Quality of Service Aware Routing Protocol for Flying Adhoc Networks

*A **Thesis***

Submitted in fulfillment of the requirements for the award of degree of

Doctor of Philosophy

by

Atul Malhotra

(Registration no. 951603001)

under the supervision of

Dr. Sanmeet Kaur

Associate Professor

Department of Computer Science and Electrical Engineering,

Eastern Washington University, Spokane, WA, USA

(Formerly Associate Professor, Computer Science and Engineering Department

Thapar Institute of Engineering and Technology, Patiala, Punjab, INDIA)

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

June 2024

Contents

List of Figures

List of Tables

List of Algorithms

List of Abbreviations

MANET	Mobile Adhoc Network
FANET	Flying Adhoc Network
UAV	Unmanned Aerial Vehicle
VANET	Vehicular Adhoc Network
DSDV	Destination Sequenced Distance Vector
OLSR	Optimized Link State Routing
AODV	Adhoc On-demand Distance Vector
TORA	Temporally Ordered Routing Algorithm
ZRP	Zone Routing Protocol
HWMP	Hybrid Wireless Mesh Protocol
GPSR	Greedy Perimeter Stateless Routing
DSR	Dynamic Source Routing
ARPAM	Adhoc Routing Protocol for Aeronautical Mobile Adhoc Network
USMP	UAV Search Mission Protocol
DOLSR	Directional Optimize Link State Routing Protocol
MPR	Multi Point Relays
MPCA	Mobility Prediction Clustering Algorithm
RGR	Reactive Greedy Reactive
GPMOR	Geographic Position Mobility Oriented Routing
GRHAA	Geographical Routing Protocol for Heterogeneous Aircraft Adhoc Networks
P-OLSR	Predictive-Optimized Link State Routing
ML-OLSR	Mobility and Load aware-Optimized Link State Routing
BR-AODV	Boids of Reynolds-Adhoc On-demand Distance Vector
GCS-Routing	Ground Control Station-Routing
FSR	Fisheye State Routing
ECRNET	Energy Aware Cluster-Based Routing in Flying Ad-Hoc Networks
ETX	Expected Transmission Count
GPS	Global Positioning System

DREAM	Distance Routing Effect Algorithm for Mobility
LET	Link Expiration Time
OLSR-ETX	Optimized Link State Routing-Expected Transmission Count
GPNC-SP	Grid Position No Center-Sensitive Protocol
G-OLSR	Greedy Optimized Link State Routing
LCO-OLSR	Low Control Overhead Optimized Link State Routing
LEBR	Link Availability Estimation Based Routing
RREQ	Route Request
RREP	Route Reply
AFP	Adaptive Forwarding Protocol
FGQPA	Fountain-code based Greedy Queue and Position Assisted
PAR	Power Allocation and Routing
MQSPR	Multiple Quality of Service Parameters based Routing
ADRP	Adaptive Density-based Routing Protocol
SARP	Stable Ant-based Routing Protocol
FANT	Forward ANT
BANT	Backward ANT
NS2	Network Simulator 2
LSTM	Long Short Term Memory
QMR	Q-learning based Multi-objective optimization Routing
Q-FANET	Q-Learning based routing protocol for FANET
FNTAR	Future Network Topology-aware Routing
DSR-PM	Dynamic Source Routing protocol based on path reliability and link monitoring repair
PAPR	Packet Arrival Prediction Routing
QTAR	Q-Learning-Based Topology-Aware Routing
S-ELHR	Stability-based Energy- Efficient Link-State Hybrid Routing
ADS-B	Automatic Dependent Surveillance-Broadcast
GCS	Ground Control System
DTN	Delay Tolerant Networks
A-GR	ADS-B system aided geographic routing
DRS	Directional Routing Scheme
RARP	Robust and Reliable Predictive Routing
GeoSaw	Geographic Spray and Wait
GRP	Geographical Routing Protocol

SRS	Skeleton Routing Scheme
ECRNET	Energy-aware Cluster based Routing
IMRL	Intelligent Multi-hop Route Localization
BICSF	Bio-Inspired Clustering Scheme for FANETs
DPSO	Directional Particle Swarming Optimization
NCMCR	Network Coding based Multipath Cooperative Routing
RLNC	Random Linear Network Coding
ETT	Estimated Transmission Time
NC-OLSR	Network Coding based Optimized Link State Routing
SD-UAVA	Software Defined Unmanned Areal Vehicle Architecture
RTORA	Rapid Re-establish Temporally Ordered Routing Algorithm
UPD	Update packet
CLR	Cleared Packet
LEPR	Link Stability Estimation-based Preemptive Routing
NS3	Network Simulator-3
JarmRout	Jamming Resilient Multipath Routing Protocol
XLinGO	Cross-layer Link quality and Geographical-aware beaconless Opportunistic Routing
PPA	Positive Progress Area
NPA	Negative Progress Area
DFD	Dynamic Forwarding Delay
QARP	Quality of Service Aware Routing Protocol
GQPSO	Gaussian Quantum Particle Swarm Optimization
MDRMA	Multi-Data Rate Mobility-Aware
MA-DP-AODV	Mobility Aware and Dual Phase Adhoc On-demand Distance Vector
MDA-AODV	Mobility and Direction Aware Ad-hoc on Demand Distance Vector Routing

Certificate

I hereby certify that the work which is being presented in this thesis entitled “**Quality of Service Aware Routing Protocol for Flying Adhoc Networks**”, in partial fulfillment of the requirement for the award of degree of “**Doctor of Philosophy**” submitted in Computer Science and Engineering Department, Thapar Institute of Engineering and Technology (Deemed University), Patiala, India, is an authentic record of my own work carried out under the supervision of **Dr. Sanmeet Kaur** and refers other research works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

(**Atul Malhotra**)

Regn. No. 951603001

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

(**Dr. Sanmeet Kaur**)

Associate Professor

Department of Computer Science and Electrical Engineering,

Eastern Washington University, Spokane, WA, USA

(Formerly Associate Professor, Computer Science & Engineering Department

Thapar Institute of Engineering and Technology, Patiala, Punjab, INDIA)

Acknowledgements

First and foremost, I would like to thank **Almighty** for being my strength and pillar (as a humble being) to complete this task successfully. He has given me an opportunity to believe in my passion and pursue my dreams. I could never have done this without his divine blessings. I would like to express my sincere appreciation to my supervisor **Dr. Sanmeet Kaur**, Associate Professor, Department of Computer Science and Electrical Engineering, Eastern Washington University, Spokane, WA, USA (Formerly Associate Professor, Computer Science and Engineering Department, Thapar Institute of Engineering and Technology, Patiala, India), for being a pillar of support and encouragement throughout my research work. Her guidance helped me in all the time of research and writing this thesis. Her experience, strength, tenderness and willfulness, has taught me valuable lessons of life, which are going to be of immense help to me in taking decisions in going forward. I could not have imagined having a better advisor and mentor for my Ph.D study. My sincere thanks are due to **Dr. Shalini Batra**, Associate Professor and Head, Computer Science and Engineering Department (CSED), Thapar Institute of Engineering and Technology (Deemed University), Patiala (India), for providing me the necessary administrative assistance in completion of the work. I am thankful to my Ph.D committee members, **Dr. Shalini Batra**, Professor and Head (CSED), **Dr. A. K. Verma**, Professor (CSED) and **Dr. Rajesh Khanna**, Professor (ECED) for their constructive comments and regularly ensuring the progress of my research work. I would always be very thankful towards the cooperation and encouragement extended to me by all the faculty members of Computer Science and Engineering Department, Thapar Institute of Engineering and Technology (Deemed University), Patiala (India) especially **Dr. Parteek Bhatia** and **Dr. Abhishek Khanna** for sharing their expertise and ideas throughout my Ph.D tenure. I'd also like to thank **Dr. Gurbinder Singh**, Registrar, TIET for his continuous support and faith in me. I offer my deepest gratitude towards my parents, **Smt. Yash** and **Sh. Anil Malhotra** whose love and affectionate blessings have been a constant source of inspiration in making my vision a reality. I am also grateful to my wife **Smt. Sania Malhotra** and my daughter **Ms. Amayra Malhotra** for their love, encouragement, motivation, and confidence in me. I also acknowledge the cooperation and encouragement extended to me by my friends at Thapar Institute of Engineering and Technology, especially **Dr. Abhishek Khanna, Dr. Himanshu Jindal, Dr. Monika Bharti, Ms. Ankita Wadhawan, and Ms. Sugandhi**.

