing protocols in comparison.

The nodes wireless interface was configured to cover the area of 1000m*500m with data transfer rate of 11mbps since all wireless node models are associated with IEEE 802.11 interfaces. The standard random way point (RWP) mobility model was employed to initiate the nodes motion and the uniform generation speed ranging from 5m/s to 30m/s were used in this study. The nodes were allowed to move freely in the area 1000m*500m while assigning different battery levels and different mobility speed to the nodes.

4.2.2 Discussion: Varying number of nodes and its impact on packet delivery ratio in single path

Figure 4.3 shows the PDR for the routing protocols under comparison. It is evident that the Q-PSO's PDR is higher relative to the other routing methods in comparison. Regardless of the increase in number of nodes that join the network, its PDR remains above 90%. This is attributed to exploring the congestion status on the nodes and availability of multiple paths that can be utilised from the source node to the destination node thus Q-PSO is scalable as it consistently delivers data packets even when the number of nodes increases on the network because of clustering the network and having the communication for the member nodes being done by the cluster head nodes. It is worth noting the PDR was above 80% for all PSO-based routing methods. However, the proposed Q-PSO routing method has a PDR which was over 90% regardless of the number of nodes in the MANET network.

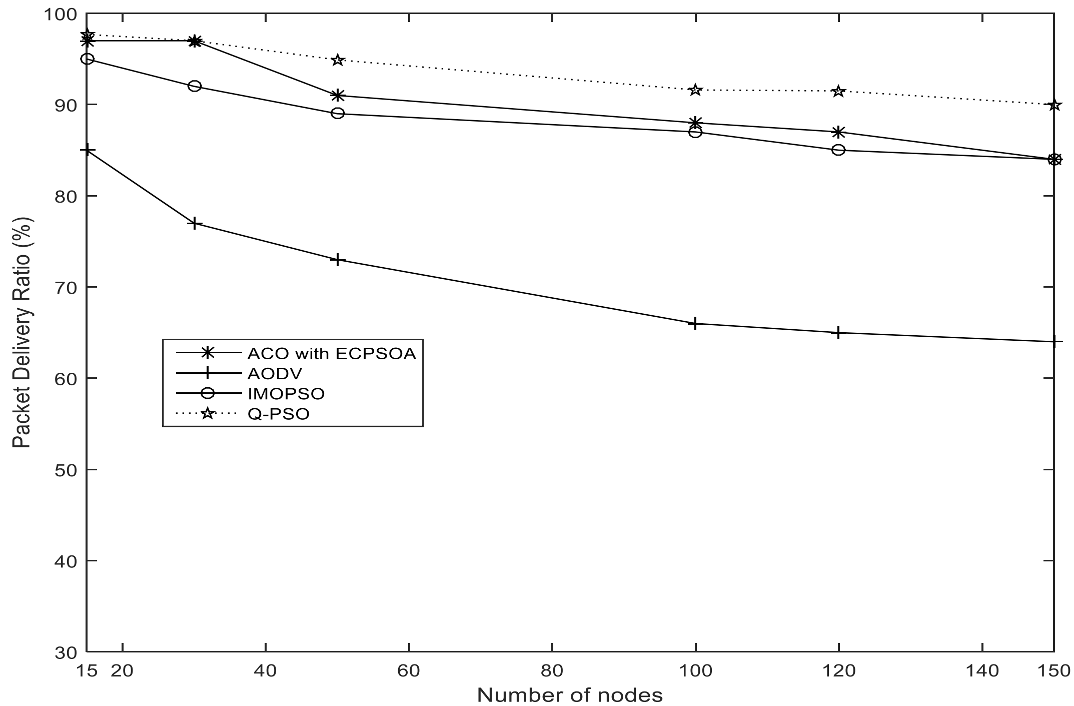

Figure 4.3 Packet delivery ratio in single path routing

4.2.3 Network lifetime

The lifetime of a network is measured as the time when the first node in the network's battery power is exhausted. From Figure 4.4, it has been observed that in the Q-PSO scenario, the first node battery is depleted at 1500 rounds. The ACO with ECPSOA and IMOPSO routing methods get the first node's battery depleted at the same time, that is at 1400 rounds. The Q-PSO battery is only exhausted after more iterations than those of the other three metrics (ACO with ECPSOA, IMOPSO and AODV) under comparison. The AODV routing method's first node battery is depleted after 900 rounds. The Q-PSO has the highest lifetime as compared to AODV, ACO with ECPSOA and IMOPSO methods.

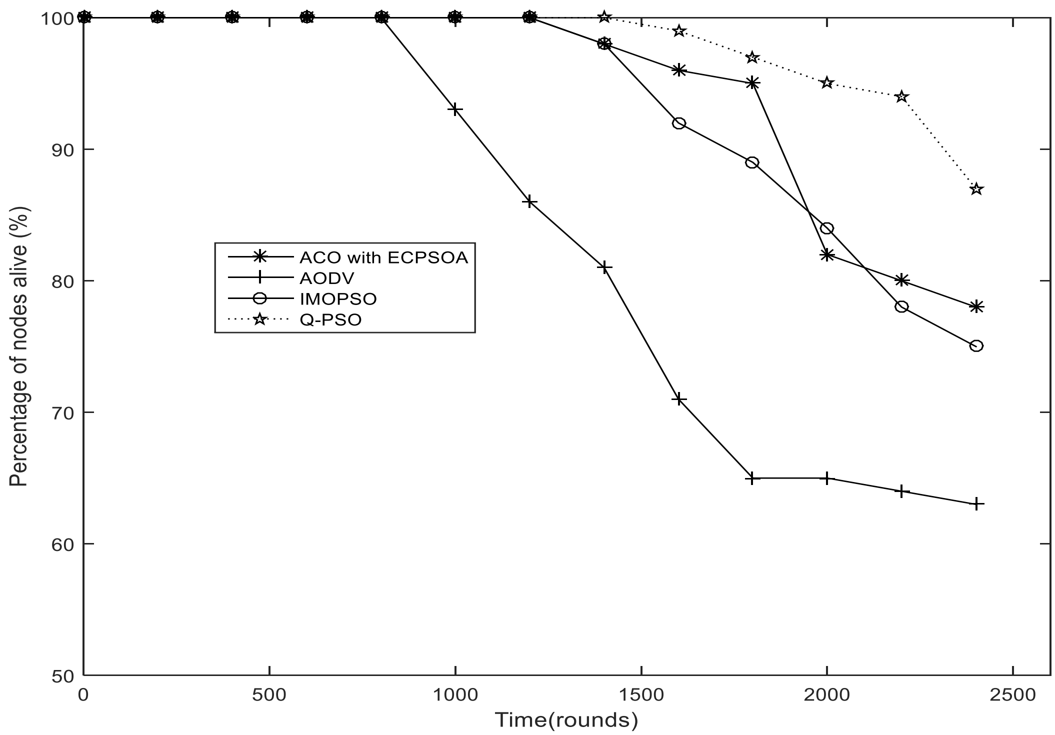

Figure 4.4 Network lifetime in single path Q-PSO

4.2.4 Discussion: Varying mobility on average jitter in single path

The Q-PSO has less jitter than the other three routing methods under comparison. The Q-PSO has less jitter values at different mobility speeds (see Figure 4.5). Regardless of node mobility, the average jitter of Q-PSO remain at less than 0.25seconds. The average jitter of other routing methods under comparison has an increase of jitter by around 7% when mobility changes from 10m/s to 20m/s. The other routing methods under comparison do not factor in the congestion metrics of the next-hop neighbours when deciding on the routing path for the data packets and hence their respective average jitters are much higher than that of the proposed Q-PSO routing method.

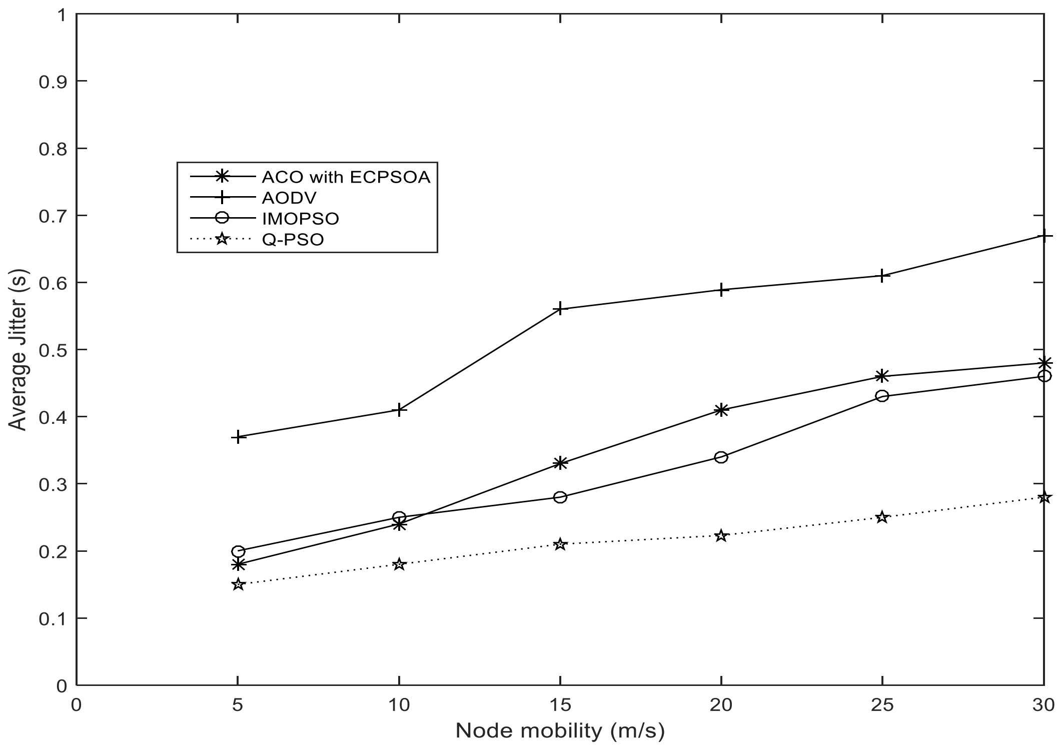

Figure 4.5 Node mobility speed versus average jitter

4.2.5 Discussion: Varying communication range on routing overhead in single path

A low communication overhead has been observed on Q-PSO relative to other routing methods under comparison. As communication range increases, there was a gradual decrease in the number of control packets sent from the source to the destination in Q-PSO and other routing methods as well (see Figure 4.6). At high communication ranges, there was some decrease in number of control packets required to establish the path from the source node, to the destination node for all the routing methods under comparison to the proposed Q-PSO. However, the number of control packets required to establish the routes from source to the destination node were less for Q-PSO as compared to ACO with ECPSOA, IMOPSO and AODV. This can be attributed to Q-PSO's ability to explore on next-hop neighbour nodes' residual energy and computation of congestion metrics on various paths to destination node(s). This ultimately minimises frequent route maintenance and updates as compared to ACO with ECPSOA, IMOPSO and AODV routing methods/protocols. The routing overhead is the ratio of the number of control packets sent to the number of control packets received, and therefore its unit of measurement is dimensionless.

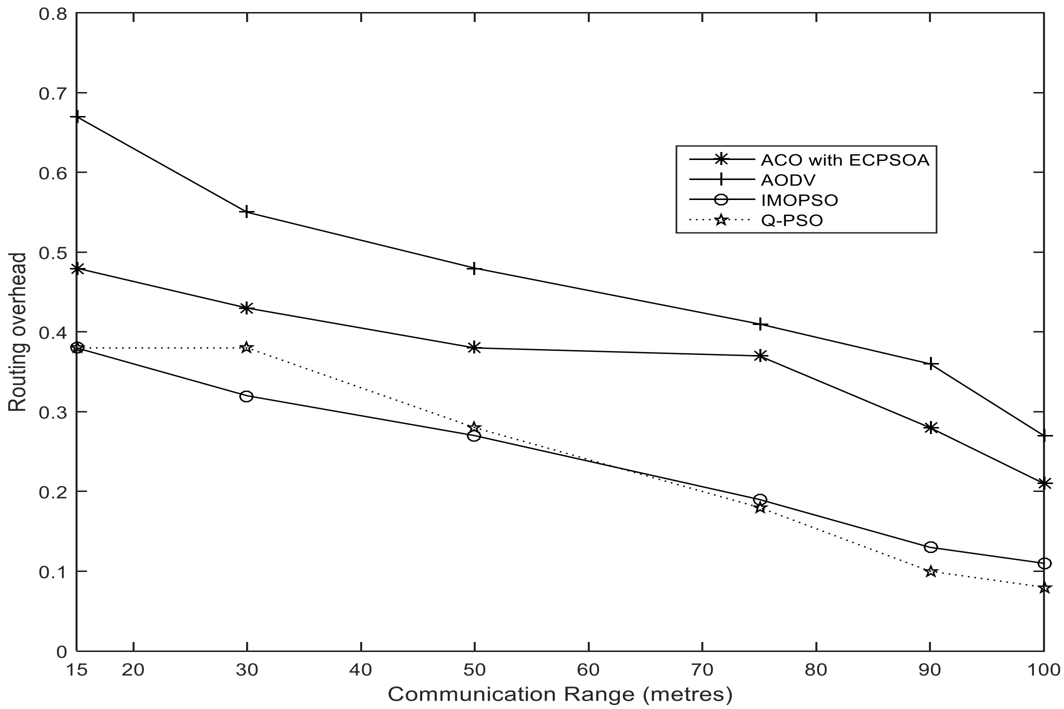

Figure 4.6 Impact of varying communication range on routing overhead

4.2.6 Discussion: Varying mobility on average end-to-end delay in single path

At different mobility speeds, Q-PSO outcompetes the rivals (ACO with ECPSOA, IMOPSO and AODV). This is because Q-PSO checks on the residual energy of nodes and the congestion metrics for the next-hop neighbours before selecting the route. At a high mobility of 30m/s, the average end-to-end delay in ACO with ECPSOA and IMOPSO increases to around 140ms, whilst for AODV it increases to over 350ms because of frequent route maintenance and subsequent exploration of new paths for routing data packets. The average end-to-end delay for the proposed Q-PSO remains almost the same around 100ms at different node mobility speeds.

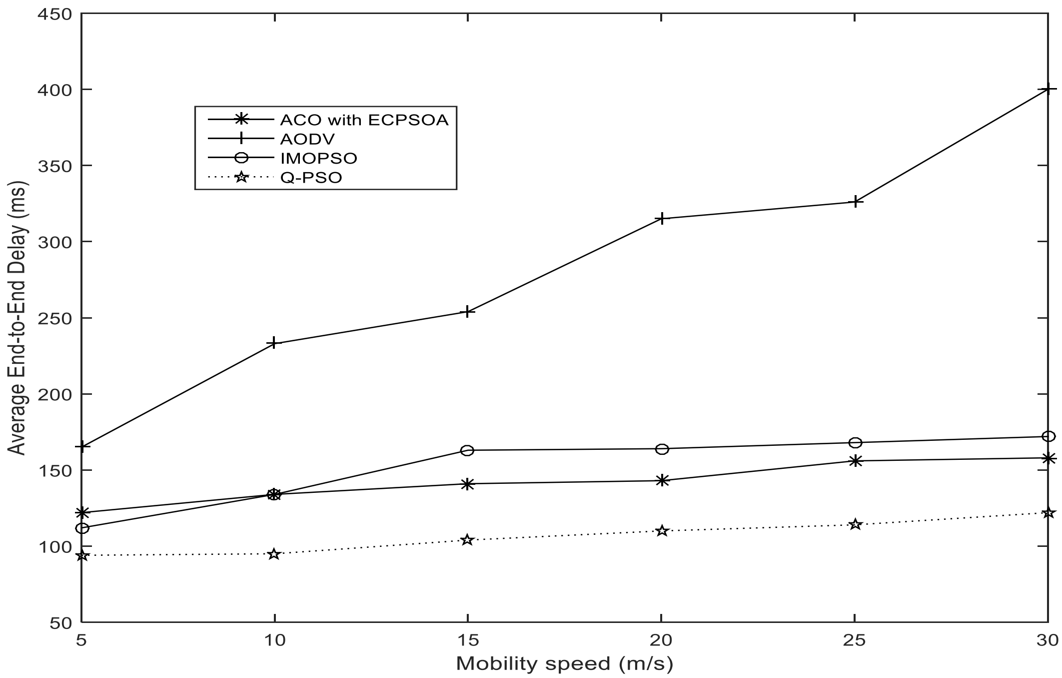

Figure 4.7 Node mobility speed versus average end-to-end delay

4.3 EXPERIMENT 2: EVALUATION AND VALIDATION OF Q-PSO IN MULTIPATH SCENARIO

4.3.1 Experimental setup

Q-PSO multipath routing method is an extension of single path Q-PSO routing, but with the additional functionality of storing in memory stack all the possible routes that have been found from the source node to the destination node. To implement and evaluate the performance of the proposed Q-PSO in multipath routing performance in relation to other routing protocols under comparison, NS-2 simulator was used together with the same conditions as tabulated in Table 4.1. 150 nodes were used in multipath path routing. RWP mobility model was employed to initiate the nodes motion and the uniform generation speed ranging from 5m/s to 30m/s was used. The nodes were allowed to move freely in the 2-dimensional space area 1000m*500m while assigning different battery levels and different mobility speed to the nodes.

4.3.2 Discussion: Varying number of nodes and its impact on packet delivery ratio in multipath routing

Figure 4.8 shows the PDR for the routing protocols under comparison. It is evident that the Q-PSO's PDR is higher relative to the other routing methods in comparison. Regardless of the increase in number of nodes that join the network, Q-PSO's PDR remain above 90%. This is attributed to exploring the congestion status on the nodes and availability of multiple paths that can be utilised from the source node to the destination node, thus Q-PSO is scalable as it consistently delivers data packets even when the number of nodes increases on the network because of clustering the network and having the communication for the member nodes being done by the cluster head nodes. In comparison with Q-PSO's PDR in single path (see Figure 4.3) there is a slight improvement of around 0.1% increase in the PDR ratio.