Patiala

June, 2024 (Atul Malhotra)

Abstract

Adhoc networks have been a curious research domain since their inception with the initial adhoc network research focusing on effective routing of data among the nodes. As the adhoc networks do not have any infrastructural device for centralized management and operations, each adhoc node has to fulfil the functionality of an administering node like a router and an end node itself. This setup resulted in the evolution of mobile adhoc networks in which multiple autonomous mobile nodes communicate and exchange data among each other using adhoc routing protocols to fulfil a specific task. With the evolution of UAVs, the mobile adhoc networks got extended into the flying adhoc networks in which multiple autonomously flying nodes communicate with each other independently exchanging data to fulfil the functionality of multiple applications. The primary issue with flying adhoc networks is handling the dynamicity of autonomously flying nodes to effectively exchange data among them. Due the frequent topology changes, varying node speeds, and varying node density, the flying adhoc network exhibit link breakages resulting in packet loss impacting throughput of the network. Also the route recovery process takes time to identify alternative route for packet delivery among nodes. This results in increased end to end delay for packet deliveries. To address these challenges , an efficient Quality of Service Aware Routing Protocol has been proposed for flying adhoc networks. The protocol takes into consideration the dynamic characteristics of flying adhoc networks to formulate a routing mechanism which can effectively route data among the flying nodes. The proposed QARP protocol focuses on identifying the most optimal nodes for forwarding the data to the destination and minimizing the delay in the data delivery. To fulfil these objectives, the proposed QARP adopts the heuristics of nature inspired firefly algorithm to perform the route discovery in which the neighbour nodes with least delay towards the destination are identified for each node in the network. Then the heuristic of gaussian quantum particle swarm optimization algorithm is used to identify the

least delay packet forwarding nodes for data delivery to the destination. The usage of this hybrid approach resulted in achieving efficiency and optimization in terms of packet delivery ratio, delay, throughput, routing overhead, and energy efficiency for delivering packets when compared with other routing protocols like MDRMA, MA-DP-AODV, and MDA-AODV. The comparative analysis has been carried out through the simulation using NS-2.35 simulator. The evaluation of the protocols has been done in three different scenarios of varying node density, varying number of connections, and varying packet transmission rate. In all the three scenarios, the proposed routing protocol performed better in comparison to its counter parts with respect to different performance evaluation parameters. The comparative analysis of the proposed protocol clearly showed its effectiveness in the efficient delivery of data among the flying nodes by reducing the delay, minimizing routing overhead, improving the packet delivery ratio, and increasing the throughput.

Chapter 1

Introduction

Flying Adhoc Networks (FANETs) consist of a group of flying Unmanned Arial Vehicles (UAV) communicating and coordinating with each other to accomplish a designated task without any human involvement. UAVs have realized diversified applications in the form of search and destroy missions, border monitoring, traffic monitoring, remote surveillance, *etc.*, due to which, communication among flying UAVs becomes a subject of interest. Like every other type of adhoc network, FANETs have evolved gradually starting from a single large-sized UAV performing the assigned task to a group of small-sized UAVs collectively operating to fulfill a particular purpose. Using multiple UAVs simplifies the completion of a particular task in contrast to using single UAV as if one of the UAVs becomes dysfunctional, the rest of UAVs can take over the responsibility. Moreover, the involvement of multiple UAVs allows for flexibility in task assignment, coordinated working approach, and failure tolerant collaborative operation. So, multi-UAV systems eliminate the drawback of single-handed operation where if the only node experiences any kind of malfunction, the whole mission is voided.

Flying Adhoc Network (FANET) has emerged as an extension to conventional adhoc networks and have attained a lot of popularity in the recent past due to their ability to provide network connectivity to flying devices in an adhoc mode autonomously. Several applications of FANETs have been identified in [1][2][3], highlighting different spheres of their usages, but routing of data has been a matter of prime concern for FANETs to operate effectively in any of the application scenarios. Data routing in FANETs has been a challenging task as they have further extended some of the challenges faced by Mobile Adhoc Networks (MANETs) and Vehicular Adhoc Networks (VANETs) [4]. Researchers have experimented with the existing routing protocols of MANETs and VANETs in order to evaluate their suitability for FANETs [5, 6, 7, 8, 9]. Figure 1.1 depicts a typical scenario of FANETs in which flying nodes communicate autonomously in varied operational environments.

Figure 1.1: Flying UAVs communicating in adhoc mode

1.1 Difference between FANETs, VANETs, and MANETs

FANETs could be distinctly identified from existing adhoc networks based on their utility, application, connection among nodes and application objectives. The following discussion highlights some key differentiating factors among FANETs and existing adhoc networks.

i. The degree of mobility in case of FANETs is considerably more in comparison to MANETs and VANETs as the nodes in FANETs are flying UAVs and node speeds can go as high as several hundred kilometers per hour.

ii. Corresponding to mobility speed, change in topology is also considerably faster as compared to MANETs and VANETs.

iii. Node density in case of FANETs is considerably less as compared to MANETs and VANETs as UAVs have to be significantly distant apart to avoid any chances of a collision in the air.

iv. In FANETs, the nodes remain in a line of sight for the communication majority of the time, but this may not be the case for MANETs and VANETs.

v. Computational processing and storage capability of FANETs is larger in comparison to MANETs and VANETs.

FANETs exhibit quite dynamic characteristics as compared to other types of adhoc networks due to the inherent differences in their functionality. Due to these distinct characteristics, FANETs have been treated as a separate type of adhoc networks. The following points highlight the key characteristics of FANETs.

i. Flying adhoc networks exhibit a high degree of mobility as a result of high travelling speed of flying nodes.

ii. The location changes happening for the nodes are very frequent in FANETs due to high mobility.

iii. The topology changes occurring for FANETs are also quite high because of frequent location changes happening for nodes.

iv. The density of nodes varies rapidly due to the rapid topology changes.

v. The power consumption required by nodes is high since FANETs have to execute complex tasks collaboratively.

Table 1.1 presents some major differences between MANET, VANET and FANET in a concise manner.