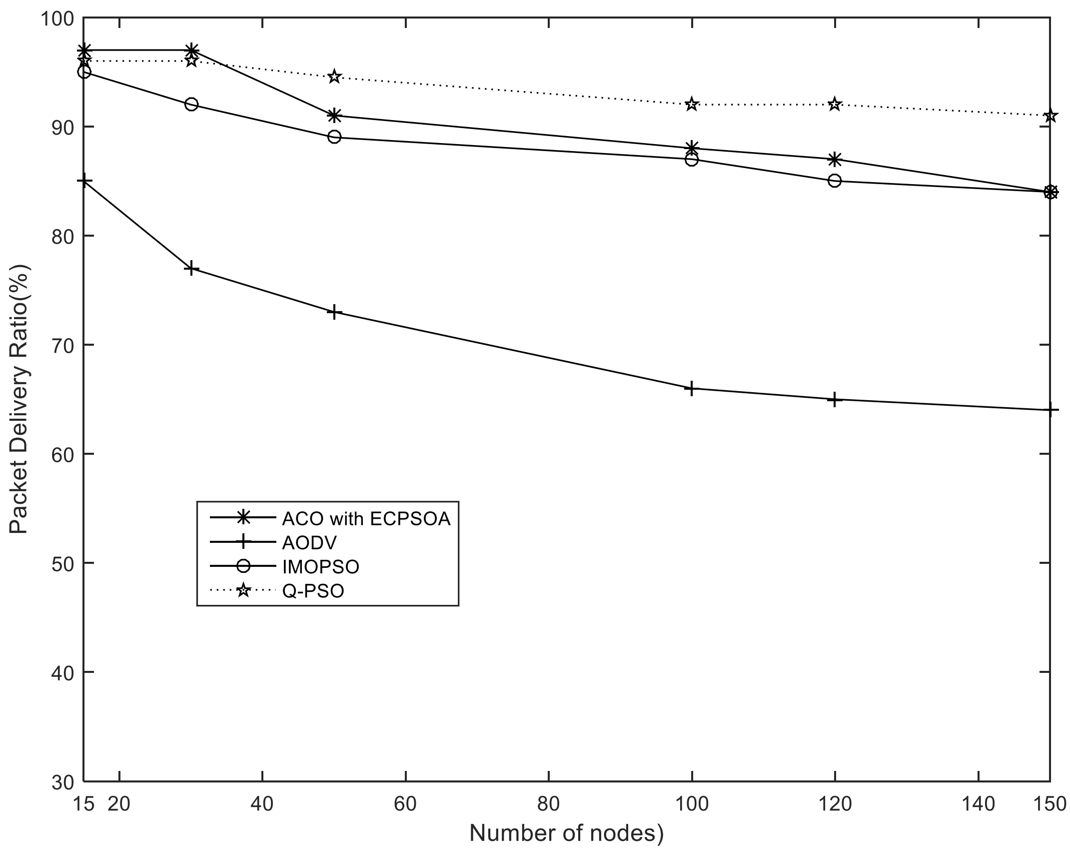

Figure 4.8 Packet Delivery Ratio in multipath routing

4.3.3 Network lifetime in multipath routing

There is a slight improvement in network lifetime, i.e., the round where the first node's battery power is exhausted in the multipath Q-PSO. In the multipath Q-PSO routing method, the first node's battery life is depleted after 1600 rounds as compared to 1500 in the single path Q-PSO (see Figure 4.4). This shows that the network lifetime improves slightly in a multipath scenario as compared to single path Q-PSO. The results shows that the multipath Q-PSO has a higher network lifetime as compared to ACO with ECPSOA, IMOPSO and AODV routing methods.

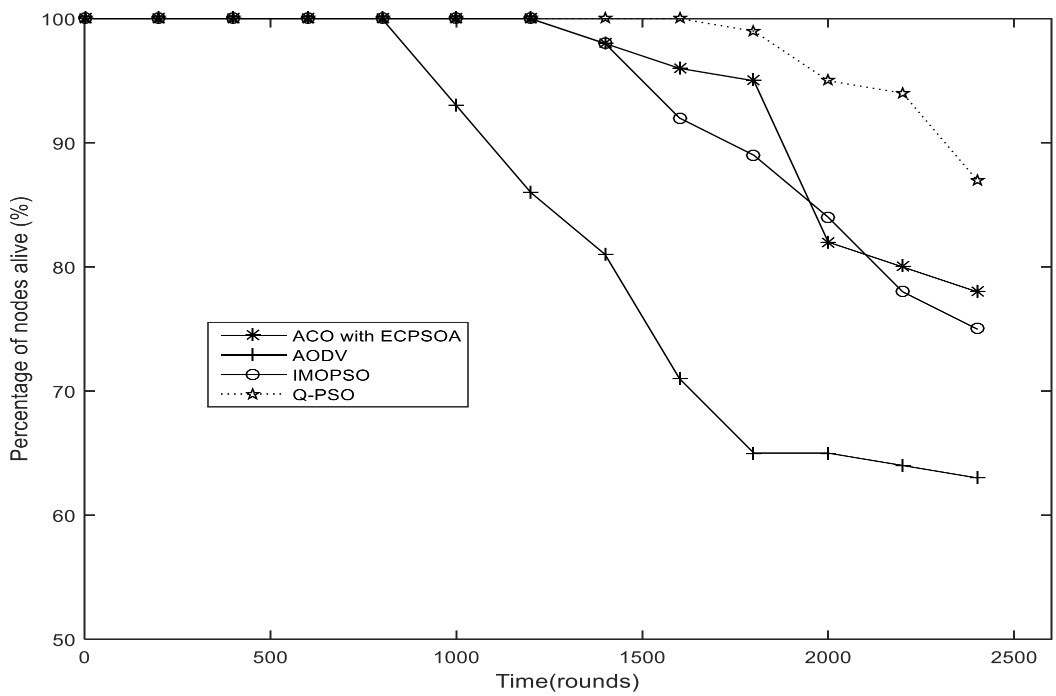

Figure 4.9 Network lifetime in the multipath routing Q-PSO routing

4.3.4 Discussion: Varying mobility on average jitter in multipath routing

The average jitter in the multipath Q-PSO is less than the other routing methods under comparison. Checking of congestion on various next-hop neighbours before choosing the routes has a positive impact on reducing the average jitter. There has been a slight decrease in average jitter by 20% in the multipath Q-PSO as compared to single path Q-PSO (see Figure 4.5) mainly because of availability of redundant paths as well as the overall congestion metrics to the destination node(s) that were identified during the route discovery stage. Thus, the average jitter for Q-PSO was less than 0.2seconds even when mobility increases to 30m/s whilst other routing methods under comparison had average jitter that is above 0.2seconds even at low mobility of 5m/s.

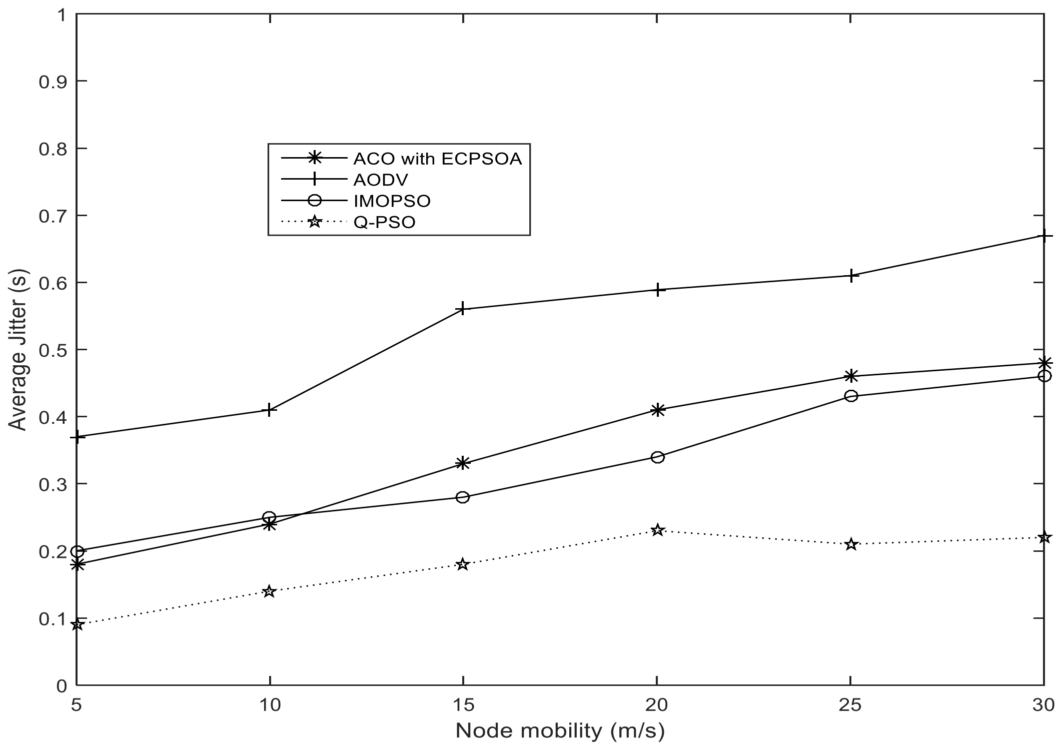

Figure 4.10 Varying node mobility speed and its impact on average jitter

4.3.5 Discussion: Varying communication range and its impact on routing overhead in multipath

The proposed Q-PSO has the overall lowest communication overhead as compared to the other three routing methods under comparison. There is a significant change in the routing overhead in a multipath Q-PSO as compared to single path routing (see Figure 4.6). This is because there are alternative paths to the destination in a multipath Q-PSO, hence the reduction in the number of control packets that are to be released when the MANET network topology changes because alternative paths to the destination are known.

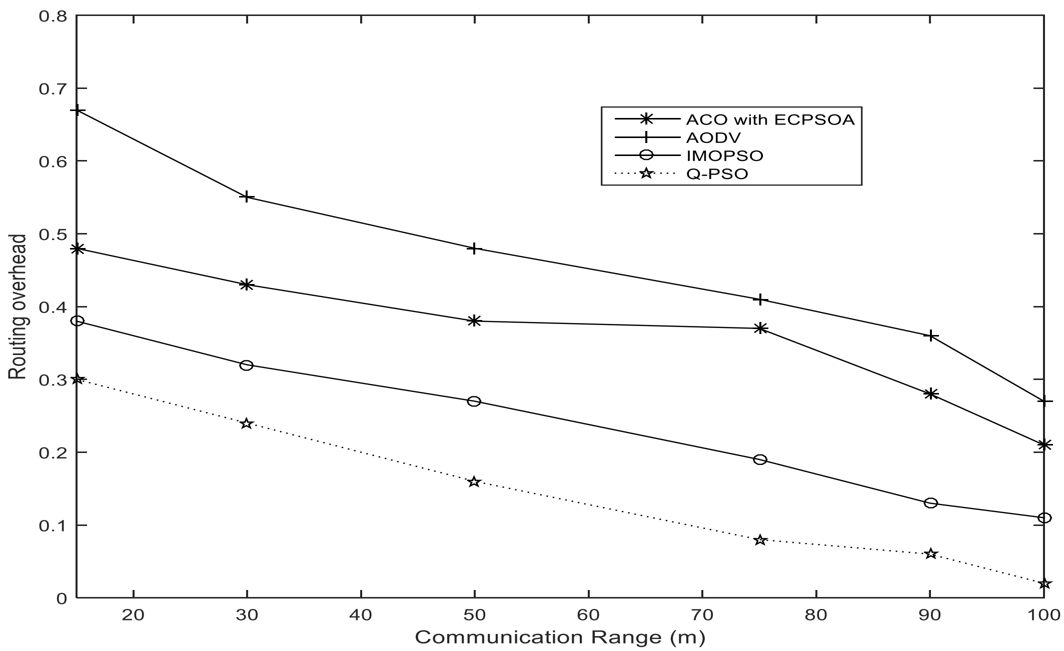

Figure 4.11 Routing overhead varying node communication range

4.3.6 Discussion: Varying mobility on average end-to-end delay in multipath routing

The average end-to-end delay of the proposed multipath Q-PSO is better than the routing methods (ACO with ECPSOA, IMOPSO and AODV), even when mobility changes to a high of 30m/s. An average low end-to-end delay of less than 100 m/s was observed. There was a significant decrease of 13% in average end-to-end delay in the multipath Q-PSO compared to the single path Q-PSO routing (see Figure 4.7).

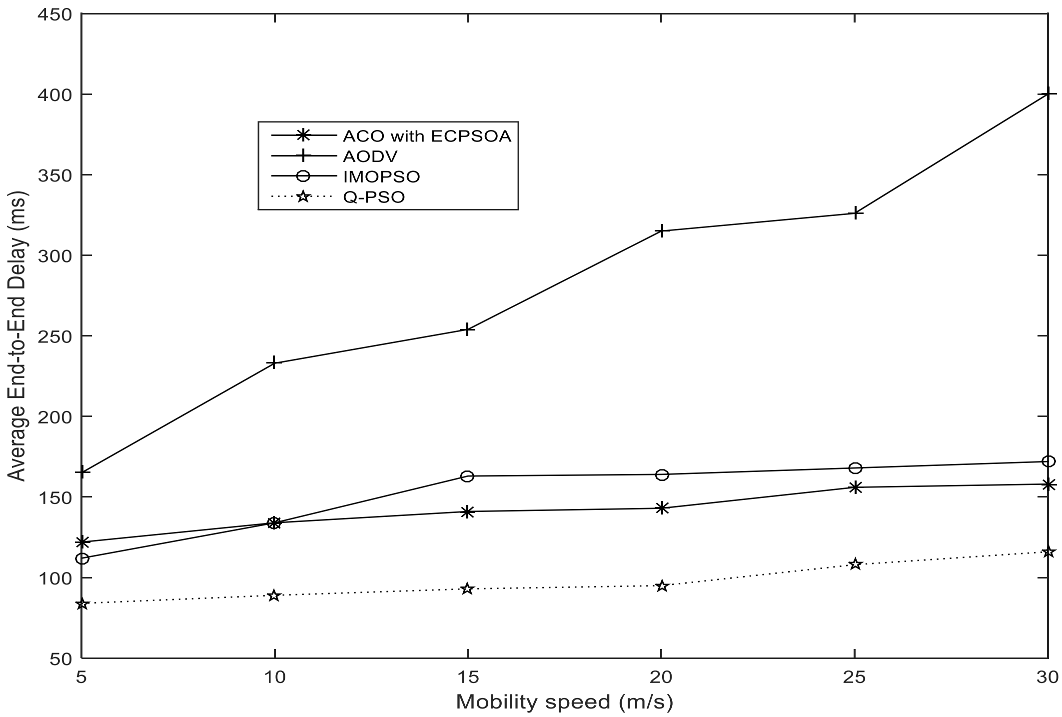

Figure 4.12 Node mobility speed versus average end-to-end delay

4.4 VALIDATION OF THE RESEARCH ON USING Q-PSO ROUTING PROTOCOL

Table 4.2 shows the summary of the results of the newly developed routing protocol termed Q-PSO routing, in both single path and multipath routing relative to other routing protocols. The summary of simulation results shows that the proposed O-PSO produced better results relative to other nature-inspired routing protocols and AODV.

Table 4.2 Simulation results for various performance metrics on Q-PSO

PERFORMANCE METRIC	**ROUTING PROTOCOL**					
	Variable Parameter	**Q-PSO in single path**	**Q-PSO in multipath**	**ACO with ECPSOA**	**AODV**	**IMOPSO**
Routing overhead	Communication range (metres)	*Routing overhead*				
	15	0.38	0.3	0.48	0.67	0.38
	30	0.38	0.24	0.43	0.55	0.32
	50	0.28	0.16	0.38	0.48	0.27
	75	0.18	0.08	0.37	0.41	0.19
	90	0.1	0.06	0.28	0.36	0.13
	100	0.08	0.02	0.21	0.27	0.11
Average end-to-end delay	Mobility speed (m/s)	*Average end-to-end delay (milliseconds)*				
	5	94	84	122	165	112
	10	95	89	134	233	134
	15	104	93	141	254	163
	20	110	95	143	315	164
	25	114	108	156	326	168
	30	122	116	158	400	172
Average jitter	Mobility speed (m/s)	*Average jitter (seconds)*				
	5	0.15	0.09	0.18	0.37	0.2
	10	0.18	0.14	0.24	0.41	0.25
	15	0.21	0.18	0.33	0.56	0.28
	20	0.22	0.23	0.41	0.59	0.34
	25	0.25	0.21	0.46	0.61	0.43
	30	0.28	0.22	0.48	0.67	0.46
Packet Delivery Ratio	Number of nodes	*PDR (%)*				
	15	97.7	96	97	85	95
	30	97	96	97	77	92
	50	94.9	94.5	91	73	89
	100	91.6	92	88	66	87
	120	91.5	92	87	65	85
	150	90	91	84	64	84
Network Lifetime	Time (rounds)	*Percentage of nodes alive (%)*				
	0	100	100	100	100	100
	400	100	100	100	100	100
	800	100	100	100	100	100
	1 000	100	100	100	93	100
	1 400	100	100	98	81	98
	1 800	97	99	95	65	89
	2 200	94	94	80	64	78
	2 400	87	87	78	63	75

4.5 CHAPTER SUMMARY

This chapter presented the overall experimental setup that was conducted on Q-PSO routing protocol. The experiments were conducted on NS-2 simulator, RWP model and CBR traffic model was adopted in the simulations scenarios. Maximum mobility speed was set to 30m/s and the simulation time was 240 seconds. The routing metrics: PDR, routing overhead, average jitter, average end-to-end delay and network lifetime were used to check on the performance of the proposed routing protocols.

Two Q-PSO approaches were simulated being single path and multipath routing. Q-PSO routing method achieves better performance relative to other nature-inspired routing methods under comparison. However, multipath routing approaches achieve slightly better results as compared to single path routing approach. This can be attributed to the fact that new paths are already known, if the previous shortest route become unavailable or congested. In the event of the best path failure, redundant paths can be used, and load distribution is achieved in multipath routing, hence the network lifetime was greater relative to single path routing. Network lifetime is high on Q-PSO due clustering the network and having only the cluster heads handling communication. The member nodes in the cluster enters into '*sleep*' state thereby conserving the battery lives.

Q-PSO was producing better performance relative to the other routing methods it was compared to. This is all attributed to the exploration of congestion levels for next-hop neighbours before the route can be decided. From the Q-PSO routing method, it has been proven that nature-inspired routing methods that are hybridised with queuing theory tend to perform better relative to those routing methods which are purely based on swarm-based routing alone.

CHAPTER 5. QUACS EXPERIMENTAL EVALUATIONS AND RESULTS

5.1 EXPERIMENT 1: EVALUATION AND VALIDATION OF QUACS RELATIVE TO ANT COLONY SYSTEM

5.1.1 Experimental setup

A Random Waypoint model (RWP) has been used in the experiments. Nodes begin by moving randomly towards a chosen destination at a set velocity. The simplicity of the RWP model has been the reason for its dominant use in MANET simulations. Proposed methods of routing in ad hoc networks need to be benchmarked against other existing protocols to check if they are better than other existing routing methods. Node mobility is set at a maximum speed of 30m/s in our simulations. Node mobility is the most important trait of MANETs.

For the purposes of showing the performance of QUACS routing method, it is going be compared against other ant routing protocols such as AntHocNet, AntSense and Associativity-based Routing (ABR- which is a non-ant routing method). The AntHocNet and AntSense have been chosen because there is extensive literature on these two methods whilst the ABR has been used because it takes the stability factor into consideration during routing of data packets. Table 5.1 shows the simulation parameters used in the experiments.

Table 5.1 Simulation Parameters

Simulation parameter	**Values used**
Time of simulation	30,60,120,180,240 seconds
MANET simulation area	500m*500m
Mobility model used	Random Way Point (RWP)
Type of traffic model	Constant Bit Rate (CBR)
Radio transmission range of node	30m
MAC protocol	IEEE 802.11 DCF
Data packet size	512KB
Total Bandwidth	2MB
Data rate	4 packets per second
Node's buffer size	50 packets
Maximum speed of mobile node	10,20,30m/s

This section presents simulation results of the proposed QUACS (combination of ACS and queuing theory) method and the ACS (which does not use queuing theory). Its purpose is to show the importance of queuing theory as shown in the QUACS method. QUACS routing method performance is compared to the ACS method which does not explore buffer space availabilty before sending of data packets. The simulation results show that the proposed QUACS method outperforms the ACS systems in packet delivery ratio, average end-to-end delay as well as number of hops involved in exchange of data packets. The results are explained in detail in subsequent sections.

5.1.2 Discussion: Varying communication range on average end-to-end delay

The average end-to-end delay of QUACS and ACS decreases as communication range increases. At a communication range of 30m, QUACS clearly outperform ACS as shown in Figure 5.1. Increase in the communication range results in a decrease in the average length between communicating nodes. Average end-to-end delay of QUACS decreases at a higher communication range due to the reduction in number of nodes that are involved in the exchange of data packets. A decrease in average end-to-end delay entails data packets arriving at the intended destination in a short space of time. This is ideal in a MANET where quicker communication is needed in relaying information in emergency situations.

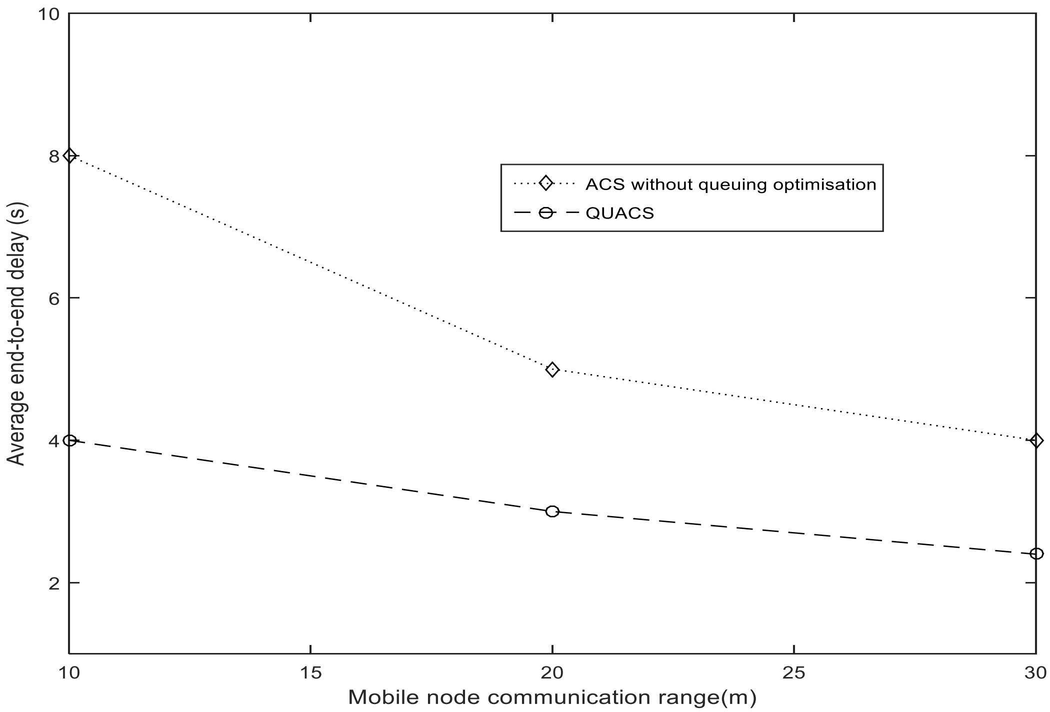

Figure 5.1 Average end-to end delay in QUACS versus ACS

5.1.3 Discussion: Varying node communication range on packet delivery ratio

Results of simulations where the radius of communication was varied in the experiments of QUACS and ACS are presented. The communication range used in the simulations were 10m, 20m and 30m. The maximum speed of the nodes was set to 30m/s. Figure 5.2 shows the results of packet delivery in QUACS versus ACS. At 10m the packet delivery ratio of QUACS and ACS were almost similar, and as the communication range increased QUACS performed better than ACS. This is atrributed to the fact that at higher communication ranges, the number of hops are minimised since more nodes can be reached directly as compared to where the communication range is small. The data packets are delivered quickly as the number of nodes to be explored decreases. This is so because, since nodes that were previously equal to 2-hops away from the current node can be explored directly when the distance increases (now appear as one-hop neighbour).

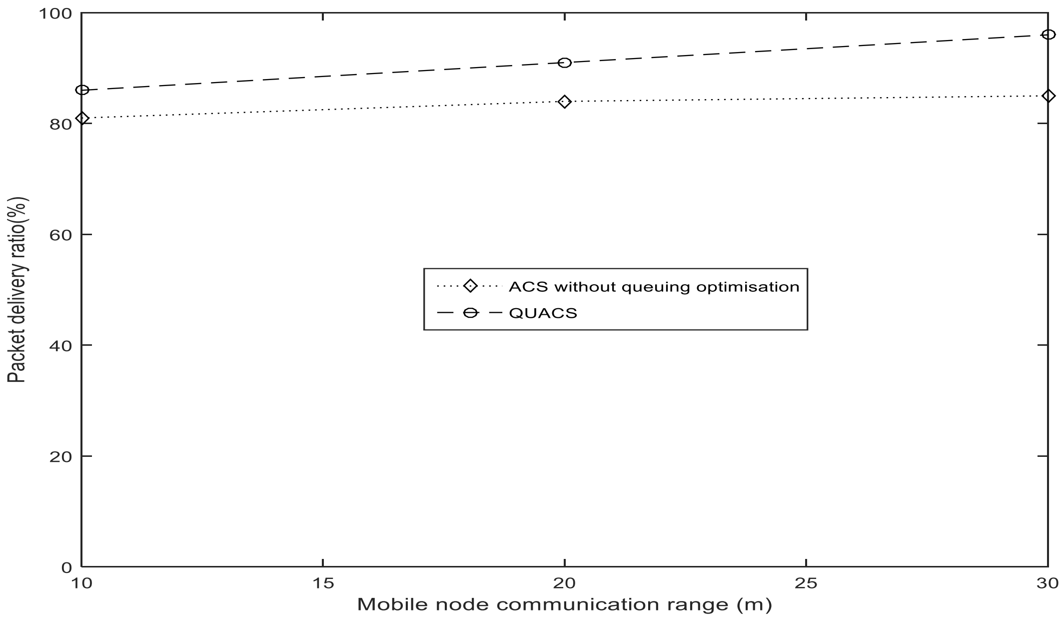

Figure 5.2 Packet delivery ratio in QUACS versus ACS

5.1.4 Discussion: Varying node mobility speed to determine average end-to-end delay in QUACS and ACS

Figure 5.3 shows the average end-to-end delay varying node speed. The node speed was varied from 10m/s, 20m/s and 30m/s. At higher mobility of 30m/s, there are more frequent changes in network topology as new nodes join, and old nodes leave the MANET. Maintenance of paths becomes difficult as the number of nodes increases as well. The simulation results show that at low speed of 10m/s, the average end-to-end delay is almost similar for QUACS and ACS. As node speed increases to 30m/s QUACS outperforms ACS. This is because the QUACS method checks node stability and buffer space availability before choosing the route. As for ACS, when node speed is 30m/s, it becomes difficult to adapt to changes in network topology using the route link failure notification and request error messages.

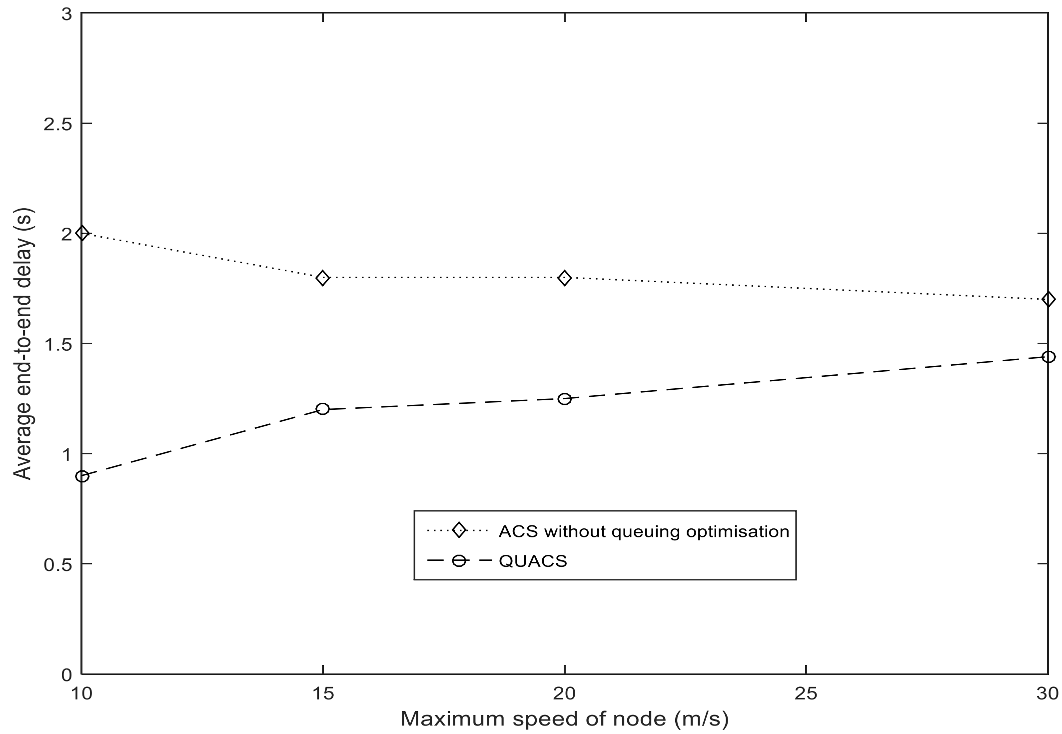

Figure 5.3 Varying node speed to determine average end-to-end delay in QUACS and ACS

5.1.5 Discussion: Varying communication range to average number of hops

Figure 5.4 shows the average number of hops in QUACS and ACS. The communication range was varied from 10m, 20m and 30m. There is an inverse relationship between the average number of hops for QUACS and ACS. The decrease in number of hops for QUACS is more pronounced than in ACS due to checking buffer space availability and stability of the nodes before sending data packets in QUACS. As communication range increases, the number of hops decreases. The decrease in number of hops is because when transmission range increases, the nodes which were two or even three hops away can now be reached as a 'one-hop' neighbour. This increase in communication range is attributed to a decrease in end-to-end delay as well.

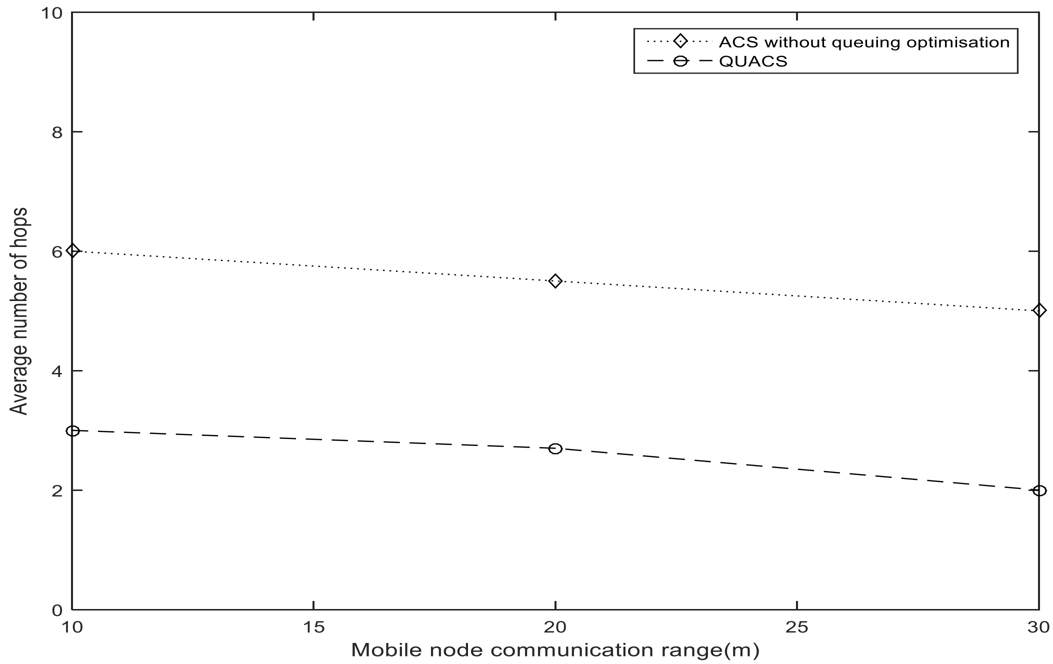

Figure 5.4 The average number of hops in QUACS versus ACS

5.2 EXPERIMENT 2: EVALUATION AND VALIDATION OF QUACS RELATIVE TO OTHER ROUTING PROTOCOLS

5.2.1 Experimental setup

This section presents simulation results of the proposed QUACS method in relation to other widely used ant routing methods and ABR. The simulations were done on an area of 500m*500m. Mobility speed was altered to check on its impact on the PDR on QUACS and other routing methods. Also, scalability was another factor that was taken into consideration whereby the number of nodes were increased to check if the performance of the QUACS and other routing methods remained the same.

5.2.2 Discussion: Varying mobility on packet delivery ratio

Figure 5.5 shows Packet Delivery Ratio (PDR) versus the speed at which nodes were moving i.e. 10m/s, 20m/s and 30m/s. Varying the node speed was done to see if the mobility of the nodes affects PDR. At low speed of 10m/s, PDR, the proposed QUACS and other three routing methods (ABR, AntSense and AntHocNet) were all above 90%. As node mobility increased to 30m/s there was a gradual decrease in PDR for QUACS as well as the other three routing methods under comparison. However, the PDR for QUACS remains over 94%. This can be attributed to the fact that at a high mobility, the stability factor and congestion metrics are all factored into consideration when routing data packets across the network. There is a high PDR for both QUACS and ABR, though the PDR for QUACS remains superior. A significant decline in PDR for AntSense and AntHocNet can be attributed to frequent route maintenance when communication links between nodes breaks, down when mobility increases to 30m/s.

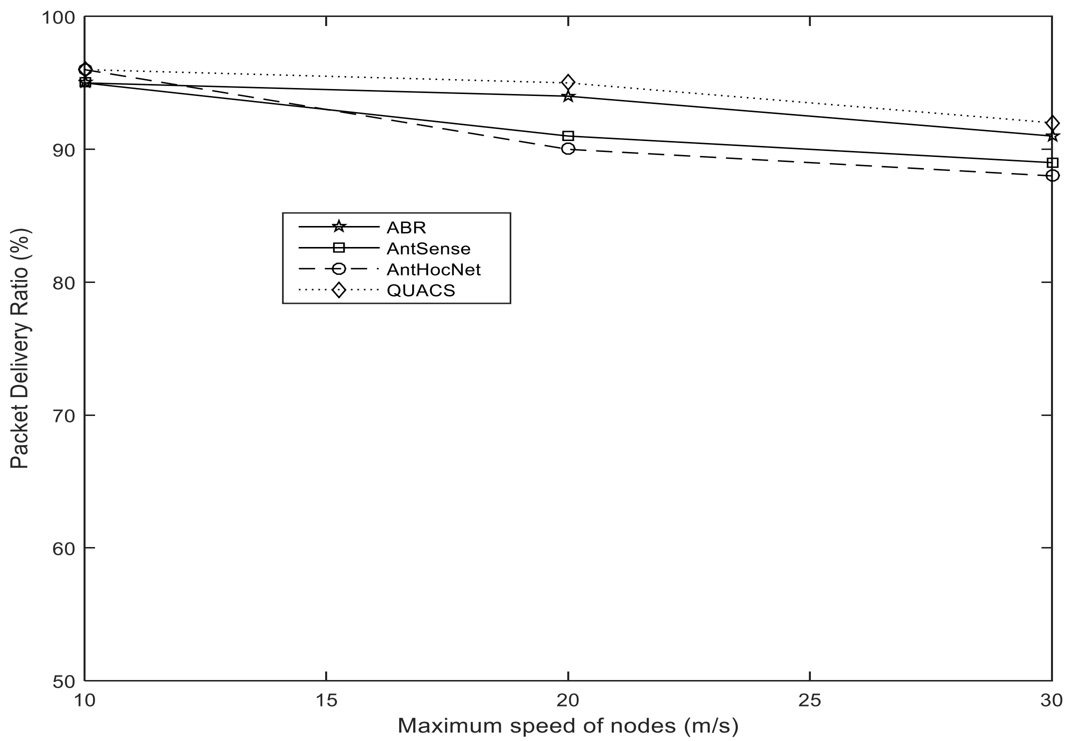

Figure 5.5 Packet delivery ratio versus node mobility

5.2.3 Discussion: Varying number of nodes to determine communication overhead

The communication overhead of QUACS is less than those of AntHocNet, AntSense and ABR, even if the network size grows to around 200 nodes (Figure 5.6). This is because in QUACS, routes are checked together with the buffer size limits and stability for each node before best route can be established. As the network grows through new nodes joining the network, the communication overhead increases marginally for the proposed QUACS routing protocol to 900 bits. However, its increase is low compared to other ant routing and ABR routing protocols. This can be attributed to the increase in the nodes that must be checked regarding their stability before checking on buffer capabilities when deciding the route to be used.

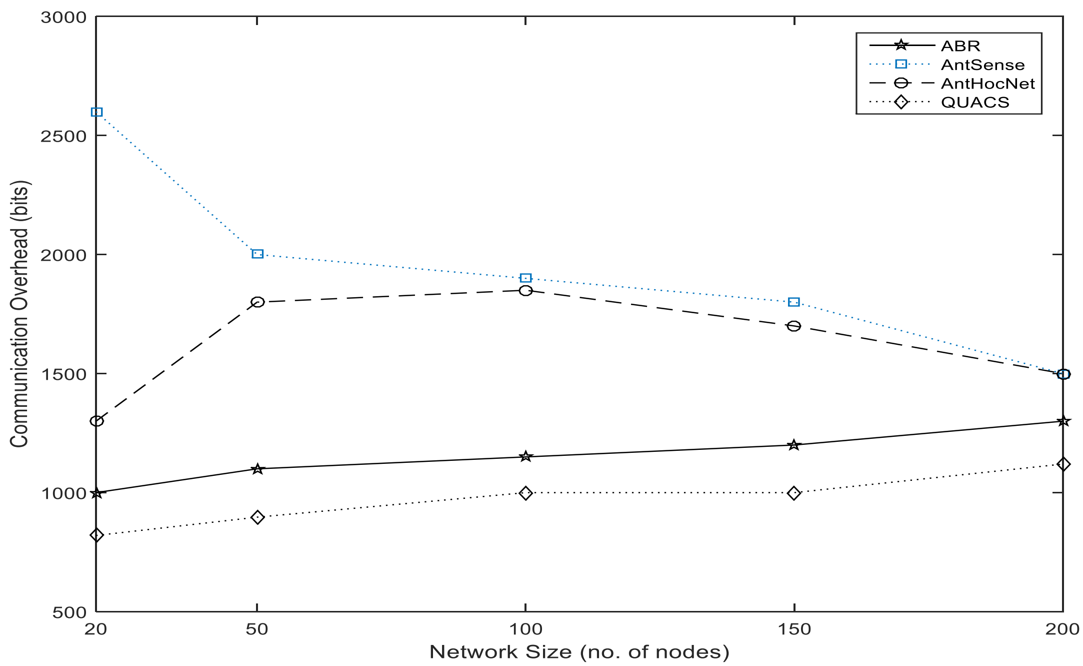

Figure 5.6 Communication overhead versus network size

5.2.4 Discussion: Varying network size on average end-to-end delay

Average end-to-end delay as shown in Figure 5.7 is less for QUACS irrespective of the network size as compared to other routing methods (ABR, AntSense and AntHocNet). This shows that the proposed QUACS routing method is scalable. Low end-to-end-delay on QUACS and ABR was observed as compared to AntSense and AntHocNet. A consistent in end-to-end delay for QUACS of an average of 5 seconds was observed. When the network size increases to around 200 nodes, the end-to-end delay of ABR marginally increased by around 20%. This maybe due to link failure and the time required by the localised query control packets in finding alternative routes. As the network grew to 200 nodes, AntSense's average end-to-end delay dropped by almost 50%.