Table 1.1: Difference between MANET, VANET and FANET

Characteristics	MANET	VANET	FANET
Degree of mobility	Low	Medium	High
Location changes	Low	Medium	High
Topology changes	Low	Medium	High
Variation in node density	Low	Medium	High
Power consumption	Low	Medium	High

1.2 Evolution of FANET routing protocols

Since the emergence of adhoc networks, the researchers have tried to establish an effective communication among the mobile nodes without the requirement of infrastructural set up. The first of its kind adhoc network came into existence in the form of Mobile Adhoc Networks (MANETs) which focused on exchanging the packets among the freely moving mobile nodes in the ground. The MANETs then evolved into Vehicular Adhoc Networks (VANETs) which focused on establishing communication among the moving vehicles on

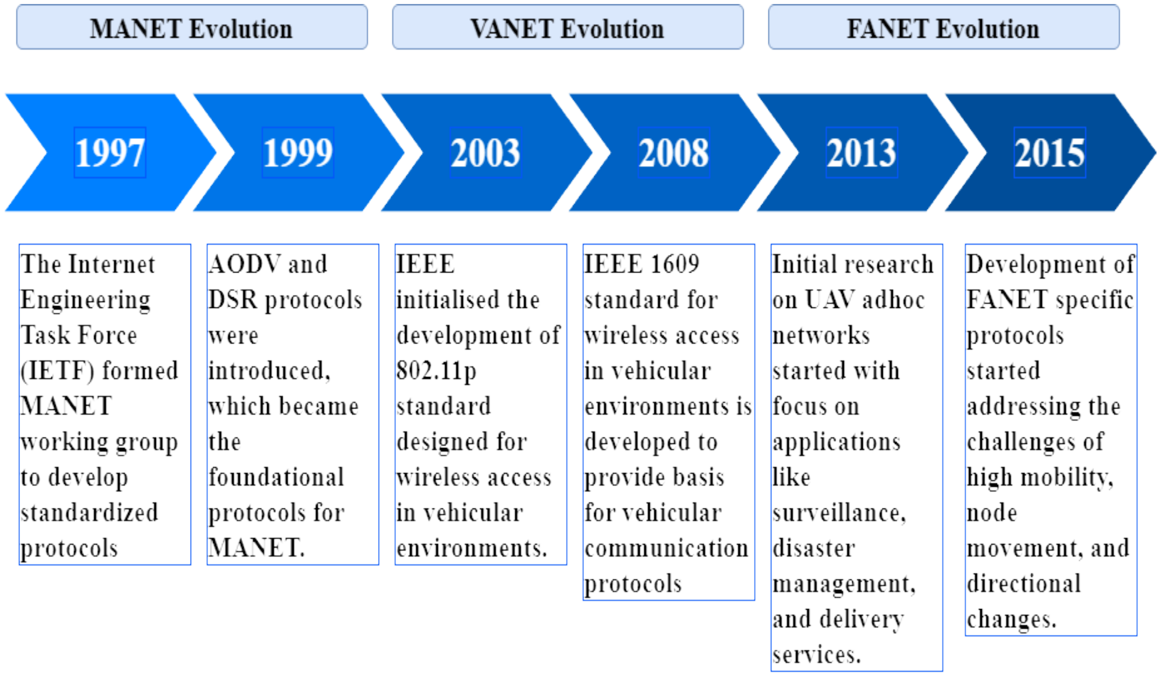


Figure 1.2: Evolution of MANET, VANET, and FANET

roads. With the advent of UAVs, the VANETs got evolved into Flying Adhoc networks (FANETs) which focused on exchanging the data packets among the autonomously flying UAVs. Figure 1.2 depicts the evolution of MANETs, VANETs, and FANETs.

In FANETs, the researchers tried to use existing routing mechanisms for mobile adhoc networks (MANETs) to route data among nodes in FANETs. The existing proactive or table driven routing protocols like Destination Sequenced Distance Vector routing (DSDV) [10] and Optimized Link State Routing (OLSR) [11] had been used for data routing with FANETs. The reactive or on-demand routing protocols such as Adhoc On-demand Distance Vector routing (AODV) [12], Dynamic Source Routing (DSR) [13] and Temporally Ordered Routing Algorithm (TORA) [14] had also been experimented for FANET routing. And the hybrid routing protocols such as Zone Routing Protocol (ZRP) [15] had been used for experimentation to test their suitability with FANETs. However, due to the inherent difference in the characteristics of FANET and MANET, the protocols underperformed for the new kind of adhoc network. In [6], Cheng *et al.* compared AODV, OLSR, and OSPF-MDR [16] routing protocols for their performances. In [17], Balandin *et al.* compared the performances of AODV, OLSR, and HWMP [18] protocols. In [8], Singh *et al.* have carried out an experimental analysis for AODV, DSDV, and OLSR protocols. In [5], Hyland *et al.* have evaluated the performances of AODV, GPSR [19], and OLSR protocols for UAV swarms and in [7], Maxa *et al.* have evaluated the performance of AODV, DSR, and OLSR routing protocols for FANETs.

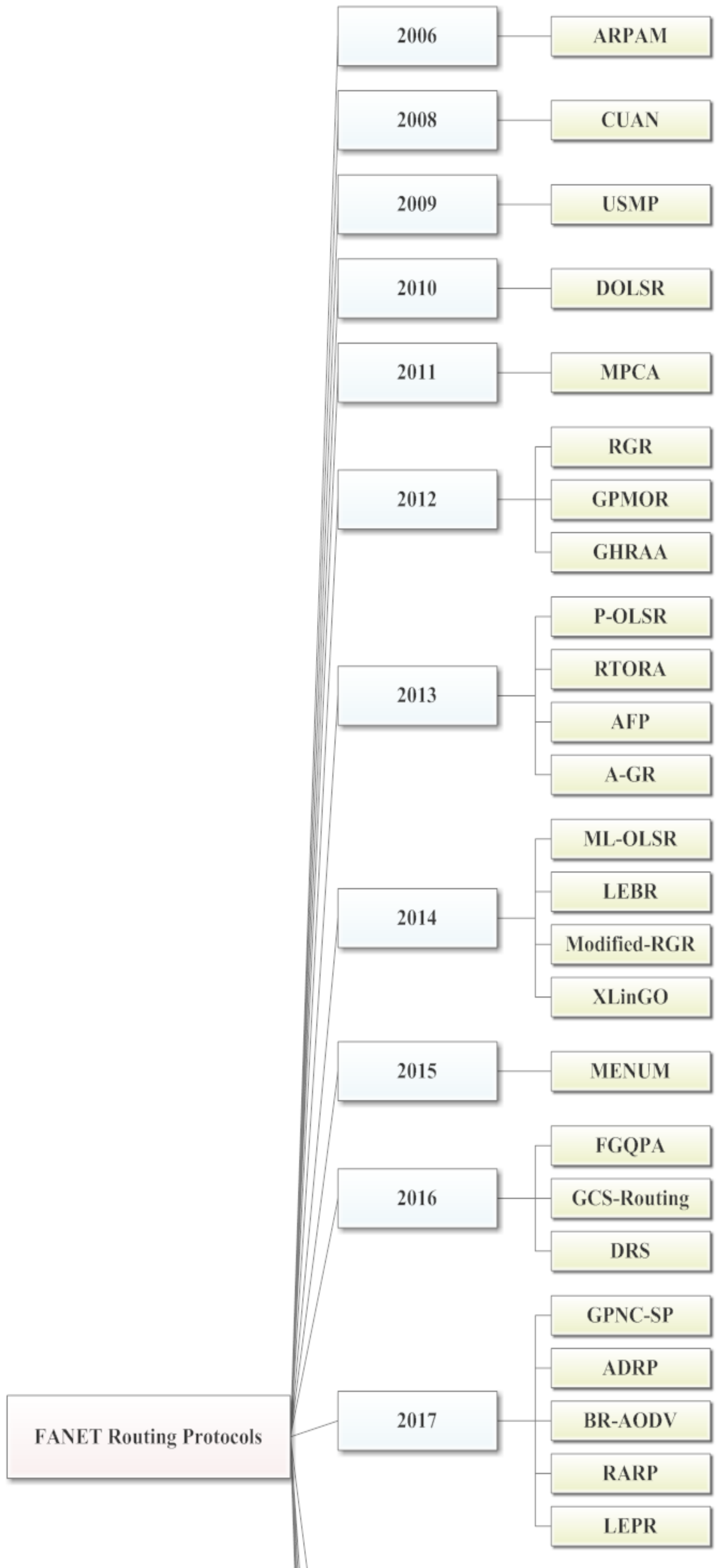
Along with the experimentation of existing MANET routing protocols, routing protocols specifically suited to the requirements of FANETs also started coming into existence. To the best of our knowledge, the first routing protocol specific to FANETs came into existence in the year 2006 in the name of Adhoc Routing Protocol for Aeronautical Mobile Adhoc Network (ARPAM) [20]. The protocol primarily used reactive route identification in combination with node position information to select optimal routes for flying UAVs. In the year 2008, a cluster based mechanism for UAV networking [21] was proposed in order to to enhance UAV cluster formation resulting in an optimal node communication. The cluster formation happened on the ground using the path plan and then the cluster rearrangement occurred in the air as per the status and requirements of inter-UAV communication.