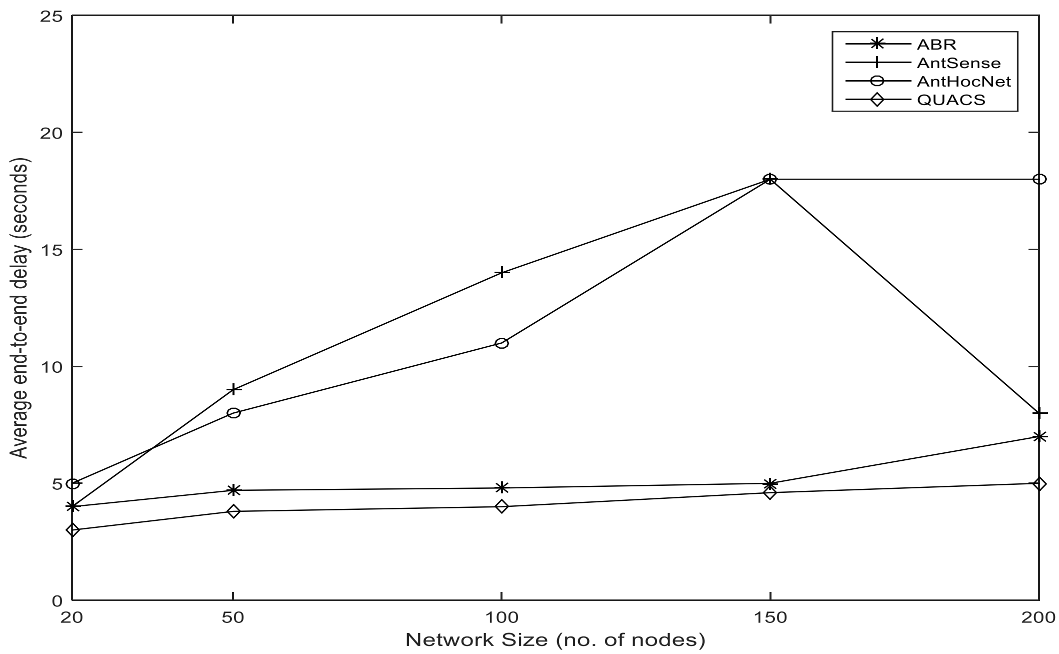

Figure 5.7 Average end-to-end delay versus the network size

5.2.5 Discussion: Varying network size on throughput

Figure 5.8 shows the throughput by varying the number of nodes on the network from 20, 50, 100, 150 and finally 200. The experiment was conducted at node mobility of 10m/s. When the number of nodes was 20, all the four routing methods have a high throughput with QUACS having more than 892 000 bits received. AntSense has the lowest throughput. QUACS, AntHocNet and ABR maintained the throughput of above 890 000 bits even when the network size increases to 150 and eventually 200 nodes. However, the stability factor consideration made QUACS and ABR perform better than the other two routing methods. Checking on the congestion levels for next-hop neighbours ensures that the overall throughput of QUACS remains greater than ABR.

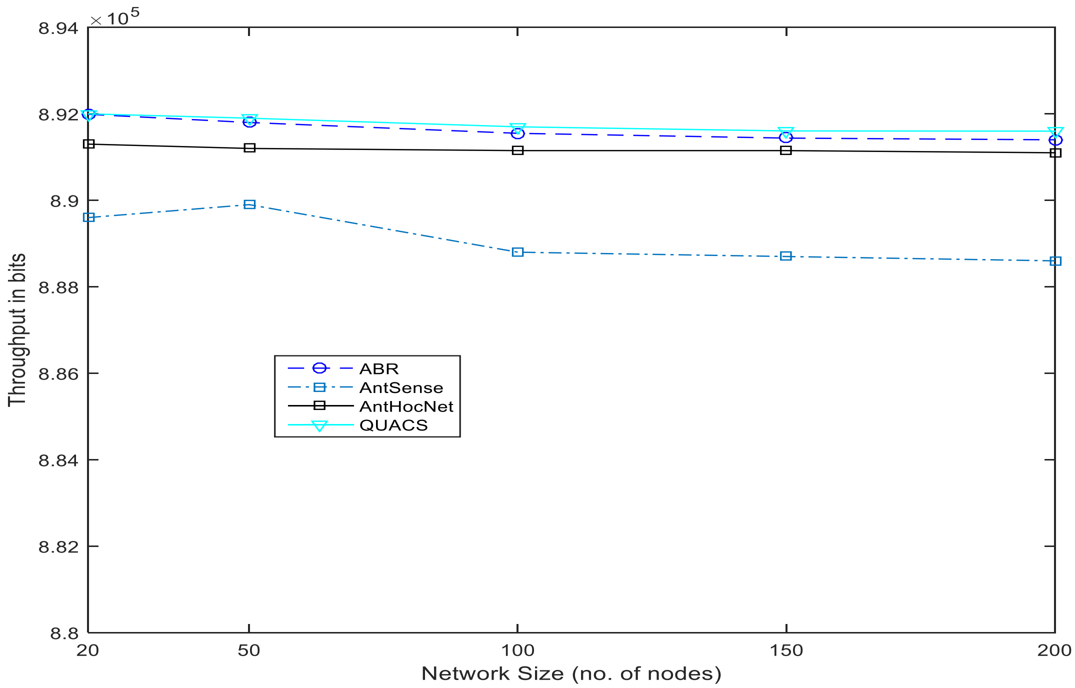

Figure 5.8 Throughput versus network size

5.2.6 Discussion: Simulation time versus average throughput

The average throughput for QUACS outweighs those of other routing protocols under comparison. This is shown in Figure 5.9. Over a simulation time of 240 seconds, QUACS and ABR average throughput has been above 80%. AntSense maintained an average throughput of 85%. At the end of the simulation time, QUACS average throughput was the highest, though ABR also averaged a throughput greater than 80.

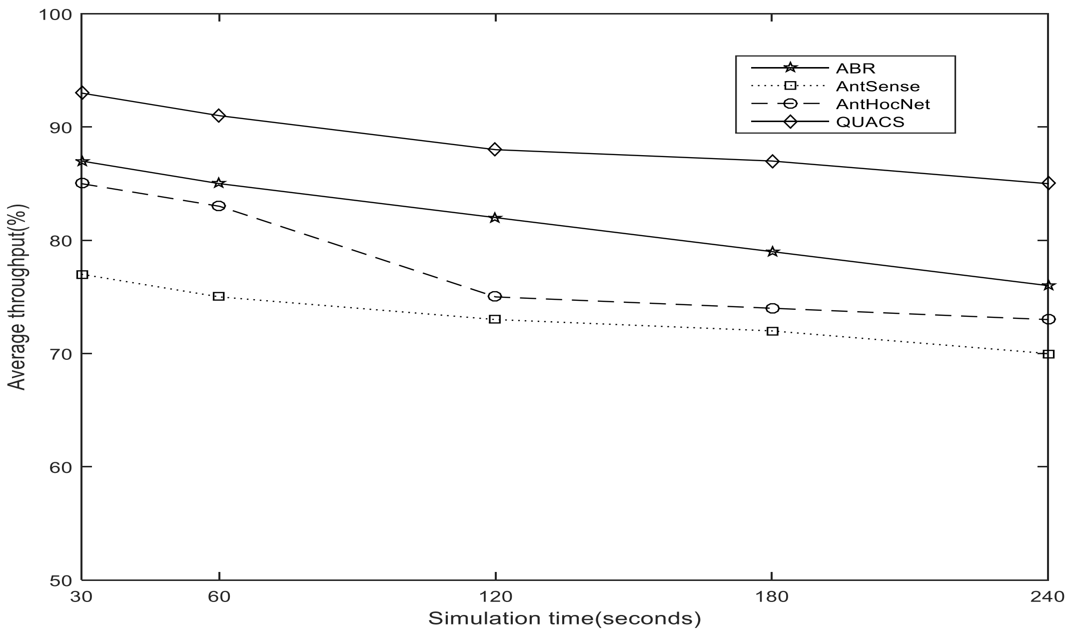

Figure 5.9 Average throughput versus simulation time

5.3 VALIDATION OF THE RESEARCH ON USING QUACS ROUTING PROTOCOL

The summary of simulation results (see Table 5.2) shows that the proposed ACO hybridised with queuing theory tend to produce better results relative to other ant-inspired routing protocols.

Table 5.2 Simulation results for various performance metrics on QUACS

PERFORMANCE METRIC	ROUTING PROTOCOL				
	Variable Parameter	**QUACS**	**ABR**	**AntSense**	**AntHocNet**
Routing overhead	Network Size	*Routing overhead in bits*			
	20	820	1 000	2 600	1 300
	50	897	1 100	2 000	1 800
	100	1 000	1 150	1 900	1 850
	150	1 000	1 200	1 800	1 700
	200	1 120	1 300	1 500	1 500
Average end-to-end delay	Network Size	*Average end-to-end delay (seconds)*			
	20	3	4	4	5
	50	3.8	4.7	9	8
	100	4	4.8	14	11
	150	4.6	5	18	18
	200	5	7	8	18
Average throughput	Simulation time (seconds)	*Average throughput (%)*			
	30	93	87	77	85
	60	91	85	75	83
	120	88	82	73	75
	180	87	79	72	74
	240	85	76	70	73
Packet Delivery Ratio	Node mobility speed (m/s)	*PDR (%)*			
	10	96	95	95	96
	20	95	94	91	90
	30	92	91	89	88
Throughput	Network size	*Throughput in bits*			
	20	892 000	819 990	889 600	891 300
	50	891 900	891 800	889 900	891 200
	100	891 700	891 550	888 800	891 150
	150	891 605	891 439	888 704	891 150
	200	891 600	891 400	888 602	891 100

5.4 CHAPTER SUMMARY

This chapter presented the overall experimental setup that was conducted on QUACS routing protocol. The experiments were conducted on NS-2 simulator, RWP model and CBR traffic model. Maximum mobility speed was set to a maximum of 30m/s and the simulation time was 240 seconds. The routing metrics being: PDR, communication overhead, average end-to-end delay and throughput were used to check on the performance of the proposed routing protocol.

The first experiment was done on ACS without queuing theory versus the proposed QAUCS (ACO with queuing theory optimisation) routing method. This was to show how queuing theory improved the performance of the QUACS routing protocol. Simulation results shows that PDR and average end-to-end delay for QUACS was higher relative to ACS without queuing theory. This is due to the fact that QUACS factors in node(s) stability, congestion status of the next-hop neighbour nodes before the path is chosen for routing of data packets.

The last experiments on QUACS were done relative to other protocols such as ABR, AntSense and AntHocNet. Even at different mobility speeds and network size, QUACS was producing better performance relative to the other routing methods it was compared to. This is all attributed to the exploration of congestion levels for next-hop neighbours before the route can be decided. From the QUACS routing method, it has been proven that nature-inspired routing methods that are hybridised with queuing theory tend to perform better relative to those routing methods which are purely based on swarm-based routing alone.

CHAPTER 6: MANET ROUTING OPTIMISATION FUTURE AREAS OF RESEARCH

6.1 INTRODUCTION

MANET optimisation is an area of increasing interest to researchers nowadays as more and more wireless devices are released into the market. In order to assist future researchers in the area of wireless ad hoc networks, a survey on the current optimisation routing was conducted. A total of 290 journal articles were classified according to our MANET optimisation routing scheme. The 290 articles were examined based on the year of publication, publication by optimisation routing technique as well as the pattern of publication in selected journals. This enabled the revealing of the current status quo in the area of swarm-based optimisation routing by identifying gaps from the under researched routing themes in wireless ad hoc networks that should be explored more in future.

6.2 EMERGING RESEARCH THEMES ON MANET OPTIMISATION ROUTING

The proposed MANET optimisation routing aims at providing useful information for subthemes that are critical in the designing of a wireless network that can be operational for a long period of time. This review was mostly based on the study of journals rather than conference proceedings papers. Conference papers contributed less than 5% of the material used. Journals were selected because they contain quality information which researchers and academics often use to disseminate new knowledge and findings on routing optimisation techniques to the research community.

Journals covering the period 2010 to 2018 were reviewed. Journal articles were selected based on the relevance to optimisation routing in MANETs and to identify emergent themes. The survey of literature found articles published in 12 internationally accredited journals, although the approach may be said to be subjective in the sense that articles published in non-English language research outlets might have been overlooked because of language barriers.

The literature review provides a foundation for understanding optimisation routing techniques in wireless networks, leading to the development of MANET optimisation routing frameworks. The year 2010 was chosen as a starting point for the publication survey as before the year 2010, there were few articles on swarm-based optimisation. From 2010, there was a phenomenal increase in the number of publications on all spheres of optimisation routing techniques, (see Figure 6.2). The following journals were selected mainly because of their relevance to optimisation routing in MANETs:

- *Applied Soft Computing*
- *Journal of Network and Computer Applications*
- *Computer Networks*
- *Ad hoc Networks*
- *Future Generation Computer Systems*
- *Information Sciences*
- *Computers and Electrical Engineering*
- *Procedia Computer Science*
- *Engineering Applications of Artificial Intelligence*
- *Swarm and Evolutionary Computation*
- *Computational Intelligence Systems*
- *Computers and Security*

After reading articles from the twelve journals on optimisation routing in MANET network, a novel routing framework was proposed as shown in Figure 6.1. Optimisation routing protocols focus on: QoS parameters, prolonging network lifetime of the MANET network and scalability among other factors as highlighted in Figure 6.1. The routing optimisation strategy comprises of: ACO, PSO, BFO, ABC, genetic based, hybrid based and other routing optimisation techniques.

The MANET network is scalable, so any new nodes that join increase the network number to N_{m+1} and vice versa, that is,(N_{m-1}) when nodes leave the MANET network as shown in Figure 6.1. Each node in the network has two roles; being source node or destination node and has routing capabilities. MANET network strives to prolong network lifetime while at the same time increasing throughput, reducing average end-to-end delay, reducing average jitter and increasing packet delivery ratio as well as reducing nodes energy consumption [132] [133] [134][135].

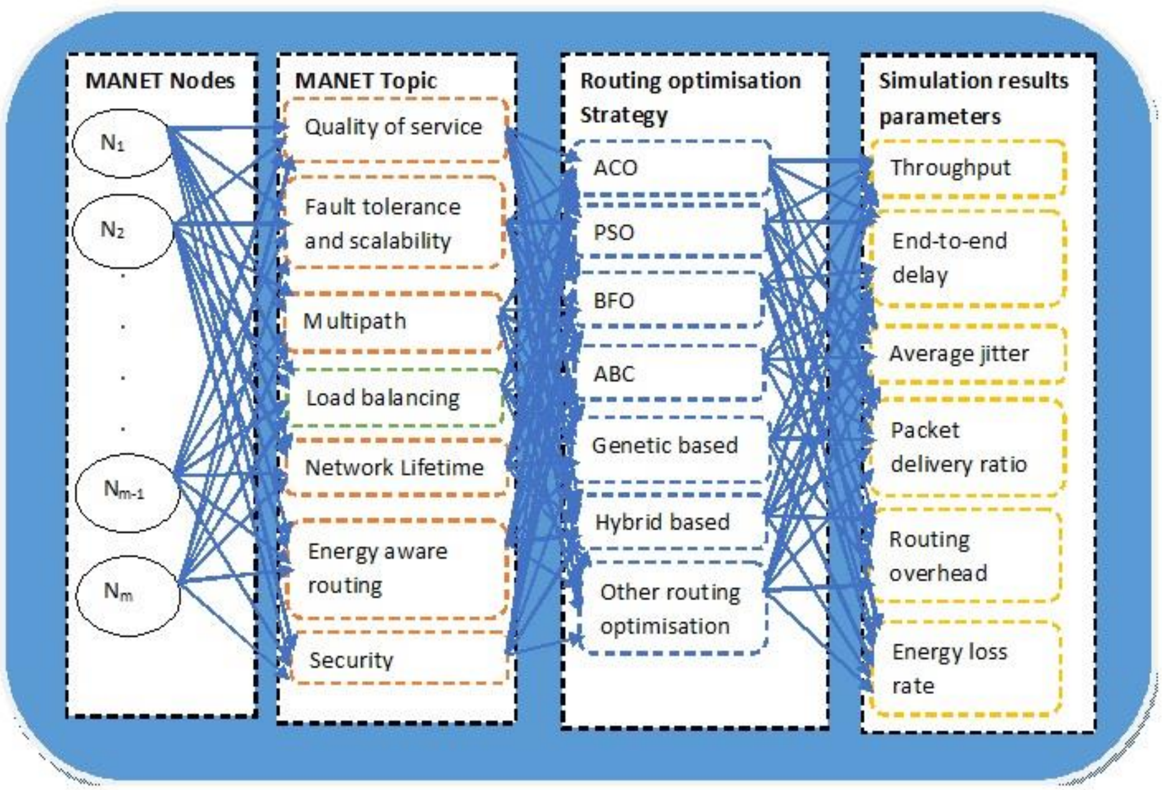

Figure 6.1 Proposed MANET optimisation routing framework

Routing protocols have been designed to enhance routing of data packets in MANET networks. From the existing literature, the following are the sub-areas that optimisation routing protocols tend to focus on:

- **Multipath routing** - availability of multiple routes between source and destination nodes extends the network lifetime. This is because other routers can be utilised in the event of other routes being heavily used, thus ensuring load balancing [18][20][120]. A MANET is a dynamic type of network where nodes join and leave anytime. Nodes that might have been intended as having a route to particular destination can leave the network. Shortest path between source node and destination nodes which results in faster communication need to be explored for routing to be more efficient [7].
- **Scalability and fault tolerance** - for a MANET network to have multiple paths, there is need for more nodes to join the network (scalability). New nodes join the network and redundant paths can be established. With redundancy paths in the network, average end-

to-end delay and jitter are reduced greatly. This is because if there is a route failure, other available paths can be used quickly. This is not the case with single path routing, where the route discovery process takes a longer time to establish in the event of node failure on the network [16][101].

- **Load balancing** -new paths found during route discovery should not have loops. Having loops results in visiting the node more than once, contributing to battery depletion and bandwidth wastage and reduced throughput [6]. Next-hop neighbours data should be checked for congestion so that data can be distributed among nodes within the network to prolong the battery life and reduce average end-to-end delay and jitter on the wireless network [11], [18], [137][16], [118]. MANET networks have limited computation and storage capacity. Once the node's buffer is full, the incoming data packets have to wait to be processed and in the process of waiting some packets may end up being dropped [32].
- **Quality of service (QoS)** - involves aggregation of a number of parameters such as: latency, jitter, routing overhead, node's residual energy, throughput, and packet delivery ratio that a routing protocol should address. However, literature proven that it is difficult to address all QoS factors at once [84], [32],[24] ,[71],[138], [89] [45], [139].
- **Security**- A MANET network has an open nature approach, that is, nodes join and leave anytime, hence designing routing protocols that factors security is one area [16],[45], [140], [141].
- **Network lifetime**- Network lifetime is a critical factor for wireless network. As the node's battery power gets depleted, the survival of the network is ultimately affected. The routing tables should be updated to reflect the current status of the network. Optimisation of routing protocols should aim to prolong the lifetime of the wireless network [16], [18], [108], [22] [142], [143], [144], [145].
- **Energy-conservation routing**: The nodes in the wireless network are usually battery-powered and once the battery is depleted, the node will no longer be able to forward and receive data in the network [1], [14], [16], [55]. Designing optimum routing protocols that integrate node energy levels and their congestion levels will help to prolong the lifetime of the wireless network [11], [32], [38], [107], [136], [126], [129].

6.3 PATTERN OF OPTIMISATION ROUTING ARTICLES BY YEAR OF PUBLICATION

Figure 6.2 shows the annual distribution of articles on *Optimisation Routing Techniques* in MANETs from 2010-2018 illustrating an annual increase. It is worth noting that many of the outputs occurred from 2016 to 2017, where previously there were fewer articles on optimisation routing approaches, that is, less than 50 articles per year.

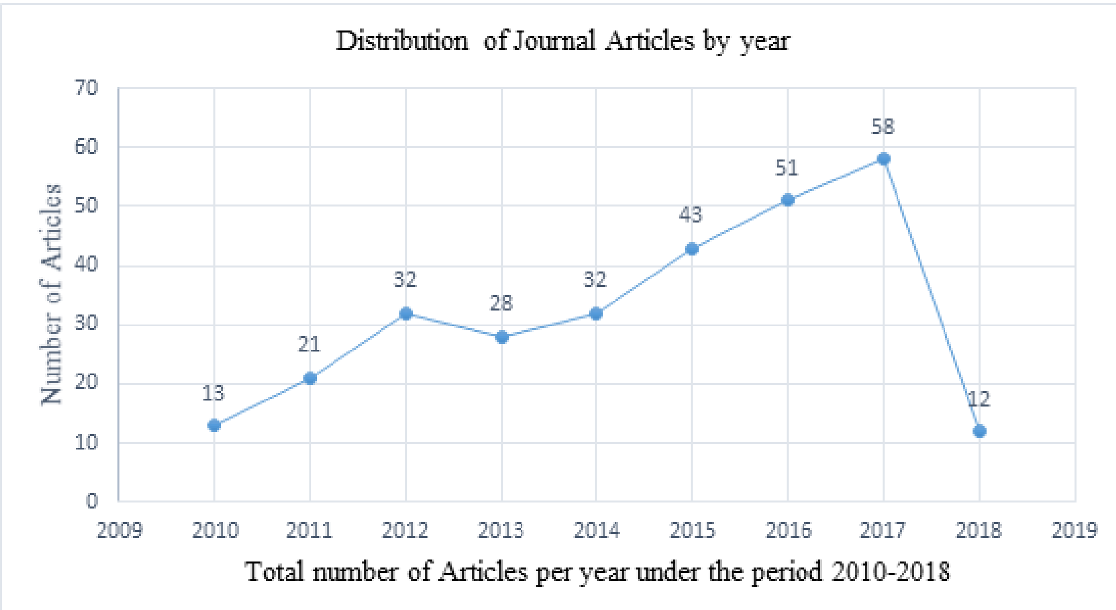

Figure 6.2 Distribution of articles by year

6.4 PATTERN OF OPTIMISATION ROUTING ARTICLES BY JOURNALS

Figure 6.3 shows the MANET articles published per Journal. The *Journal of Network and Computer Applications* has mostly published articles on optimisation routing techniques. This journal primarily focuses on issues related to communication (routing) challenges particularly in the area of wireless ad hoc networks and sensor networks. *Procedia Computer Science, Computer Science Journal and Ad hoc Networks journals* occupies position two, three and four respectively (each above 11%). *Procedia Computer Science journal* focuses more on application of computing techniques to solve real world problems. *Ad hoc networks journal* focuses on improving routing, security challenges associated with wireless networks. The rest of the journals also publish articles on optimisation routing techniques, but the proportion is less, with the least being *Computers and Security* with the publication share of 4.2% from the articles identified between 2010-2018.

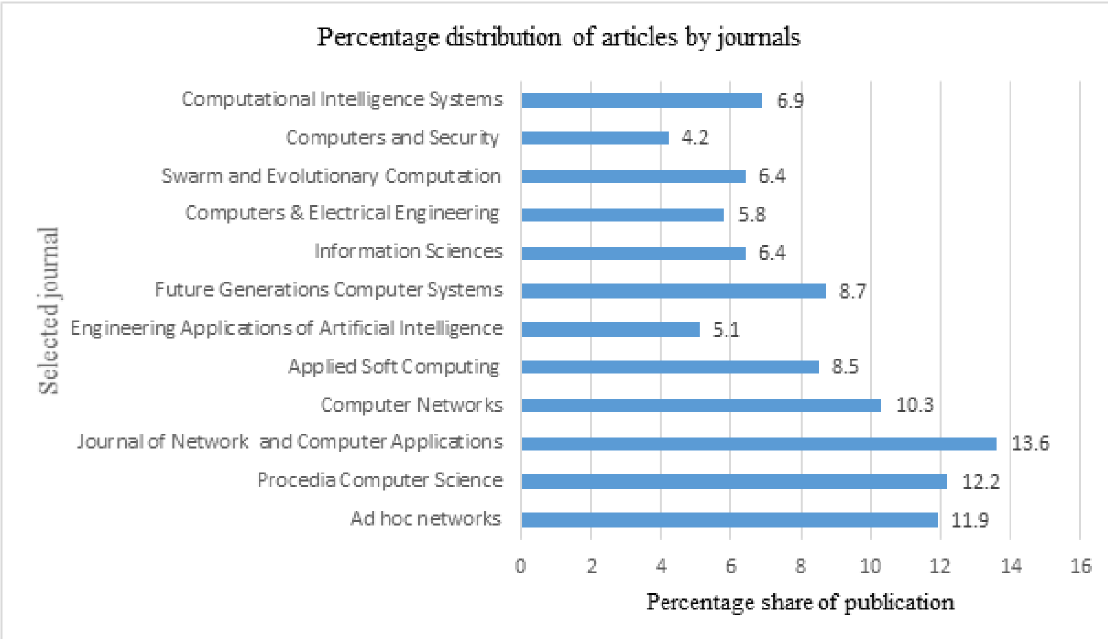

Figure 6.3 Pattern of optimisation routing articles by journal

6.5 PATTERN OF OPTIMISATION ROUTING ARTICLES BY TOPICS

Figure 6.4 shows the pattern of distribution of articles on optimisation routing techniques from 2010-2018. The most popular area of focus was *Particle Swarm Optimisation* with 117 articles, (28%), followed by *Ant Colony Optimisation* with 104 articles, (24.9%), and the least being *Bacterial Foraging Optimisation* with 18 articles, (4.3%).

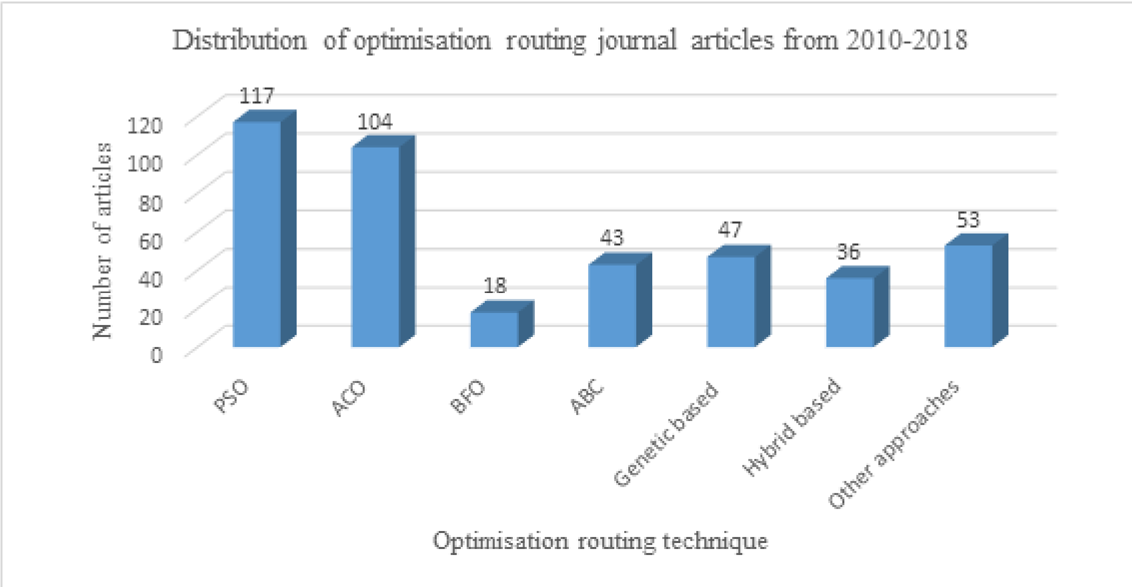

Figure 6.4 Pattern of optimisation routing technique articles by topic

After classifying the articles on pattern on optimisation by subtopics, optimisation for each swarm-based routing approach was done.

Figure 6.5 shows the percentage of articles in ABC optimisation routing technique topics, which have been classified into seven areas. Most of the articles under ABC optimisation focussed on *network lifetime* (30%) followed by *multipath routing* (25%). The least popular theme was *quality of service and fault tolerance* with each having 5% respectively. There were no publications on security.

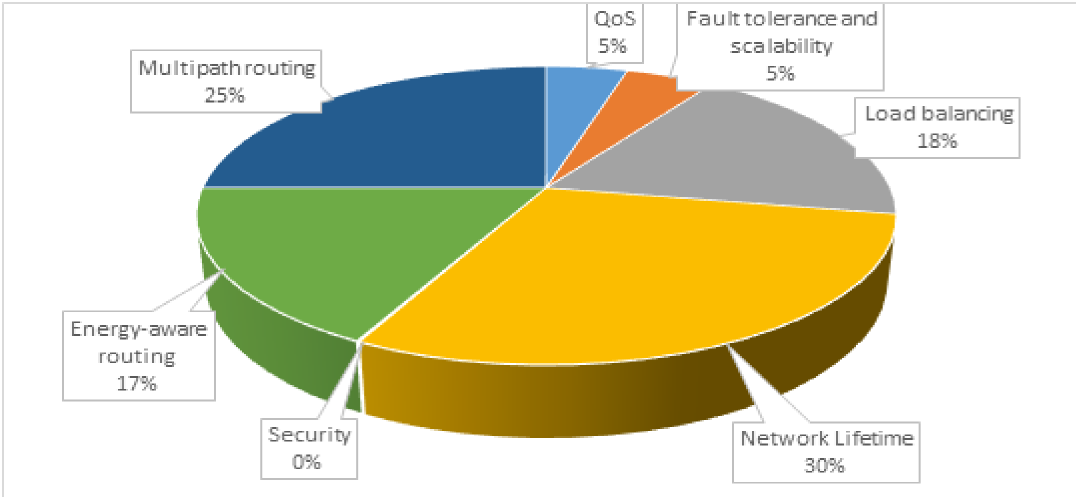

Figure 6.5 Number of ABC optimisation routing technique articles

Figure 6.6 shows percentage of articles in BFO optimisation routing technique topics. Most of the articles under BFO focussed on *energy aware routing* (34%) followed by *multipath routing* (32%). No publications were recorded on *quality of service*.

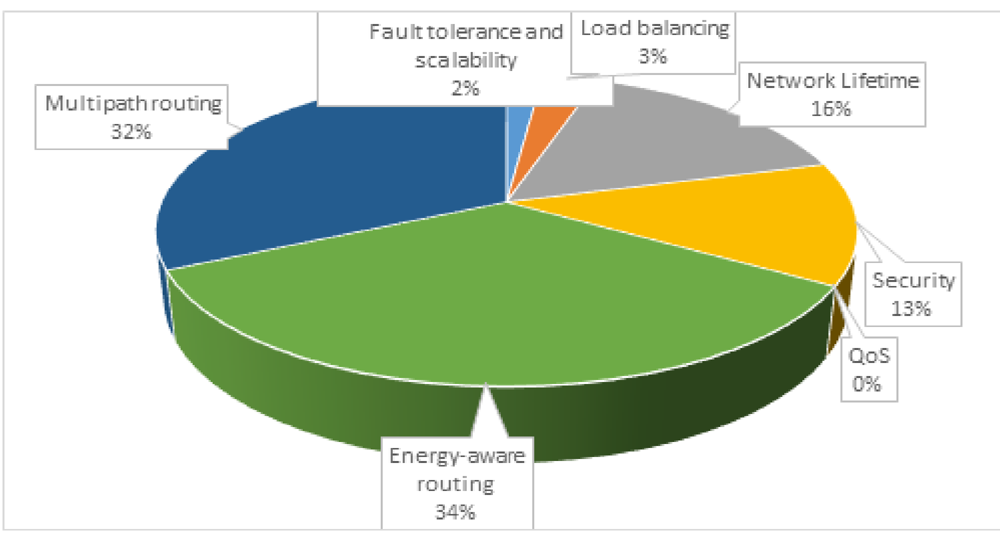

Figure 6.6 Number of BFO optimisation routing technique articles

Figure 6.7 shows the percentage of articles in ACO optimisation routing technique. Most of the articles under ACO optimisation focussed on *multipath routing* and *quality of service* with each having (19%). The least number of articles were recorded on *fault tolerance and scalability*.

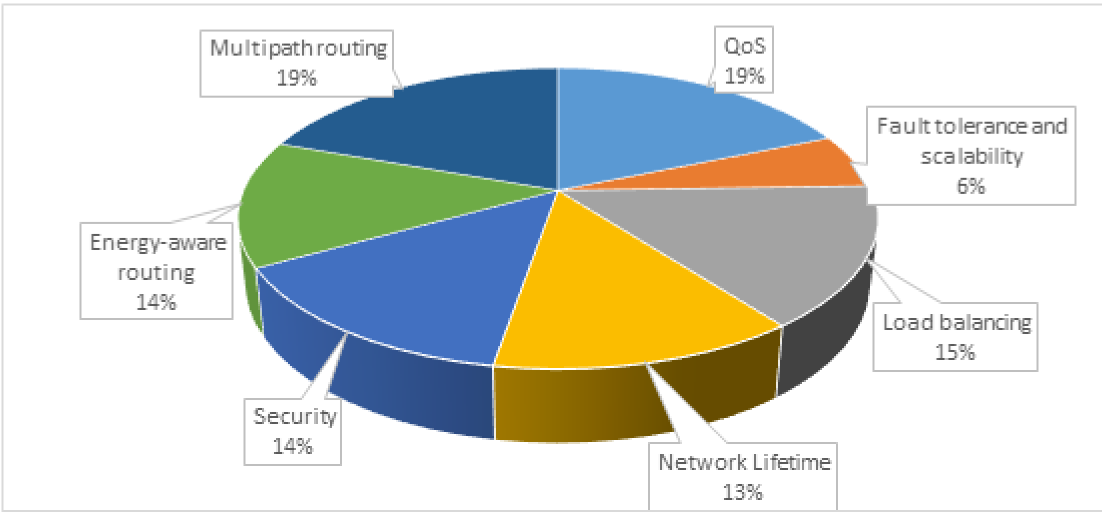

Figure 6.7 Number of ACO optimisation routing technique articles

Figure 6.8 shows percentage of articles in PSO optimisation routing technique topics. Most of the articles under PSO optimisation discussed *multipath routing* (24%) followed by *energy-aware routing* and *security*, both with 16% each. The least number of articles were recorded on *quality of service*, (6%).

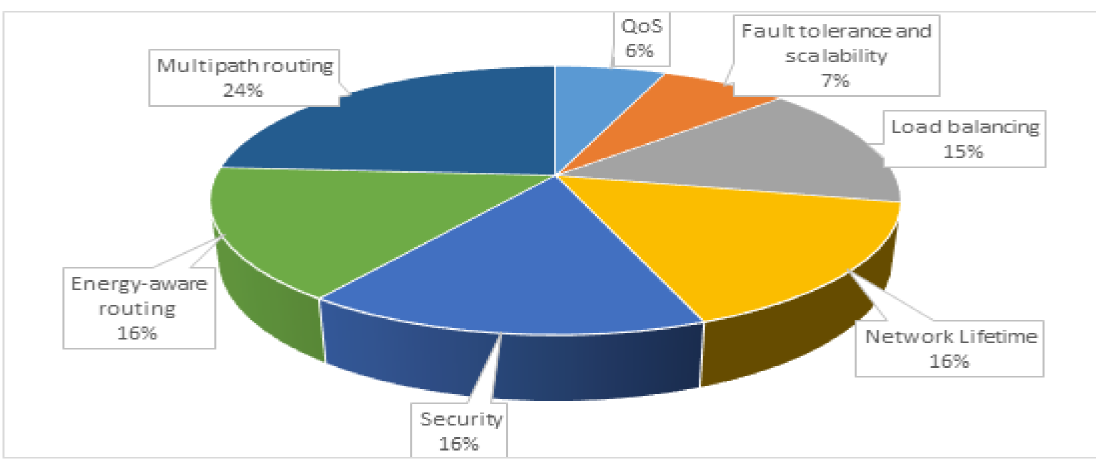

Figure 6.8 Number of PSO optimisation routing technique articles

Figure 6.9 shows the percentage of articles in Genetic Based Optimisation Routing Technique topic. Most of the articles under Genetic based optimisation routing focussed on *extending network lifetime* (36%), followed by *multipath routing* (31%). No articles were recorded on *quality of service* (QoS), *load balancing* and *security*.

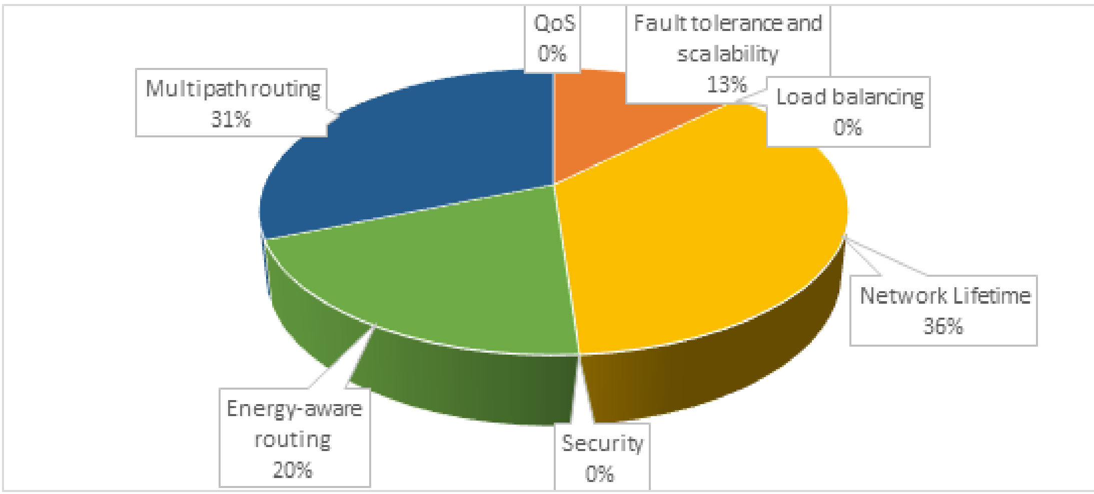

Figure 6.9 Number of Genetic based optimisation routing technique articles

Figure 6.10 shows percentage of articles in Hybrid based optimisation routing technique topics. Most of the articles under hybrid-based optimisation routing discussed *extending network lifetime* (33%), followed by *energy-aware routing* 24%. The least number of article themes were *security* (4%).