An improved communication protocol the UAV Search Mission Protocol (USMP) [22] was proposed in the year 2009, which used a combination of updated location information and waypoint conflict resolution for nodes, in order to optimize the performance of UAVs for searching missions. In the year 2010, the Directional Optimized Link State Routing Protocol (DOLSR) [23] was introduced as an extension to existing OLSR protocol. The protocol tried to minimize the MPRs by using directional antennas for routing data as well as control information among the nodes. A Mobility Prediction Clustering Algorithm for UAVs (MPCA) [24] was developed in the year 2011, which used a dictionary trie structure prediction algorithm to optimize the formation of UAV clusters and accommodate their high mobility. A

Reactive Greedy Reactive Routing Protocol (RGR) [25] for UAV adhoc network had been proposed in the 2012, which utilised the position information of the nodes along with an on-demand routing procedure based on AODV protocol to optimize routing performance for inter-UAV communication. Also, two more routing protocols namely Geographic Position Mobility Oriented Routing (GPMOR) [26] and Geographical Routing Protocol for Heterogeneous Aircraft Adhoc Networks (GRHAA) [27] were proposed in 2012 . The GPMOR protocol used a mobility prediction function in order to calculate the position of neighbour nodes and the destination and then used a prediction based metric namely metric to connect to identify feasible neighbours to connect and route packets. The GRHAA protocol is an extended form of location aided routing protocol [28] which used predetermined routes available with UAVs to establish a preliminary routing path. The protocol then optimized the established path by predicting the node movements through the utilization of location information of the nodes periodically provided to them using HELLO packets. A diagrammatic representation of the evolution of routing protocols for FANETs has been given in Figure 1.3.

1.3 Routing Protocols for FANETs

Routing protocols provide a method to identify feasible routes among nodes to deliver data to the destination. A taxonomical view of the existing protocols as shown in Figure 1.4 depicts their categorization based on core routing mechanism. Firstly, a basic classification of protocols based on single path and multipath routing has been done. Single path routing mechanisms identify a single feasible route to deliver data to the destination. Multipath routing mechanisms identify multiple parallel routes to efficiently deliver data in a distributive manner. Further, single path and multipath routing protocols have been categorized based on


FANET Routing Protocols
2006
ARPAM
2008
CUAN
2009
USMP
2010
DOLSR
2011
MPCA
2012
RGR
GPMOR
GHRAA
2013
P-OLSR
RTORA
AFP
A-GR
2014
ML-OLSR
LEBR
Modified-RGR
XLinGO
2015
MENUM
2016
FGQPA
GCS-Routing
DRS
2017
GPNC-SP
ADRP
BR-AODV
RARP
LEPR

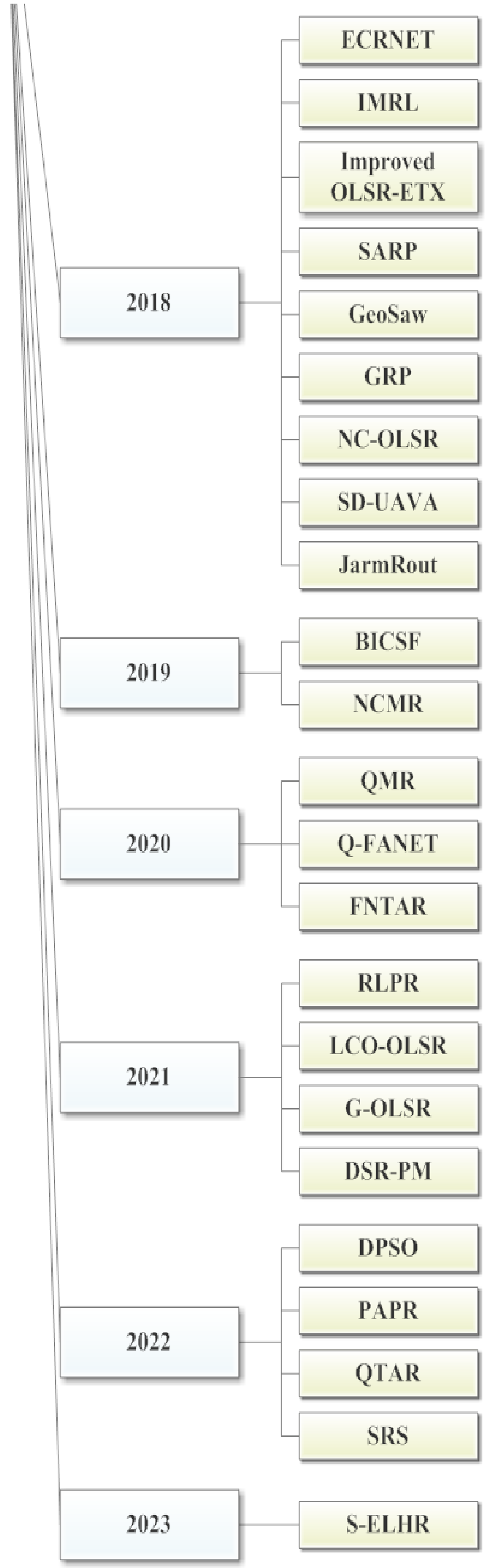


Figure 1.3: Evolution of FANET routing protocols

their core route identification mechanism into proactive, reactive, geographical and hierarchical routing protocols. Basic details of each of these core route identification mechanisms have been mentioned in the following points.

i. Proactive routing protocols: Prominently known as table-driven routing protocols, the proactive protocols store routing information of the entire network in routing table prior to initialization of data routing. The routing table is updated periodically or on the occurrence of a network change. These protocols provide the latest routing information of a network, at the cost of significant routing overhead, which leads to constrained bandwidth usage. As a result, the protocols are not suitable for networks containing a large number of nodes, exhibiting a high degree of mobility in their native form [4]. Table driven protocols as an example include Destination Sequenced Distance Vector Routing (DSDV) [10] and Optimized Link State Routing (OLSR) [11].