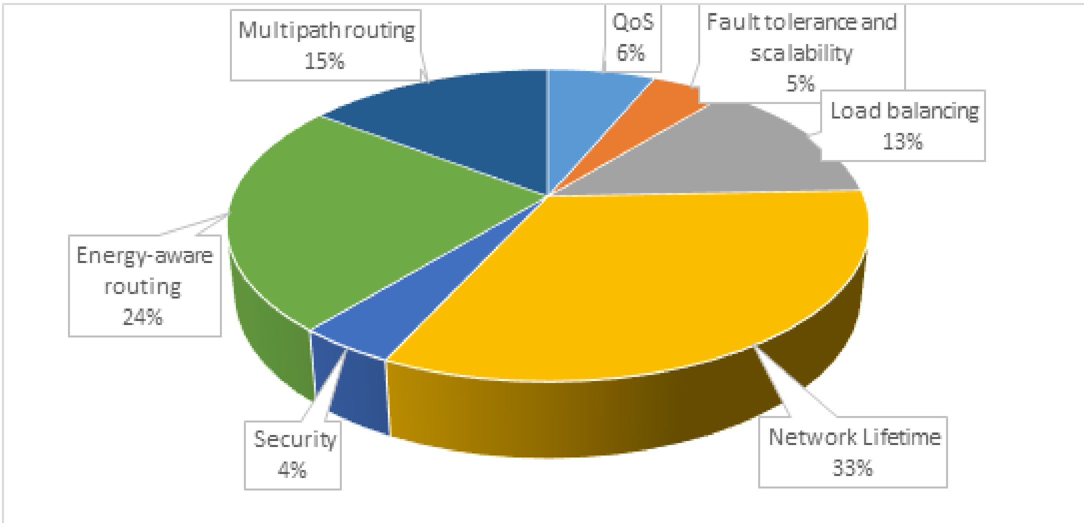

Figure 6.10 Number of Hybrid based optimisation routing technique articles

Figure 6.11 shows percentage of articles in other optimisation routing techniques. Most of the articles under other optimisation routing methods discussed *extending network lifetime* (31%), followed by *energy-aware routing* with 16%. The least number of articles were recorded on *load balancing* (5%).

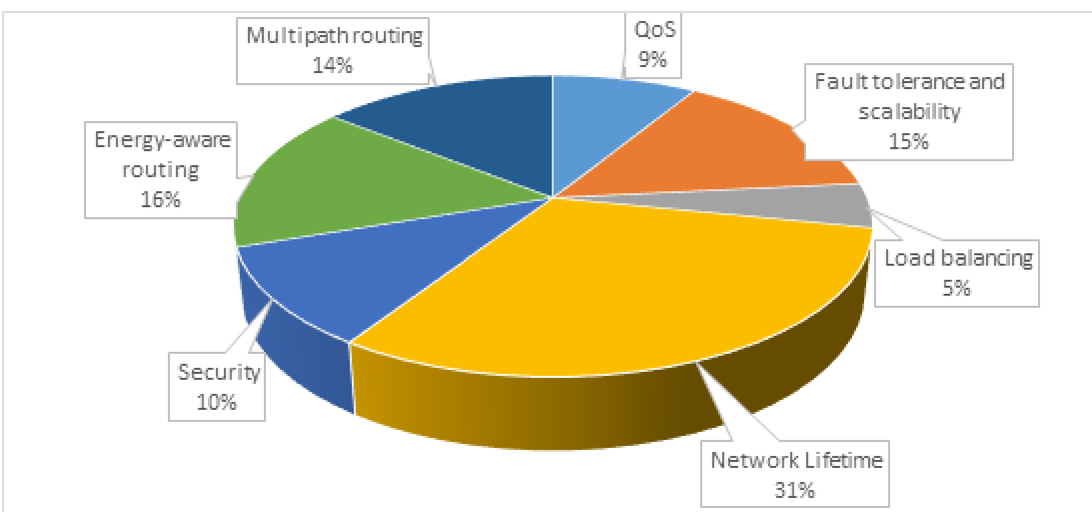

Figure 6.11 Number of other optimisation routing technique articles

6.6 OPEN RESEARCH AREAS

The results of publications on optimisation routing techniques over the past eight years have many implications for future researchers. There is a demonstrable trend in MANET research on the theme of *routing optimisation* (see Figure 6.2) from 2012 onwards with almost 30 publications recorded per year. However, the uptake in the BFO area has not been explored much, as there are only a few articles, (see Figure 6.4). Figure 1 shows the optimisation routing techniques applicable to MANETs, and the seven (7) MANET themes that designers of wireless networks routing need to address when evaluating new MANET routing protocols.

From the results presented in Figures 6.5 – 6.11, it is evident that MANET optimisation routing protocols need to be developed to address the following areas: (i) PSO routing techniques sub-topics, (particularly (a) QoS (b) scalability, and (c) fault tolerance); (ii) ACO routing techniques (sub-topics (a) security and (b) fault-tolerance and scalability); (iii) ABC routing techniques (sub-topics, (a) QoS (b) fault tolerance and (c) security); (iv) BFO routing techniques (sub-topics, (a) QoS (b) load balancing (c) fault tolerance and (d) scalability); (v) Genetic based optimisation routing techniques (sub-topics, (a) QoS (b) Security (c) and Load balancing); (vi) Hybrid optimisation routing techniques (particularly (a) QoS (b) Security and (c) Fault tolerance); and (vii) Other optimisation routing techniques (particularly (a) QoS (b) Security (c) Load balancing and (d) Fault tolerance and scalability). Considering the less discussed optimisation routing sub-topics where there are fewer published articles, the following emerge as potential research questions that future researchers could explore:

- *To what extent does factoring the security of nodes that join the network help in prolonging the network lifetime of a wireless network?*
- *Can factoring QoS, fault tolerance and scalability improve network lifetime and reduce data packet delay on wireless networks using BFO and PSO techniques?*
- *To what extent do consideration of QoS factors during route discovery and data communication enhance the network lifetime of MANET networks?*
- *To what extent do hybrid swarm-based optimisation methods (ABC-BFO) combined with genetic based optimisation methods solve multi-objective optimisation problems? Can they achieve better results such as enhancing network lifetime and reducing average end-to-*

end delay as compared to using one swarm-based or non-swarm optimisation routing approaches?

- *To what extent do a combination of scalability, fault tolerance and energy-aware techniques reduce routing overhead during route discovery, communication and maintenance in MANET networks using ABC and BFO optimisation approaches?*

6.7 COMPARATIVE EVALUATIONS OF OPTIMISATION ROUTING TECHNIQUES

This section presents the evaluation of nature-inspired routing methods mainly ACO, PSO, BFO, ABC and the proposed Queuing swarm-based optimisation method. Table 6.1 shows the strengths and weaknesses of the nature-inspired routing methods including the proposed Queuing Swarm-based routing method. From the analysis of the strengths relative to weaknesses of each method, it is evident that the proposed Queuing Swarmed-based method is better in prolonging the network lifetime and has greater throughput relative to the other nature-inspired routing methods.

It is evident in Table 6.1 that all nature-inspired routing methods strive for increasing the network lifetime so that communication can happen for a greater period of time as there is abundant literature on improving network lifetime in ad hoc networks. QoS metrics have not been adequately addressed especially on the combined metrics of average end-to-end delay, throughput, routing overhead, average jitter and security being addressed in one routing method.

Table 6.1 Comparison of queuing swarm relative to other optimisation routing techniques

Criterion	ABC	PSO	ACO	BFO	Proposed Queuing Swarm approach
Energy-aware	Clustering approach to save energy	Mostly clustering to serve battery lives	Multipath used to save battery lives	Mostly hybridised with other approaches to save battery lives	Energy-aware since stability and remaining battery lives is considered before choosing the path
Scalability and fault-tolerance	Few articles focussed on scalability to fault tolerance	Clustering approach mostly used and is scalable since new node join existing clusters or can form their own clusters depending on their location in the MANET network	Mostly single path routing approach is used and hence it is not fault tolerance since it requires time for ants to reinforce on other previously found routes	Multipath approach is adopted to enable fault tolerance	The proposed approach is scalable and fault tolerance since it explores node mobility, clusters the network and uses multipath approach and explores node's remaining battery lives in determining the routes.
Network lifetime	Literature is available that focussed more on extending network lifetime	Literature is available that focussed more on extending network lifetime	Literature is available that focussed more on extending network lifetime	Literature is available that focussed more on extending network lifetime	Checking of nodes remaining battery lives and the congestion metric for next-hop neighbours improves the network lifetime
QoS-aware	Little has been done to integrate a number of QoS parameters in routing optimisation	Little has been done to integrate a number of QoS parameters in routing optimisation	Significant strides have been made to integrate several QoS. Security aspect is still missing.	No work has been done in routing optimisation that focussed on QoS	Integration of QoS involving security is an area that can be explored further by future researchers

CHAPTER 7. CONCLUSION AND FUTURE DIRECTIONS

7.1 OVERVIEW OF THE STUDY/ RESEARCH SUMMARY

The objective of this study was to solve the problems associated with efficient routing of data packets in MANET networks. The main objective was to **develop a shortest path routing protocol that is congestion-aware and improve the wireless ad hoc network performance.** This main objective was accomplished in Chapter 3 in Section 3.8, Section 3.9 and Section 3.10. A framework which is based on queuing and swarm-based optimisation was presented. Nodes in MANET are buffer limited and data packets which come when the node's buffer is full are placed in queue or the data packets may end up being dropped. The general queuing theory and swarm-based optimisation were presented in Chapter 3 Section 3.8, from which two sub-frameworks were generated. These were termed Q-PSO and QUACS. Simulation results underpinned on the two sub-frameworks were presented in Chapter 4 and Chapter 5. Simulations results showed that with the proposed nature-inspired routing approaches, which are all congestion-aware being Q-PSO and QUACS, performed better relative to other routing methods. This main objective was supported by the following sub-objectives:

To demonstrate a reliable method of identifying routing framework for MANET network in addressing congestion status, stability of nodes and load balancing in ad hoc networks. This sub-objective was addressed in Chapter 3 Section 3.10. A QUACS routing framework was presented and thereafter QUACS routing protocol was generated which combined both the ant colony optimisation and queuing theory.

To develop an efficient routing technique that computes stability factor of nodes and levels of congestion on the network and determine if factoring nodes' stability and congestion levels improve packet delivery ratio and reduce average end-to-end delay in the ad hoc networks. This sub-objective was accomplished in Chapter 5 Section 5.1 and Section 5.2. Prior to determining the path to route data packets, the stability of nodes is explored, and stable nodes are chosen for routing data packets. This therefore minimises chances of using a route that has nodes with high chances of leaving the network. Again, the congestion metric is computed when hopping from one node to the other till the destination node and least congested routes are chosen ahead of those route(s) that are heavily congested. This helps in minimising average end-to-end delay and increases high packet delivery ratio as shown in results section of Chapter 5 Section 5.1 and Section 5.2.

To develop an improved nature-inspired routing protocol that ensures load balancing on the wireless network and determine whether it improves the performance of the network. The weakness of routing approaches that attempt to address load balancing in wireless ad hoc networks has been addressed by multipath routing approach in Q-PSO method which has been presented in Chapter 3 Section 3.9. The proposed O-PSO routing method was tested relative to other routing methods and the simulations showed that Q-PSO especially multipath routing performance exceeds those of other routing methods it was compared to in terms of network lifetime, average jitter, average end-to-end delay and routing overhead.

To design ways to come up with a detailed roadmap for swarm-based optimisation research domains for future wireless networking researchers and academics. MANET optimisation routing framework that can be used as a guide by future researchers who want to explore more on swarm-based optimisation routing techniques have been covered in this study. This is done to determine areas that have not been researched more, and hence still need to be researched further. The MANET optimisation routing framework will assist researchers in exploring the researched and less researched areas. This will provide a niche under which future researchers can base their research on. This objective was addressed in Chapter 6 Section 6.2 and Section 6.5.

7.2 RESOLUTIONS TO RESEARCH QUESTIONS

In trying to solve the problems associated with efficient routing of data packets in MANET networks, the main research question was:

How can a swarm intelligent routing capability support management of congestion-awareness and performance in MANETs?

This has been addressed by the development of the Queuing swarm optimisation framework that was presented in Chapter 3 Section 3.8. The queuing swarm optimisation framework is a hybrid of swarm -based optimisation and queuing theory. Two sub-frameworks focussed on PSO and

ACO all being hybridised with queuing theory were presented to increase the network lifetime and improves packet delivery ratio on the wireless network. The main research question was supported by the following sub-questions:

How can nature-inspired techniques, which check on nodes stability be mimicked to solve shortest path routing problem in MANET networks?

Nature-inspired routing approaches using ACO, BFO, ABC, and ABC have been presented in literature to show how they can be used in routing data packets in MANET networks. This detailed literature review was done in Chapter 2 Section 2.6 up to Section 2.10. However, these four swarm-based optimisation routing methods do not consider the nodes stability factor when routing data packets in MANET. Inclusion of stability during path discovery before routing data packets in MANET has been addressed in the QUACS routing method in Section 3.10.5.

Do hybridisation of nature-inspired routing and queuing theory approaches result in better performance in MANET networks routing?

Two optimisation routing methods that are a result of hybridising swarm-based optimisation coupled with queuing theory were generated and presented in Section 3.9 and Section 3.10. The QUACS and Q-PSO routing methods were compared with other routing methods in Chapter 4 Section 4.2- Section 4.3 and Chapter 5 Section 5.1- Section 5.2. In all the simulations results, the performance of nature-inspired methods hybridised with queuing theory produced better results relative to the routing methods they were compared to. This is mainly because of the ability to check congestion status of the next-hop neighbours before choosing the route in QUACS and Q-PSO routing methods.

How can load balancing routing using multipath and single path routing help in prolonging network lifetime through integrated particle swarm optimisation with queuing theory?

This sub-question was answered in Chapter 3 Section 3.9 with the presentation of the Q-PSO routing method. Load balancing was achieved through adaption of multipath routing approach and the selection of next-hop neighbours was done depending on the congestion status of the neighbour node. Queuing theory hybridised with PSO technique in multipath routing results in fault tolerance. The routes that have a problem due to congestion can be avoided in favour of less congested routes since redundant paths are established during route discovery phase. Performance evaluations of single path and multipath were presented and both outperform the other routing methods they were compared to in the experimental evaluations and results in Chapter 4 Section 4.2 and Section 4.3.

Is there any MANET routing framework based on swarm-based optimisation that guide current and wireless ad hoc network researchers?

This sub-question was answered through detailed literature survey that was done in Chapter 6 Section 6.2 and Section 6.6. A swarm-based optimisation routing framework was presented in Section 6.2 that includes optimisation themes that anyone who wants to explore more on MANET optimisation routing should focus on. There have been uncovering of potential research areas by identifying literature gaps from less researched themes and potential research areas that future researchers should explore more on.

7.3 SUMMARY OF CONTRIBUTIONS

7.3.1 Theoretical contributions

This study contributed to the body of knowledge through coming up with a MANET optimisation routing framework that contains sub-themes. The sub-themes provide the platform from which anyone who would want to research more on wireless ad hoc network can draw an area for more research from the proposed framework. The focus areas of research from which research on MANET optimisation one can routing as presented in Chapter 2 Section 2.4.1 are: network lifetime, quality of service, energy-aware and security.

The sub-themes that emerged from literature were ACO, PSO, ABC, BFO, Genetic and hybridised methods. A MANET optimisation routing framework was presented in Chapter 6 Section 6.2. The literature survey enabled identification of gaps on swarm-based routing optimisation methods. This enabled the researcher to identify that queuing theory and stability factor were not considered in determining potential paths that are efficient in relaying data packets from source node to destination node(s).

A new Queuing swarm-based optimisation routing framework was developed in Chapter 3 Section 3.8. The novelty of this queuing framework is that, it incorporates queuing theory in addition to the traditional swarm-based optimisation. This enables increase in: network lifetime, reduced routing overhead and decrease in both average end-to-end delay and average jitter. Low average end-to-end delay and jitter ensures that communication is relayed to the users in a short period of time as compared to the other routing methods under comparison in Chapter 4 Section 4.2 - Section 4.3 and Chapter 5 Section 5.1 - Section 5.2. Achieving a low average end-to-end delay is important, especially when routing data in critical areas such as emergency medical rescue operations where information must be passed and received quickly.

7.3.2 Methodological contributions

The approach that was used in this study started with a detailed review on literature to get the current status quo of swarm intelligence-based routing approaches in MANET. The process involved scouting of journals and conference papers on the domain, that is, swarm-based optimisation routing. Approaches in swarm intelligence such as; ant colony optimisation and particle swarm optimisation have been investigated. Subsequently, different swarm intelligence-based protocols have been studied.

Based on these protocols, the researcher designed, built and implemented new QUACS and Q-PSO protocols. The developed routing methods have proven to be more efficient in terms of prolonging the MANET network lifetime, energy-aware saving in routing data packets across the networks and ensure survivability of the MANET for some time. These routing protocols (being Q-PSO and QUACS) were embedded in the NS-2 simulator to study their performance in comparisons with other protocols that have been developed by previous researchers in the same domain.

Therefore, the methodology adopted in this study was experimental in the sense that it started by coming up with routing protocols that are nature-inspired particularly PSO and ACO. Nature inspired routing protocols were infused with queuing theory making it more efficient in improving network lifetime. Hybridisation of nature-based optimisation and queuing theory proved beyond doubt that it produces better performance results in terms of throughput, packet delivery ratio, average jitter and average end-to-end delay. The proposed Q-PSO and QUACS routing protocols were presented in Chapter 3 Section 3.9 and Section 3.10. Another methodological contribution is the new MANET optimisation routing framework from which future researcher can tap on to enable them to develop better ad hoc network routing protocols.

7.3.3 Conclusions for the empirical study

Nature-inspired protocols have been mimicked in solving the communication challenges in wireless networks. However, but they tend to focus mostly on the 'next-hop' in determining routing path from the source to the destination, which can suffer from congestion-related problems. Focussing on next-hop neighbours only when choosing the shortest path to route data packets can lead into following the path with least number of hops but the path might be congested. This therefore, results in increased average end-to-end delay and average jitter and low packet delivery ratio and throughput. The prime objective of this study was to design an efficient shortest path that is congestion-aware in routing data packets on the MANET. An efficient data packets transfer from the source node to the destination node(s) involving checking the congestion levels of the next-hop neighbours was presented. Two routing methods underpinned on swarm-based routing and queuing theory were presented in Chapter 3 were Q-PSO and QUACS.