   To minimize the shortcomings of conventional adhoc routing protocols, additional functionality has been included into them like position awareness and grid positioning, which allowed the routing protocols to identify the instantaneous status of nodes in the network [29] [30] . Some examples are P-OLSR [31] and ML-OLSR [32].

ii. Reactive routing protocols: Prominently referred to as on-demand routing protocols, the route identification mechanism is initiated as and when required by a source node for packet routing. On the contrary, the routing table of the nodes is vacant, as the routing table is not stored by the nodes when no communication is required among the nodes. This means that nodes only save the route for the current communicating nodes. Since, the protocols do not allow for the periodic exchange of control messages, it leads to conserving the bandwidth for effective communication. However, the reactive route discovery increases the communication delay, before the inter-node communication could

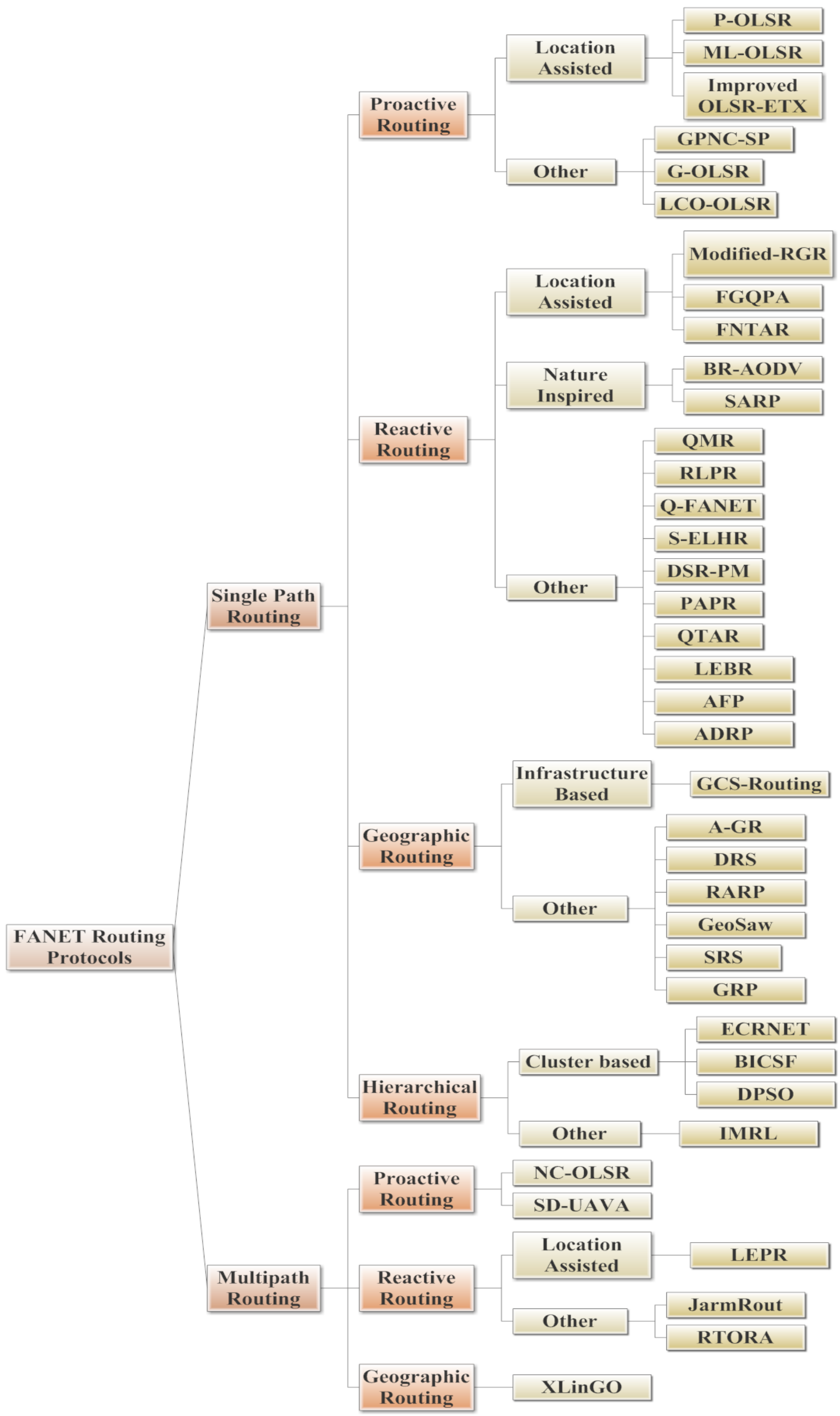


Figure 1.4: Taxonomical view of routing protocols for FANETs

initiate [33, 34]. Such protocols could be suitable in the scenarios of less dense FANETs operating for delay tolerant applications. Reactive routing protocols include Dynamic Source Routing (DSR) [13] and Adhoc On-demand Distance Vector Routing (AODV) [12].

The reactive routing protocols have been extended to include added functionality such as location assistance and nature inspired behaviour of biological creatures. Location assistance allows routing mechanisms to track the current location of fast flying nodes in order to make routing decisions efficiently [35, 36]. Example of such protocols is Modified-RGR [37].

Nature inspired algorithms incorporate the biological behavioral characteristics of any naturally existing entity like insects, birds or animals. These algorithms serve by providing optimized data input to conventional routing mechanisms for producing routing decisions. However, their operational capabilities bring along with them some drawbacks in the form of communication latencies and network overheads. Examples of nature inspired routing protocols are AntHocNet [38], BeeAdhoc [39], and BR-AODV [40].

iii. Geographic/Position based Routing Protocols: Position based or geographic routing protocols utilize the physical position information of the nodes to perform routing operations within the network. These protocols require each node may be equipped with hardware that can provide information about their current location, which will become the base for the route calculation. The protocols work by first estimating the position of the destination node using the information provided by positioning hardware or location prediction technique, and then based on that information, use any appropriate basic routing approach to deliver packets to the destination. Example of position based routing is Greedy Perimeter Stateless Routing (GPSR) [19].

The functionality of position based routing protocols has been augmented by the use of infrastructural devices like ground control systems, in order to take routing decisions centrally and convey them to all the nodes [41]. Example of such routing protocol is GCS-Routing [42].

iv. Hierarchical Routing Protocols: In hierarchical routing protocols, the level of hierarchy becomes the decisive factor for whether to incorporate a proactive approach or reactive approach for performing the routing decisions. Most of the times, the primary routing decisions are delivered using proactively identified routes and thereafter, a reactive approach is used at a higher level of the hierarchy to issue route requests by the nodes. These protocols experience drawbacks in terms of the complexity they offer for routing operations and addressing scheme used for inter-node communication, which ultimately influences the related factors for communication within the network. An example of hierarchical routing protocol is Fisheye State Routing (FSR) [43].

For FANETs, cluster based hierarchical arrangement of nodes has been used to manage routing in the scenarios of high node density. The clustering helps in distributively managing the routing operations by dividing large number of nodes into smaller groups and then performing routing among them. For inter-cluster routing, one node from each cluster holds the responsibility of communicating with other clusters in a particular direction [44]. Example of one such routing protocol is ECRNET [45]

1.4 Design Considerations

Since, FANETs are considered as a separate class of adhoc networks, the differentiating factors among FANETs and other types of adhoc networks have created a need to re-address their existing design considerations. On the other hand, there are some distinct design considerations for FANETs which have been presented in the following points.

i. A flexible and scalable network is always preferred for collaborative task accomplishment. Multi-UAV communication simplifies the completion of a particular assignment by using the distributive work approach [46, 47, 48]. For this kind of communication, efficient FANET routing protocols should be designed to allow numerous UAVs to communicate together with minimal overhead[49].

ii. Adaptiveness is always preferred whenever there is a high possibility of changes in the operational parameters of nodes operating within the network [50, 51]. With a highly dynamic behavior, FANETs require a significant level of adaptiveness to accommodate highly mobile nodes with varying routes and variable inter-distance. To neutralize the inherent dynamicity, FANETs require adaptive physical layer and network layer protocols.

iii. A fail-safe network is always preferred whenever the nodes are operating in an adhoc mode [52, 53]. With a high degree of mobility and autonomous flying characteristics of nodes, there are significant chances of failure due to any kind of hardware or software fault. Alternatively, any kind of network attack against the nodes could also lead to node failure. Environmental conditions such as unexpected weather changes could also lead to deterioration of data links. So, to cater to a fail-safe network, FANETs require adaptive transport layer, network layer, and physical layer protocols [54].

iv. One of the major design considerations for FANETs is latency. Latency becomes an issue whenever we are dealing with time-sensitive FANET applications such as real-time monitoring. For such kind of applications, delayed delivery of data packets could lead to disastrous consequences. Low latency delay sensitive FANET routing protocols are required to be developed to mitigate such issues.

v. For multi-UAV operated FANETs, collecting data from the environment and ground as in the case of search and rescue operations could be a prominent task. During such operations, the flying nodes require relaying the data either in the form of images or videos to the ground stations typically termed as command and control centers. Such kind of communication requires a significant amount of bandwidth with very stringent delay constraints. Moreover, multiple coordinated UAV operations require some amount of bandwidth for primitive communication among nodes for collaboration and control. Also, there are some constraints for bandwidth usage in FANETs such as:

   - Communication channel capacity
   - UAV speed
   - Susceptibility of wireless links to error
   - Broadcast communication with minimalistic security

   So, there is a requirement for the development of protocols which can satisfy the bandwidth demands of FANETs

vi. Implementation of FANETs requires the deployment of FANET hardware on the UAVs. The weight of the hardware is a point of concern as most of the UAVs are lightweight and have a limited weight lifting capability. Also, UAVs are expected to perform a variety of tasks, for which, they are equipped with a variety of sensors. For small sized UAVs, installing FANET hardware in combination with different sensors could become challenging as available space for the installation of such hardware could be limited.

All the discussed design considerations lead a pathway for the development of efficient, scalable, adaptive and dynamic FANETs. Developing communication protocols focusing on these design considerations will help in optimizing inter-node communication and allowing disrupted networks to converge quickly and start communicating with the least possible delay.

1.5 Research Gaps

The literature reviewed in Chapter 2 has given an insight into the numerous existing routing techniques for forwarding data among the flying nodes in FANETs. Some of the protocols have been adapted to be used with FANETs while some other were newly developed routing solutions. Each routing method has its own benefits and drawbacks. Some techniques were able to provide a significant level of effective communication among the flying nodes, while the others were merely getting a feasible route to communicate with the destination [55], in a highly dynamic environment. In an effort to identify and address the shortcomings in the existing routing techniques, the following discussion highlights the issues observed during the literature review:

1. **Infeasible usage of Proactive and Reactive routing approaches for highly dynamic environment**: Proactive and reactive routing approaches have been the primitive routing mechanisms suitable for routing data in adhoc environment, where the proactive approach tends to initially gather the complete network information for routing purpose, the reactive approach tries to identify a route as and when required. But both of these approaches could not effectively provide efficient data delivery to flying nodes in an adhoc environment. Proactive routing fails to keep the routing table updated with the exact route to all the frequently location changing high speed flying nodes [31][17][42], reactive routing struggles to identify a feasible route to deliver the data in a highly dynamic environment with scarce number of nodes [56][17][57][58][35]. Both of these routing approaches have underperformed in providing acceptable packet

delivery ratio, end to end delay and routing overheads. Although some variations of these protocols have been developed, which could enhance the routing performance to a certain extent but still could not provide a reliable communication among the nodes where node density was lesser [59].

2. **Issues with geographic routing approaches**: Geographic routing approaches tend to exploit the location information of the nodes to track the frequently changing node position. For this purpose, they need to exchange extensive amount of control packets at regular intervals, which result in increased network overhead. Although many variation of geographic routing protocols have been developed in [60][61][62][63][26][27][64][22], but were ineffective in sparsely populated FANETs, introduced significant routing overhead and consumed high energy, which revealed their inappropriateness for use in real time applications.

3. **Issues with hierarchical and hybrid routing approaches**: Hierarchical routing is specifically suited to networks with high node density, where the routing effort could be simplified by dividing larger network into smaller clusters and then defining separate routing instances for intra-cluster and inter-cluster routing. Hierarchical routing protocols used for FANETs [65][24][21] showed reasonable performance in delivering data among the flying nodes thereby providing lesser delay and better packet delivery ratio, but consumed extensive time duration for calculating optimal route to the destination, which could lead to routing failure for a highly mobile scenario.

   On the other hand, hybrid routing protocols have also been tested for FANET routing in [17] where it outperformed proactive and reactive protocols in terms of efficient data delivery but was not comfortable in handling high mobility and frequent topology changes for nodes.

4. **Issues with nature inspired routing approaches**: Many nature inspired routing approaches have been discussed based upon ant colony optimization algorithm [66][67][68] and bee colony optimization algorithm [68][69], which were specifically tailored to adapt to varied characteristics of FANET for effectively routing data among nodes. The routing techniques were able to efficiently deliver data with better throughput and lower delays in case of lower node density. But with increased node density, the techniques become inefficient by introducing high routing overheads, lower throughput and high end to end delay resulting in a communication denied network.

   Considering the issues identified in the discussion above [54], there is a stringent requirement to develop a feasible technique for routing data among the flying nodes in an effective and efficient manner without incurring any significant network overhead. Due to increasing utilization of self flying UAVs for replacing conventional human involvement like goods delivery, surveillance, search and destroy military operations, agricultural implementations, geographical surveys and mapping etc., development of an optimal FANET routing mechanism will aid in delivering enhanced performance in terms of packet delivery ratio, throughput, routing overhead, and end to end delay. Also, it will result in quality task achievements with significantly reduced effort.

1.6 Research Objectives

The objectives of the proposed research work are as follows.

1. To explore and analyse the existing techniques for routing in FANETs.

2. To design and develop a QOS aware routing protocol for FANETs.

3. To validate the functionality of the proposed routing protocol through extensive simu-

lations and implementation in a practical scenario.

1.7 Research Methodology

In order to achieve the objectives listed in the previous section, the methodology followed is presented below:

Objective 1: To explore and analyse the existing techniques for routing in FANETs.

To understand the functional variations and characteristics of routing in FANETs, different routing algorithms have been studied, in order to gain in depth knowledge of them and understand the precise requirements for an optimal routing mechanism to be designed for FANETs. During this activity, routing mechanisms exhibiting different routing strategies, namely, proactive routing, reactive routing, geographic routing, multipath routing, hybrid routing, and nature inspired routing have been studied and analysed to understand different shortcomings and drawbacks of the existing routing techniques. Various quality of service parameter like throughput, packet delivery ratio, jitter, routing overhead, end to end delay have been used to observe and interpret the routing performance of various routing mechanisms. The inferences have been concluded in a collective manner so that a base for a favourable efficient routing solution could be formulated which supported in the development of proposed Quality of Service Aware Routing Protocol (QARP) for FANET.