Q-PSO routing, starts by clustering the network into logical groups using particle swarm optimisation technique. Then from the clusters formed, a cluster head is selected based on the node with the highest remaining battery live. The nodes are rotated periodically to be eligible to be selected as cluster heads based on residual battery live. Checking of next-hop neighbours that should be chosen as feasible relay cluster heads depends on the congestion status of those cluster head nodes. Communication is done for the cluster by the cluster head node and this has been demonstrated by the simulated results in Chapter 4 Section 4.2 and Section 4.3. Communication being handled by the cluster head node helps in prolonging the network lifetime, decrease routing overhead and decrease in average end-to-end delay and jitter of the MANET network.

The second routing method, QUACS routing method is also nature-inspired based on ant colony optimisation hybridised with queuing theory. The routing method starts by computing the stability factor of the nodes. Only nodes whose stability factor are considered as stable following computation of stability factor are involved in routing ahead of the less stable nodes. Forward and backwards ants are used for route exploration and reinforcing found routes. More pheromones are deposited on the path that has less congestion, thereby improving on the packet delivery ratio and reduced routing overhead. The inclusion of stability factor during route discovery reduces chances of previously found routes breaking up due to nodes moving out of the network. The simulation results in Chapter 5 Section 5.1 and Section 5.2 showed that QUACS produces better performance relative to other colony optimisation routing methods.

7.4 LIMITATIONS AND FUTURE DIRECTIONS

(a) Methodological and Theoretical limitations

This study has presented a novel approach to routing data packets in an efficient way using nature-inspired approaches. Both proposed Q-PSO and QUACS routing methods probabilistically choose routes that have less congestion. However, there exists more opportunity to integrate security aspect in both QUACS and Q-PSO routing methods to be able to check on malicious nodes that can join the MANET network. Malicious nodes might join the network and advertise themselves as having potential route to the destination and divert traffic from the network. This results in denial of service attacks, high average end-to-end delay and low throughput which are not good where quick data communication is needed, especially in emergency medical rescue operations.

The proposed nature-inspired routing methods might need to have been implemented on the live MANET network, but in this research only simulations were done. The literature survey was done using journal and conference proceedings that were only published in English. There might have been an oversight of other journals and conferences that might be relevant to the topic under study due to language barrier.

(b) Future work

The results of publications on optimisation routing techniques over the past eight years (2010-2018) have many implications for future researchers especially on those areas that have not received adequate attention. There is a demonstrable trend in MANET research on the theme of *routing optimisation* (see Figure 6.2) from 2012 onwards with almost 30 publications recorded per year. However, the uptake in the BFO area has not been explored much, as there are only a few articles, (see Figure 6.4). Figure 6.1 shows the optimisation routing techniques applicable to MANETs, and the seven (7) MANET themes that designers of wireless networks routing need to address when evaluating new MANET routing protocols. Considering the less discussed optimisation routing sub-topics where there are fewer published articles, the following emerge as potential research questions that future researchers could explore as presented in Chapter 6 Section 6.6:

- To what extent does factoring the security of nodes that join the network help in prolonging the network lifetime of a wireless network?
- Can factoring QoS, fault tolerance and scalability improve network lifetime and reduce data packet delay on wireless networks using BFO and PSO techniques?
- To what extent do consideration of QoS factors during route discovery and data communication enhance the network lifetime of MANET networks?
- To what extent do hybrid swarm-based optimisation methods (ABC-BFO) combined with genetic based optimisation methods solve multi-objective optimisation problems? Can they achieve better results such as; enhancing network lifetime and reducing average end-to-end delay as compared to using one swarm-based or non-swarm optimisation routing approaches?
- To what extent do a combination of scalability, fault tolerance and energy-aware techniques reduce routing overhead during route discovery, communication and maintenance in MANET networks using ABC and BFO optimisation approaches?

8. REFERENCES

[1] B. Nancharaiah and B. Chandra Mohan, “The performance of a hybrid routing intelligent algorithm in a mobile ad hoc network,” *Comput. Electr. Eng.*, vol. 40, no. 4, pp. 1255–1264, 2014.

[2] G. S. Sharvani, N. K. Cauvery, and T. M. Rangaswamy, “Different types of swarm intelligence algorithm for routing,” *ARTCom 2009 - Int. Conf. Adv. Recent Technol. Commun. Comput.*, pp. 604–609, 2009.

[3] M. Kuchaki Rafsanjani and H. Fatemidokht, “FBeeAdHoc: A secure routing protocol for BeeAdHoc based on fuzzy logic in MANETs,” *AEU - Int. J. Electron. Commun.*, vol. 69, no. 11, pp. 1613–1621, 2015.

[4] “World internet access.” [Online]. Available: https://techpoint.africa/2018/03/08/global-internet-users-to-hit-5billion-by-2025/. [Accessed: 24-Sep-2018].

[5] A. Giagkos and M. S. Wilson, “BeeIP – A Swarm Intelligence based routing for wireless ad hoc networks,” *J. Inf. Sci.*, vol. 265, pp. 23–35, May 2014.

[6] O. Souihli, M. Frikha, and M. Ben Hamouda, “Load-balancing in MANET shortest-path routing protocols,” *Ad Hoc Networks*, vol. 7, no. 2, pp. 431–442, 2009.

[7] S. K. Sahana, M. AL-Fayoumi, and P. K. Mahanti, “Application of Modified Ant Colony Optimization (MACO) for Multicast Routing Problem,” *Int. J. Intell. Syst. Appl.*, vol. 8, no. 4, pp. 43–48, 2016.

[8] P. S. Hiremath and S. M. Joshi, “Energy Efficient Routing Protocol with Adaptive Fuzzy Threshold Energy for MANETs Energy Efficient Routing Protocol with Adaptive Fuzzy Threshold Energy for MANETs,” *Int. J. Comput. Networks Wirel. Commun.*, vol. 2, no. April, pp. 402–407, 2012.

[9] S. Jamali, L. Rezaei, and S. J. Gudakahriz, “An energy-efficient routing protocol for manets: A particle swarm optimization approach,” *J. Appl. Res. Technol.*, vol. 11, no. 6, pp. 803–812, 2013.

[10] S. S. Basurra, M. De Vos, J. Padget, Y. Ji, T. Lewis, and S. Armour, “Energy efficient zone based routing protocol for MANETs,” *Ad Hoc Networks*, vol. 25, pp. 16–37, 2015.

[11] Y. L. Wang, M. Song, Y. F. Wei, Y. H. Wang, and X. J. Wang, “Improved ant colony-based multi-constrained QoS energy-saving routing and throughput optimization in wireless Ad-hoc networks,” *J. China Univ. Posts Telecommun.*, vol. 21, no. 1, pp. 43–53,

2014.

[12] R. Khoshkangini and S. Zaboli, “Efficient Routing Protocol via Ant Colony Optimization (ACO) and Breadth First Search (BFS),” *International Conference on Internet of Things (iThings 2014)*, no. iThings. pp. 375–381, 2014.

[13] M. A. Abid and A. Belghith, “Stability routing with constrained path length for improved routability in dynamic MANETs,” *Pers. Ubiquitous Comput.*, vol. 15, no. 8, pp. 799–810, 2011.

[14] F. Correia and T. Vazão, “Simple ant routing algorithm strategies for a (Multipurpose) MANET model,” *Ad Hoc Networks*, vol. 8, no. 8, pp. 810–823, Nov. 2010.

[15] A. M. Zungeru, L.-M. Ang, and K. P. Seng, “Classical and swarm intelligence based routing protocols for wireless sensor networks: A survey and comparison,” *J. Netw. Comput. Appl.*, vol. 35, no. 5, pp. 1508–1536, Sep. 2012.

[16] M. Azharuddin, P. Kuila, P. K. Jana, and S. Thampi, “Energy efficient fault tolerant clustering and routing algorithms for wireless sensor networks,” *Comput. Electr. Eng.*, vol. 41, no. C, pp. 177–190, 2015.

[17] H. A. Ali, M. F. Areed, and D. I. Elewely, “An on-demand power and load-aware multi-path node-disjoint source routing scheme implementation using NS-2 for mobile ad-hoc networks,” *Simul. Model. Pract. Theory*, vol. 80, pp. 50–65, 2018.

[18] A. Mohajerani and D. Gharavian, “An ant colony optimisation based routing algorithm for extending network lifetime in wireless sesnor networks,” *J. Wirel. Networks*, vol. 22, pp. 637–2647, 2016.

[19] N. Papanna, A. R. M. Reddy, and M. Seetha, “EELAM: Energy efficient lifetime aware multicast route selection for mobile ad hoc networks,” *Appl. Comput. Informatics*, Vol 15 Issue 2, pp. 120-128, 2017.

[20] S. Chatterjee and S. Das, “Ant colony optimization based enhanced dynamic source routing algorithm for mobile Ad-hoc network,” *Inf. Sci. (Ny).*, vol. 295, pp. 67–90, 2015.

[21] S. A. Alghamdi, “Load balancing ad hoc on-demand multipath distance vector (LBAOMDV) routing protocol,” *EURASIP J. Wirel. Commun. Netw.*, vol. 2015, no. 1, p. 242, 2015.

[22] M. Mohammadnezhad and A. Ghaffari, “Hybrid routing scheme using imperialist competitive algorithm and RBF neural networks for VANETs,” *Wirel. Networks*, vol. 25,

no. 5, pp. 2831–2849, 2019.

[23] Y. Yue, L. Cao, B. Hang, and Z. Luo, “A swarm intelligence algorithm for routing recovery strategy in wireless sensor networks with mobile sink,” *IEEE Access*, vol. 6, pp. 67434–67445, 2018.

[24] A. Karmel, V. Vijayakumar, and R. Kapilan, “Ant-based efficient energy and balanced load routing approach for optimal path convergence in MANET,” *Wirel. Networks*, 2019.

[25] R. C. Biradar and S. S. Manvi, “Reliable neighbor based multipath multicast routing in MANETs,” *Commun. Comput. Inf. Sci.*, vol. 132 CCIS, no. PART 2, pp. 33–43, 2011.

[26] H. Safa, M. Karam, and B. Moussa, “Journal of Network and Computer Applications PHAODV : Power aware heterogeneous routing protocol for MANETs,” *J. Netw. Comput. Appl.*, vol. 46, pp. 60–71, 2014.

[27] W. A. Jabbar, M. Ismail, R. Nordin, and S. Arif, Power-efficient routing schemes for MANETs: A survey and open issues, *Wireless networks* vol. 23, No. 6., pp. 1917-1952 Springer US, 2017.

[28] R. K. Singh, T. P. Singh, and J. Vats, “Load Balancing in Mobile Ad-Hoc Networks: A Review.,” *Int. Journal of Advanced Research in Computer Science,* Vol2, No. 3, pp. 324-328, 2011.

[29] M. Al-Obaidy and A. Ayesh, “Energy efficient algorithm for swarmed sensors networks,” *Sustain. Comput. Informatics Syst.*, vol. 5, pp. 54–63, 2015.

[30] T. Senthilkumaran and V. Sankaranarayanan, “Dynamic congestion detection and control routing in ad hoc networks,” *J. King Saud Univ. - Comput. Inf. Sci.*, vol. 25, no. 1, pp. 25–34, 2013.

[31] P. Antoniou, A. Pitsillides, T. Blackwell, A. Engelbrecht, and L. Michael, “Congestion control in wireless sensor networks based on bird flocking behavior,” *Comput. Networks*, vol. 57, no. 5, pp. 1167–1191, 2013.

[32] G. S. , Jung-Yoon Kim, Tomar, L. Shrivastava, and S. S. Bhadauria, “Load balanced congestion adaptive routing for randomly distributed mobile adhoc networks,” *Wirel. Pers. Commun.*, vol. 77, no. 4, pp. 2723–2733, 2014.

[33] S. Halder, M. Mazumdar, P. Chanak, and I. Banerjee, “FTLBS : Fault Tolerant Load Balancing,” *Proceedings from the Innternal Conferene on Advances in Computing and Information Technology,* pp. 621–631, 2012

[34] S. Gajurel and Mark Heiferling, "A Distributed Location Service for MANET using Swarm Intelligence," *2009 IEEE Mobile WiMAX Symposium*, pp. 220-225, 2009.

[35] S. Saha and S. S. Pathak, "A NOVEL SWARM INTELLIGENCE BASED ROUTING SCHEME FOR MANET USING WEIGHTED PHEROMONE PATHS," in *IEEE MILCOM 2006 - 2006 IEEE Military Communications conference, Washington, DC* , pp. 1–7, 2006.

[36] M. H. Hassan, M.A. Jubair, S.A Mostafa, H. Kamaludin, A.Mustapha, M.F.Fudzee and H. Mahdin, "A general framework of genetic multi-agent routing protocol for improving the performance of manet environment," *IAES Int. J. Artif. Intell.*, vol. 9, no. 2, pp. 310–316, 2020.

[37] H. Shokrani and S. Jabbehdari, "A Survey of Ant-Based Routing Algorithms for Mobile Ad-hoc Networks," in *International Conference on Signal Processing Systems*, pp. 323–329, 2009.

[38] M. Moza and S. Kumar, "Improving the Performance of Routing Protocol using Genetic Algorithm," *Int. J. Comput. Netw. Inf. Secur.*, vol. 8, no. 7, pp. 10–16, 2016.

[39] U. Suganya, B. Saranya, M. Sathiya, R. Gowthami, and G. Karpagam, "Improving Multicast Capacity in Mobile Ad Hoc Network by using Cluster based Hybrid Multi-Path Routing Algorithm," *Compusoft*, vol. 4, no. 5, pp. 1748–1753, 2015.

[40] K. Khan and W. Goodridge, "Fault Tolerant Multi-Criteria Multi-Path Routing in Wireless Sensor Networks," *Int. J. Intell. Syst. Appl.*, vol. 7, no. 6, pp. 55–63, 2015.

[41] R. Desai, "Maximizing Throughput using Adaptive Routing Based on Reinforcement Learning," vol. 3395, pp. 3391–3395, 2017.

[42] H. N. Saha and P. Mitra, "Intelligent Energy Aware Fidelity Based On-Demand Secure Routing Protocol for MANET," *Int. J. Comput. Netw. Inf. Secur.*, vol. 10, no. 4, pp. 48–64, 2018.

[43] P. I. Basarkod and S. S. Manvi, "Mobility and QoS aware anycast routing in Mobile ad hoc Networks," *Comput. Electr. Eng.*, vol. 48, pp. 86–99, 2015.

[44] G. A. Walikar and R. C. Biradar, "A survey on hybrid routing mechanisms in mobile ad hoc networks," *J. Netw. Comput. Appl.*, vol. 77, Issue C, pp. 48–63, 2017.

[45] R. M. Ramadan, S. M. Gasser, M. S. El-Mahallawy, K. Hammad, and A. M. El Bakly, "A memetic optimization algorithm for multi-constrained multicast routing in ad hoc

networks," *PLoS One*, vol. 13, no. 3, pp. 1–18, 2018.

[46] S. Yang, H. Cheng, and F. Wang, "Genetic Algorithms With Immigrants and Memory Schemes for Dynamic Shortest Path Routing Problems in Mobile Ad Hoc Networks," in *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART C: APPLICATIONS AND REVIEWS*, pp. 52–63, 2010.

[47] C.Priyadharshini and K.ThamaraiRubini, "PSO BASED ROUTE LIFETIME PREDICTION ALGORITHM FOR MAXIMIZING NETWORK LIFETIME IN MANET," in *IEEE 2012 International Conference on Recent Trends in Information Technology, Chennai, Tamil Nadu*, pp. 270–275, 2012.

[48] C. J. Arthi Arumugam, "Secure Multicast Tree Construction Using Bacterial Foraging Optimization (BFO) for MANET," *Circuits Syst.*, vol. 7, pp. 4154–4168, 2016.

[49] S. M. Adam and R. Hassan, "Delay aware reactive routing protocols for qos in manets: A review," *J. Appl. Res. Technol.*, vol. 11, no. 6, pp. 844–850, 2013.

[50] U. Bharti and M. Trehan, "Routing Protocol in Mobile Ad-Hoc Networks : A Review," vol. 7, no. 4, pp. 4–7, 2016.

[51] L. Naik.L, R. U.Khan, and R. B.Mishra, "Analysis of Node Density and Pause Time Effects in MANET Routing Protocols using NS-3," *Int. J. Comput. Netw. Inf. Secur.*, vol. 8, no. 12, pp. 9–17, 2016.

[52] K. Khan and W. Goodridge, "Energy Aware Ad Hoc On-Demand Multipath Distance Vector Routing," *Int. J. Intell. Syst. Appl.*, vol. 7, no. 7, pp. 50–56, 2015.

[53] R. Suraj, S. Tapaswi, S. Yousef, K. K. Pattanaik, and M. Cole, "Mobility prediction in mobile ad hoc networks using a lightweight genetic algorithm," *Wirel. Networks*, vol. 22, no. 6, pp. 1797–1806, 2016.

[54] D. J. Persis and T. P. Robert, "Reliable Mobile Ad-Hoc Network Routing Using Firefly Algorithm," *Int. J. Intell. Syst. Appl.*, vol. 8, no. 5, pp. 10–18, 2016.

[55] A. Mahapatro and P. M. Khilar, "Mobility and energy aware distributed clustering protocol for ad hoc sensor networks," *Proc. - 2011 Annu. IEEE India Conf. Eng. Sustain. Solut. INDICON-2011*, vol. 23, no. 2, pp. 105–113, 2011.

[56] Z. Iqbal, S. Khan, A. Mehmood, J. Lloret, and N. A. Alrajeh, "Adaptive Cross-Layer Multipath Routing Protocol for Mobile Ad Hoc Networks," *J. Sensors*, vol. 2016, 2016.

[57] M. Boulaiche and L. Bouallouche-Medjkoune, "EGGR: Energy-aware and delivery

Guarantee Geographic Routing protocol,” *Wirel. Networks*, vol. 21, no. 6, pp. 1765–1774, 2015.

[58] A. Ahmed, A. Hanan, and I. Osman, “Description of Black Hole Attack Behaviour in MANET,” vol. 4, no. 12, pp. 322–329, 2016.

[59] M. Saleem, G. A. Di Caro, and M. Farooq, “Swarm intelligence based routing protocol for wireless sensor networks: Survey and future directions,” *Information Sciences.*, vol. 181, no. 20, pp. 4597–4624, 2011.

[60] N. Kettaf, H. Abouaissa, T. V. Duong, and P. Lorenz, “An efficient QoS routing algorithm for solving MCP in ad hoc networks,” *Telecommun. Syst.*, vol. 33, no. 1–3, pp. 255–267, 2006.

[61] B. Ramachandran and S. Shanmugavel, “Received Signal Strength-based Cross-layer Designs for Mobile Ad Hoc Networks,” *IETE Tech. Rev.*, vol. 25, no. 4, pp. 192–200, 2013.

[62] A. Golestan, M. Fazeli, and A. Patooghy, “A hybrid routing based on ant colony optimization algorithm and fuzzy logic for lifetime enhancement in wireless sensor network,” *Adv. Environ. Biol.*, vol. 8, no. 10, pp. 700–706, 2014.