Objective 2: To design and develop a QOS aware routing protocol for FANETs.

To fulfil the second objective, an efficient QOS aware routing protocol (QARP) for FANETs has been proposed, which incorporates the concept of geographic on-demand nature inspired delay aware routing mechanism. The protocol focuses towards reducing the transmission delay primarily by formulating a stable route with least delay for packet delivery, which has resulted in lesser bandwidth utilization in terms of routing overhead, leading to availability of bandwidth for actual data transmission. This factor has helped in achieving better packet delivery ratio, throughput, and energy efficiency.

The routing mechanism incorporates nature inspired characteristics of firefly algorithm to optimize the route discovery process in a highly mobile environment with frequent link breakages. Further, to optimize the route establishment process, the Gaussian behaved particle swarm optimization has been incorporated so as to provide stable routes for efficient packet delivery. This has resulted in higher throughput and lower delay in packet delivery.

Objective 3: To validate the functionality of the proposed routing protocol through extensive simulations and implementation in a practical scenario.

To achieve the third objective, the proposed routing mechanism has been simulated using Network Simulator-2 (NS2) for the purpose of evaluating its performance. Three different scenarios have been considered as per the behavioural characteristics of FANETs for the purposed of the experimentation. In the first scenario, the proposed routing protocol has been evaluated for its performance in the situation of varying node density. In the second scenario, the proposed routing protocol's performance evaluated in terms of varying number of connections among nodes. In the third scenario, the proposed protocol has been evaluated in terms of varying transmission rate. For all these scenarios, a common set of quality service parameters, namely, delay, packet delivery ratio, routing overhead, throughput, and energy consumption have been used to prove the efficiency of the proposed routing protocol in comparison to existing routing protocols.

1.8 Research Contribution

The major contribution of this thesis is to develop a quality of service aware routing protocol for flying adhoc networks. The excerpts of the contribution are as follows:

- A comprehensive literature review has been carried out to understand the functionality of the state of the art adhoc network routing protocols for FANETs in order to understand the performance issues impacting the data delivery in adhoc networks.
- The quality of service metrics affecting the protocols' performance have been identified so as to quantify the performance of proposed routing mechanism.
- A detailed analysis of the different routing mechanisms has been done focusing upon their core data routing functionality and their performance of delivering the packets in a dynamically varying network.
- The nature inspired optimization algorithms have been explored further due to their inherent capability to provide an optimal solution to complex problems. The algorithms suitable for optimizing the adhoc routing problems have been identified.
- A geography aware on-demand nature inspired delay aware routing mechanism has been proposed which has the capability to provide optimal routes to dynamically moving path changing nodes. The routing mechanism incorporated the heuristics of firefly algorithm into the route discovery mechanism to identify least delay neighbour nodes for data delivery. Then the Gaussian behaved particle swarm optimization has been used to decide upon an optimal route for packet delivery.
- The proposed mechanism has been implemented in NS-2 for the purpose of experimentation in exhaustive scenarios.
- A comparative analysis of the proposed protocol's performance is done for evaluating its efficiency in routing the packets against other FANET routing protocols.

1.9 Thesis Organization

This thesis has been arranged into six chapters. An overview of the chapters is given below.

Chapter 1 provide the introduction to flying adhoc networks (FANETs) in which the discussion focuses upon the functional characteristics uniquely identifying the FANETs from other types of adhoc networks. The chapter explains the design considerations, and the routing protocols used to route data for FANETs. Then the discussion elaborates the research gaps, research objectives, research methodology, research contribution, thesis organization, and chapter summary.

Chapter 2 discusses the literature published on the development of routing protocols for FANETs. The literature includes routing protocols belonging to various categories namely proactive routing, reactive routing, geographic routing, multipath routing, hybrid routing, and nature inspired routing. The literature review highlights the salient features, characteristics, strengths, and weaknesses of various routing protocols in different adhoc communication scenarios. Based upon the analysis of performance evaluation quality of service metrics, effectiveness of different routing protocols in different scenarios has been evaluated.

Chapter 3 discusses the simulation based performance analysis of existing MANET routing protocols used for FANET routing. To analyse the performance of various routing mechanisms, exhaustive simulations have been performed using Network Simulator-2 (NS-2), a discrete event simulator. The protocols tested in the experimentation have been Adhoc On-demand Distance Vector (AODV), Adhoc On-demand Multipath Distance Vector (AOMDV), Optimised Link State Routing (OLSR), and Zone Routing Protocol (ZRP). The protocols have been simulated using the scenarios with variations in node speed and number of nodes. The evaluation of the protocols has been done using the parameters namely packet delivery ratio, normalized routing load, average end to end delay, and throughput.

Chapter 4 discusses the proposed Quality of Service Aware Routing Protocol (QARP)for FANETs. Firstly,a network model depicting a scenario has been discussed in which the proposed FANET routing protocol could be implemented for effective data delivery in an adhoc mode. Next, the assumptions required for effective execution of the proposed routing protocol have been discussed. Subsequent part of the chapter discusses the methodology of the proposed FANET routing protocol which describes the functionality of the protocol getting optimized in two different phases. In the first phase of route discovery, the nature inspired Firefly algorithm optimizes the position of the nodes to allow the identification of prospective nodes for effective data delivery. In the second phase, the modified Gaussian Quantum Particle Swarm Optimization algorithm identifies the least delay nodes for packet delivery. In this way the delay awareness in the route discovery and route establishment allows for optimal data delivery to the destination in the network of UAVs.

Chapter 5 discusses the performance evaluation of the proposed FANET routing protocol in comparison to the other existing routing protocols. The simulation scenarios included varied number of nodes, varied number of links, and varied packet transmission rates in order to evaluate the performance of the proposed routing protocol against the existing protocols exhaustively. The protocols have been evaluated for their performance in terms of delay, packet delivery ratio, routing overhead, throughput, and energy consumed with respect to number of connections, packet transmission rate, and number of nodes. The proposed routing protocol outperformed the rest of the protocols in terms of all the performance parameters.

Chapter 6 concludes the research work presented in this thesis and presents the future implications. It has been concluded that the results given by the proposed protocol are very promising as the experimental implementation reflects an optimal routing performance of data routing among the flying nodes as compared to the other routing protocols. The future directions for this research could be the inclusion of multi-path load balancing in designing a routing protocol for FANETs.

1.10 Chapter Summary

This chapter discusses the routing mechanisms of various FANET routing protocols operating in varied routing scenarios. The chapter discusses the differences between FANETs, VANETs, and MANETs highlighting their distinct features and characteristics. The evolution of FANET routing has been discussed for the protocols which existed over a period of time starting from year 2006. Further a discussion on different types of existing FANET routing protocols has been done mentioning their salient features. The design considerations required for the development of an efficient FANET routing protocol have been discussed. The chapter further discusses the research gaps present in the existing literature which are required to be addressed in the future research. Based on the research gaps, the research objectives of this research have been formulated. Corresponding to the research gaps, the research methodology has been devised which has been followed to accomplish this research. The chapter further discusses the research contribution of this research work mentioning the contributions towards filling the research gap. And finally the thesis organization and chapter summary has been discussed

Chapter 2

Literature Review

This chapter discusses the literature related to the existing routing protocols for FANETs. There has been a significant development of routing mechanisms in the recent past and those protocols have used many different routing methodologies to find feasible routes to destination. The protocols in this discussion have been divided into two basic types of single path routing protocols and multipath routing protocols. Each of these types have further been classified into proactive, reactive, position based, and hierarchical routing protocols. All the routing protocols have been reviewed in-depth by understanding their routing mechanisms and identifying their salient features and characteristics, strengths, weaknesses, and quality of service parameters based on which they have been tested for their performance.