[63] Y. Jahir, M. Atiquzzaman, H. Refai, A. Paranjothi, and P. G. LoPresti, “Routing protocols and architecture for Disaster Area Network: A survey,” *Ad Hoc Networks*, vol. 82, pp. 1–14, 2019.

[64] R. S. Abujassar, “Mitigation fault of node mobility for the MANET networks by constructing a backup path with loop free: enhance the recovery mechanism for pro-active MANET protocol,” *Wirel. Networks*, vol. 22, no. 1, pp. 119–133, 2016.

[65] P. Deepalakshmi and S. Radhakrishnan, “An ant colony-based multi objective quality of service routing for mobile ad hoc networks,” *Eurasip J. Wirel. Commun. Netw.*, vol. 2011, no. 1, pp. 1–13, 2011.

[66] V. R. Budyal and S. S. Manvi, “ANFIS and agent based bandwidth and delay aware anycast routing in mobile ad hoc networks,” *J. Netw. Comput. Appl.*, vol. 39, no. 1, pp. 140–151, 2014.

[67] D. Sinha and R. Chaki, “MALBACO - A New Multi-Agent Load Balanced Ant Colony Optimization Algorithm for MANETs,” in *IEEE*, 2009, pp. 861–865.

[68] K. M. Bakwad, S.S. Pattanaik, B.S. Sohi, S.Devi, B.K. Panigrahi, S.Das and M.R.

Lohokare , "Hybrid Bacterial Foraging with Parameter free PSO," in *World Congress on Nature & Biologically Inspired Computing (NaBIC 2009)*, 2009, pp. 1077–1081.

[69] Y. Shao and H. Chen, "Cooperative Bacterial Foraging Optimization," in *International Conference on Future BioMedical Information Engineering*, 2009, pp. 484–488.

[70] R. V. Kulkarni, Venayagamoorthy, G. K., A. Miller, and C. H. Dagli, "Network-centric Localization in MANETs based on Particle Swarm Optimization," in *Symposium, IEEE Swarm Intelligence*, 2008.

[71] W. Sun, M. Tang, L. Zhang, Z. Huo, and L. Shu, "A survey of using swarm intelligence algorithms in IoT," *Sensors (Switzerland)*, vol. 20, no. 5, 2020.

[72] S. Prasad, P. Singh, and C. S. Rai, "Swarm Based Intelligent Routing for MANETs" *Int. J. Recent Trends Eng.*, vol. 1, no. 1, pp. 153–158, 2009.

[73] P. Vijayalakshmi, S. A. J. Francis, and J. Abraham Dinakaran, "A robust energy efficient ant colony optimization routing algorithm for multi-hop ad hoc networks in MANETs," *Wirel. Networks*, vol. 22, no. 6, pp. 2081–2100, 2016.

[74] P. Singh, "Favorable Trail Detection using ACO-Bellman Algorithm in VANETs," *Int. J. Mod. Educ. Comput. Sci.*, vol. 8, no. 1, pp. 33–39, 2016.

[75] A. M. Zungeru, L.-M. Ang, and K. P. Seng, "Termite-hill: Performance optimized swarm intelligence based routing algorithm for wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1901–1917, Nov. 2012.

[76] Z. Yiwen, L. Juan, N. Jing, and L. Xiaoyu, "Hybrid artificial bee colony algorithm with chemotaxis behavior of bacterial foraging optimization algorithm," *International Conference on Natural Computation*, 2011, pp. 1171–1174.

[77] H. Sheng, C. Hao-Wen, L. Chun-Ling, and S. Tsung-Ying, "Biologically adaptive artficial bee colony for numerical optimization," in *Fifth International Symposium on Computing and Networking*, 2017, pp. 187–193.

[78] Y. Wanxia, L. Lina, and Zhang Weicum, "Traffic Prediction method based on RBF neural network with improved artcificial bee colony algorithm," in *8th International Conference on Intelligent Networks and Intelligent Systems*, 2015, pp. 141–144.

[79] M. Kaliappan, S. Augustine, and B. Paramasivan, "Enhancing energy efficiency and load balancing in mobile ad hoc network using dynamic genetic algorithms," *J. Netw. Comput. Appl.*, vol. 73, pp. 35–43, 2016.

[80] B. Pongsarum and M. Phayung, “The evaluated measurement of combined genetic algorithm and artficial immune system,” *Int. J. Electr. Comput. Eng.*, vol. 7, no. 4, pp. 2071–2084, 2017.

[81] C. J. A. Bastos-Filho, W. H. Schuler, A. L. I. Oliveira, and L. N. Vitorino, “Routing algorithm based on Swarm Intelligence and Hopfield Neural Network applied to communication networks,” *Electron. Lett.*, vol. 44, no. 16, pp. 995–997, 2008.

[82] M. Sheikhan and E. Hemmati, “PSO-Optimized Hopfield Neural Network-Based Multipath Routing for Mobile Ad-hoc Networks,” *Int. J. Comput. Intell. Syst.*, vol. 5, no. 3, pp. 568–581, 2012.

[83] P. C. Hsiao, T. C. Chiang, and L. C. Fu, “Static and dynamic minimum energy broadcast problem in wireless ad-hoc networks: A PSO-based approach and analysis,” *Appl. Soft Comput. J.*, vol. 13, no. 12, pp. 4786–4801, 2013.

[84] V. V. Mandhare, V. R. Thool, and R. R. Manthalkar, “QoS Routing enhancement using metaheuristic approach in mobile ad-hoc network,” *Comput. Networks*, vol. 110, pp. 180–191, 2016.

[85] V. Mahadevan and F. Chiang, “iACO : A Bio-inspired Power Efficient Routing Scheme for Sensor Networks,” *Int. J.*, vol. 2, no. 6, pp. 972–977, 2010.

[86] R. Vallikannu, A. George, and S. K. Srivatsa, “Autonomous localization based energy saving mechanism in indoor MANETs using ACO,” *J. Discret. Algorithms*, vol. 33, pp. 19–30, 2015.

[87] M. Dorigo, E. Bonabeau, and G. Theraulaz, “Ant algorithms and stigmergy,” *Futur. Gener. Comput. Syst.*, vol. 16, no. 8, pp. 851–871, 2000.

[88] Abdulwahid H., Dai B., Huang B., and Cheu Z., “Scheduled links multicast routing protocols in MANETs,” *J. Netw. Comput. Appl.*, 2016.

[89] W. Li and W. Shen, “Swarm behavior control of mobile multi-robots with wireless sensor networks,” *J. Netw. Comput. Appl.*, vol. 34, no. 4, pp. 1398–1407, Jul. 2011.

[90] D. Kadono, T. Izumi, F. Ooshita, H. Kakugawa, and T. Masuzawa, “An ant colony optimization routing based on robustness for ad hoc networks with GPSs,” *Ad Hoc Networks*, vol. 8, no. 1, pp. 63–76, 2010.

[91] M. Achankunju, R. Pushpalakshmi, and A. V. A. Kumar, “Particle swarm optimization based secure QoS clustering for mobile ad hoc network,” in *International Conference on*

Communication and Signal Processing, ICCSP 2013 - Proceedings, 2013, pp. 315–320.

[92] A. Konak, O. Dengiz, and A. E. Smith, “Improving network connectivity in ad hoc networks using particle swarm optimization and agents,” *Int. Ser. Oper. Res. Manag. Sci.*, vol. 158, pp. 247–267, 2011.

[93] Y. Chen,, Y. Li, G.Wang, Y.Zheng, X.Qian, J.Fan and X.Cui, “A novel bacterial foraging optimisation for feature selection,” *J. Expert Syst. with Appl.*, vol. 83, pp. 1–17, 2017.

[94] J. Abugri and M. Karam, “Particle swarm optimization for minimal lossess in distribution networks,” in *12th International Conference on Information Technology-New Generations*, 2015, pp. 73–78.

[95] R. F. Malik, T. A. Rahman, R. Ngah, and S. Z. . Hashim, “The New Multipoint Relays Selection in OLSR using Particle Swarm Optimization,” *TELKOMNIKA*, vol. 10, no. 2, pp. 343–352, 2012.

[96] E. Gabaldon, F. Guirado, J. L. Lerida, and J. Planes, “Particle swarm optimization scheduling for energy saving in cluster computing heterogenous environments,” in *IEEE 4th International Conference on Future Internet of Things and Cloud Workshops*, 2016, pp. 321–325.

[97] A. Y. Saber, “Economic dispatch using particle swarm opti-mization with bacterial foraging effect.,” *J. Electr. Power Energy Syst.*, vol. 34, pp. 38–46, 2017.

[98] B. Niu, H. Wang, J. Wang, and L. Tan, “Multi-objective bacterial foraging optimisation,” *J. Neurocomputing*, vol. 116, pp. 336–345, 2013.

[99] F. Zhao, J. Si, and J. Wang, “Research on optimal schedule strategy for active distribution network using particle swarm optimization combined with bacterial foraging algorithm,” *J. Electr. Power Energy Syst.*, vol. 78, pp. 637–646, 2016.

[100] H. Chen, B. Niu, L. Ma, W. Su, and Y. Zhu, “Bacterial colony foraging optimization,” *J. Neurocomputing*, vol. 137, pp. 268–284, 2014.

[101] J. Chen, W. Yu, J. Tian, L. Chen, and Z. Zhou, “Image contrast enhancement using artificial bee colony algorithm,” *J. Swarm Evol. Comput.*, vol. 38, pp. 287–294, 2018.

[102] S. Mahajan, N. Dahiya, and D. Kumar, “A mechanism of preventing sybil attack in MANET using bacterial foraging optimization,” in *IEEE Thirteenth International Conference on Wireless and Optical Communications Networks (WOCN)*, 2016.

[103] G. S. Brar, S. Rani, V. Chopra, R. Malhotra, and S. H. Houbing, “Energy Efficient

Direction-Based PDORP Routing Protocol For WSN," *Spec. Sect. Green Commun. Netw. 5G Wirel.*, vol. 4, pp. 3182–3194, 2016.

[104] L. XiaoLong, L. LongJun, and Y. Ping, "A bacterial foraging optimization algorithm based on the particle swarm optimization," in *IEEE Conference*, 2010, pp. 1–6.

[105] B. Pitchaimanickam and S. Radhakrishnan, "A hybrid bacterial foraging using particle swarm optimization algorithm for clustering in wireless sensor networks," in *Proceedings from IEEE International Confer-ence on Science, Engineering and Management Research (ICSEMR)*, 2014.

[106] X. Zhang, X. Zhang, and C. Gu, "A micro-artificial bee colony based multicast routing in vehicular ad hoc networks," *Ad Hoc Networks*, vol. 58, pp. 213–221, 2017.

[107] Z. Zhou, D. Zhao, L. Liu, and P. C. K. Hung, "Energy-aware composition for wireless sensor networks as a service," *Futur. Gener. Comput. Syst.*, vol. 80, pp. 299–310, 2018.

[108] X. Cai, Y. Duan, Y. He, J. Yang, and C. Li, "An energy-efficient and scalable multipath routing protocol for wireless sensor networks," *Int. J. Distrib. Sens. Networks*, pp. 1–14, 2015.

[109] S. Rahmatizadeh, H. Shah-Hosseini, and H. Torkaman, "The ant-bee routing algorithm: A new agent based nature-inspired routing algorithm," *J. Appl. Sci.*, vol. 9, no. 5, pp. 983–987, 2009.

[110] F. Xia, L. Liu, J. Li, A. M. Ahmed, L. T. Yang, and J. Ma, "BEEINFO: Interest-based forwarding using artificial bee colony for socially aware networking," *IEEE Trans. Veh. Technol.*, vol. 64, no. 3, pp. 1188–1195, 2015.

[111] C. Singh, N. Kumar, and V. A. Kumar, "Ant colony algorithms in MANETs: A review," *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 1964–1972.

[112] M. S. A. Thakare and S. A. Ladhake, "Comparison of Ant Based Routing Protocols in Ad hoc Networks," *Int. J. Adv. Res. Comput. Sci. Softw. Eng.*, vol. 2, no. 4, pp. 357–360, 2012.

[113] S. E. Jubin, "Performance Comparison of ACO Algorithms for MANETs.," *Int. J. Adv. Res. Comput. Eng. Technol.*, vol. 2, no. 1, pp. 27–32, 2013.

[114] S. Gopinath and N. Nagarajan, "Energy based reliable multicast routing protocol for packet forwarding in MANET," *J. Appl. Res. Technol.*, vol. 13, no. 3, pp. 374–381, 2015.

[115] C. V. Raghavendran, G. N. Satish, and P. S. Varma, "Intelligent Routing Techniques for

Mobile Ad hoc Networks using Swarm Intelligence," *Int. J. Intell. Syst. Appl.*, vol. 5, no. 1, pp. 81–89, 2012.

[116] C. Hung-Li, C. Ping-Cheng, and H. Tsung-Chuan, "Using particle swarm optimization for enhancing hierarchical cell relay routing protocol," in *Third International Conference on Networking and Computing*, 2012, pp. 125–129.

[117] P. Ramachandran and M. Dinakaran, "Signal strength and residual power based opti-mum transmission power routing for mobile ad hoc networks," *Procedia Comput. Sci.*, vol. 92, pp. 168–174, 2016.

[118] J. Wang, Y. Cao, H. Kim, and S. Lee, "Particle swarm optimization based clustering algorithm with mobile sinks for WSN," *J. Futur. Gener. Comput. Syst.*, vol. 76, pp. 452–457, 2017.

[119] P. P. Pham and S. Perreau, "Increasing the network performance using multipath routing mechanism with load balance," *J. ad hoc networks*, vol. 2, pp. 433–459, 2004.

[120] J. Li, M. Sheng, Y. Xu, J. Li, and X. Jiang, "On throughput capacity for a class of buffer-limited MANET," *J. Ad hoc Networks*, vol. 37, pp. 354–367, 2016.

[121] J. Sztrik, "Basic Queueing Theory," in *E-book on Basic Queueing Theory*, 2010, pp. 1–193.

[122] G. Degirmenci, J. P. Kharoufeh, and R. O. Baldwin, "On the performance evaluation of query-based wireless sensor networks," *J. Perform. Eval.*, vol. 70, pp. 124–147, 2013.

[123] S. T. Shitalkumar Jain, Shrikant Kokate, Pranita Thakur, "A Study of Congestion Aware Adaptive Routing Protocols in," *Comput. Eng. Intell. Syst.*, vol. 3, no. 4, pp. 64–74, 2012.

[124] R. Ali and F. Zafar, "Bandwidth Estimation in Mobile Ad-hoc Network (MANET)," *J. Comput. Sci.*, vol. 8, no. 5, pp. 331–338, 2011.

[125] Z. Wei and L. Duo, "Routing in wireless sensor network using artificial bee colony algorithm," in *International Conference on Wireless Communication and Sensor Networks*, 2014, pp. 280–284.

[126] A. Nayyar and R. Singh, *IEEMARP- a novel energy efficient multipath routing protocol based on ant Colony optimization (ACO) for dynamic sensor networks*. Journal of Multimedia Tools and Applications, 2019.

[127] S. Kumari, "An Advanced Routing Model with Network Splitting Strategy for Vehicular Adhoc Networks (VANETS)," *Int. J. Sci. , Eng.*, vol. 8, no. 48343, pp. 38–41, 2018.

[128] J. Kumar, S. Tripathi, and R. K. Tiwari, “Routing protocol for wireless sensor networks using swarm intelligence-ACO with ECPSOA,” *Proc. - 2016 15th Int. Conf. Inf. Technol. ICIT 2016*, pp. 23–27, 2017.

[129] R. Chaudhry, S. Kumar, and T. Neetesh, “Forwarding Zone enabled PSO routing with Network lifetime maximization in MANET,” *IEEE Access*, vol. 9, no. 3, pp. 3053–3080, 2018.

[130] Y. N. Guo, J. Cheng, S. Luo, D. Gong, and Y. Xue, “Robust Dynamic Multi-Objective Vehicle Routing Optimization Method,” *IEEE/ACM Trans. Comput. Biol. Bioinforma.*, vol. 15, no. 6, pp. 1891–1903, 2018.

[131] Yannis Marinakis, M. Marinaki, and A. Migdalas, *Particle swarm optimization for vehicle rouitng problem: A survey and as comparative analysis*. Springer, Chams, 2018.

[132] B. Velusamy and S. C. Pushpan, “A review on swarm intelligence based routing approaches,” *Int. J. Eng. Technol. Innov.*, vol. 9, no. 3, pp. 182–195, 2019.

[133] P. S. Mann and S. Singh, “Improved artificial bee colony metaheuristic for energy-efficient clustering in wireless sensor networks,” *Artif. Intell. Rev.*, vol. 51, no. 3, pp. 329–354, 2019.

[134] C. J. Joshua and V. Varadarajan, “An optimization framework for routing protocols in VANETs: a multi-objective firefly algorithm approach,” *Wirel. Networks*, vol. 0123456789, 2019.

[135] N. Prathviraj and S. L. Deshpande, “Rough set based QoS enabled multipath source routing in MANET,” *Int. J. Electr. Comput. Eng.*, vol. 10, no. 2, pp. 1915–1923, 2020.

[136] P. Zhou, “Survey of Ant Colony Routing Protocols for Mobile Ad Hoc Networks,” in *International Conference on Computational and Information Sciences*, 2013, pp. 1595–598.

[137] C. Mergenci and I. Korpeoglu, “Routing in delay tolerant networks with periodic connections,” *Eurasip J. Wirel. Commun. Netw.*, vol. 2015, no. 1, 2015.

[138] Z. Sun, C. Xu, T.Wang, Y. Nie, X. Xing and J.Lue, “An Energy-Efficient Cross-Layer-Sensing Clustering Method Based on Intelligent Fog Computing in WSNs,” *IEEE Access*, vol. 7, pp. 144165–144177, 2019.

[139] R. Hajlaoui, E. Alsolami, T. Moulahi, and H. Guyennet, “Construction of a stable vehicular ad hoc network based on hybrid genetic algorithm,” *Telecommun. Syst.*, vol. 71,

no. 3, pp. 433–445, 2019.

[140] N. Melaouene and R. Romadi, "An enhanced routing algorithm using ant colony optimization and VANET infrastructure," *MATEC Web Conf.*, vol. 259, pp. 1-5, 2019.

[141] B. O. Sadiq and A. T. Salawudeen, "FANET optimization: A destination path flow model," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 4, pp. 4381–4389, 2020.

[142] S. Hasdemir, S. Yilmaz, and S. Sen, "A novel multi-featured metric for adaptive routing in mobile ad hoc networks," *Appl. Intell.*, vol. 49, no. 8, pp. 2823–2841, 2019.

[143] C. Nallusamy and A. Sabari, "Particle Swarm Based Resource Optimized Geographic Routing for Improved Network Lifetime in MANET," *Mob. Networks Appl.*, vol. 24, no. 2, pp. 375–385, 2019.

[144] F. Aftab, A. Khan, and Z. Zhang, "Hybrid Self-Organized Clustering Scheme for Drone Based Cognitive Internet of Things," *IEEE Access*, vol. 7, pp. 56217–56227, 2019.

[145] A. Khan, F. Aftab, and Z. Zhang, "BICSF: Bio-Inspired Clustering Scheme for FANETs," *IEEE Access*, vol. 7, pp. 31446–31456, 2019.