2.1 Single Path Routing Protocols

Single path routing protocols are the basic category of routing protocols in which the routing mechanism identify a single feasible route to the destination for data delivery. The route identification mechanism depends upon the type of routing algorithm incorporated within the routing protocol. There are different routing mechanisms used for routing data among flying nodes having their own unique characteristics which affect the route identification, data delivery and route maintenance procedures. The proceeding literature has presented a categorization of FANET routing protocols into proactive, reactive, geographic, and hierarchical routing based upon the routing mechanism incorporated within them briefly describing their functionality and highlighting their features and operational characteristics.

2.1.1 Proactive routing protocols

Proactive routing protocols pre-compute paths to all the destinations in the network in order for the nodes to start data delivery immediately to the destinations. The following literature discusses various protocols proposed by researchers which exhibit proactive route identification characteristics for FANETs.

Rosati *et al.* [31] proposed Predictive OLSR protocol for FANETs. The protocol used GPS information of the nodes to take routing decisions dynamically. The protocol evaluated the expected transmission count (ETX) by considering the corresponding speeds of two flying nodes to improve the routing decisions. The standard OLSR implementation used link quality extension to learn about a particular link's quality and advertised it. The inclusion of location information further augmented the link quality extension to quickly analyse the link breakage characteristic within the network. The researchers further evaluated the performance of proposed protocol in [70], against OLSR protocol using a UAV test bed.

Jiang *et al.* [32] proposed Mobility and Load Aware OLSR protocol for FANET. The protocol included two algorithms to enable enhanced routing decisions. The protocol utilized the location information of nodes to carry out route calculations. One of the algorithms, namely, mobility aware algorithm calculated the degree of stability for the nodes by using a statistical estimation of communication links. A reachability degree was calculated for nodes by assigning weights to neighbouring nodes. The other algorithm, namely, load-aware algorithm considered packets queued at communication interface of nodes and degree of interference of neighbouring links to identify nodes for route selection. The protocol performed better as compared to OLSR in terms of end-to-end delay and packet delivery ratio.

Lin *et al.* [29] proposed a Shortest Path Algorithm based on grid position for unmanned aerial systems . The routing mechanism used grid distance to reduce the sensitivity of swiftly moving UAVs. It used Dijkstra algorithm to identify the shortest route to the destination, and established adjacency relationship and topology structure with the help of perception and updating algorithm. Also, a regional reconstruction strategy had been designed for optimizing the routes dynamically. The protocol was tested for its validity against DSDV and DREAM routing protocols using MATLAB.

Xie *et al.* [30] proposed an enhanced OLSR routing protocol which considered the expiration time of links and residual energy of nodes for the scenario of ocean FANETs. The enhanced protocol used speed and relative location of UAVs for calculating the Link Expiration Time (LET), which was further used for the calculation of new Expected Transmission Count (ETX) value. For the purpose of Multi Point Relay (MPR) selection, the new ETX value and the remaining node energy were considered such that the value of residual energy should be greater than a certain threshold. The authors simulated the enhanced protocol against OLSR-ETX protocol in NS3 simulator for packet delivery ratio, end-to-end delay, and routing overhead, which proved the effectiveness of the enhanced protocol against the latter. Another modification of the OLSR protocol had been proposed by Ali *et al.* [71] in which the authors had incorporated the greedy forwarding strategy which identified the farthest node from the source to the destination. The identification of node continued till the destination was in the range of the forwarding node. Zhu *et al.* proposed an optimal routing protocol with reduced control overhead for FANETs [72]. The protocol enhanced the HELLO message mechanism by transmitting the incremental topology change information to the affected nodes. This resulted in reduced routing overhead for the overall network and provided more stable links for packet exchange. The protocol showed improved performance in terms of packet delivery, routing load, and delay.

To summarize the discussion, Table 2.1 highlights the salient features, Table 2.2 pinpoints the strengths and weaknesses and Table 2.3 provides information about the QoS parameters, namely, packet delivery ratio, packet loss ratio, end to end delay, throughput, routing overhead, and link stability used for evaluating the protocols.

Table 2.1: Salient features of proactive routing protocols

Protocol Name	Salient Features of Routing Protocol
P-OLSR [31]	• Used GPS information to extend Link Quality Extension mechanism • Used relative velocity between the UAVs to estimate quality of link .
ML-OLSR [32]	• Introduced mobility aware routing mechanism that identified the stability degree of nodes by using weighted communication links, and calculated reachability degree of UAVs by assigning weights to them, which was utilised to get stable links and stable nodes for route establishment • Introduced a load aware algorithm, which used nodes' interface queued packets and interference degree among neighbouring communication links to identify load factor.
GPNC-SP [29]	• Used logical grid distance to reduce the fast-moving nodes' sensitivity • Used perception and updating algorithm to identify and sustain adjacency relationship and topology structure • Used regional reconstruction algorithm for route optimization.

Improved OLSR-ETX [30]	• Used node speed and relative location of nodes to calculate link expiration time • Improved the ETX calculation by considering the LET in order to select a link with long duration of connectivity • The MPR selection was improved due to the inclusion of improved ETX and residual energy as the deciding factors.
G-OLSR [71]	• Avoidance of dissemination loops for improved data delivery • Performance aware self adaptive routing with ability to handle unpredictable dynamicity in topological changes.
LCO-OLSR [72]	• Modified the topology control packet to identify the stable link nodes for packet delivery • Used modified HELLO messages to disseminate incremental neighbour information.

Table 2.2: Strengths and weaknesses of proactive routing protocols

Protocol Name	Strengths	Weaknesses
P-OLSR [31]	• Quick response to topology changes • Lesser average network outage time	• Datagram loss rate increased with increase in inter-node distance.

ML-OLSR [32]	• Reduced MPR selection calculation time, path disconnections and routing table recalculation by introducing stability degree of nodes and reachability degree of nodes for MPR selection mechanism.	• Increased node mobility reduced packet delivery ratio.
GPNC-SP [29]	• Reduced network overhead by allowing nodes to broadcast their position information only when they moved from one grid to another.	• Grids with larger width required more route updations. • The protocol identified routes with larger communication distance.
Improved OLSR-ETX [30]	• Ensured longer node connectivity due to the selection of nodes using enhanced LET calculation • Improved MPR selection resulted in reduction of topology control message propagation within the network thereby reducing the routing overhead	• Incorrect GPS information could lead to erroneous LET calculation and incorrect MPR selection.
G-OLSR [71]	• Improved neighbour discovery through the use of greedy forwarding resulting in lesser delays • Avoidance of loops by denying the transmission of nodes that can cause loops in the network	• Routing control packets increased with increase in the nodes in the network.

LCO-OLSR [72]	• Reduced control overhead with the use of incremental HELLO messages • Increased packet delivery by identifying link stable nodes with the help of modified topology control messages.	• Control overhead increased with increased number of nodes and node speed.

Table 2.3: QoS metrics used for proactive routing protocols

Protocol Name	Packet Delivery Ratio	Packet Loss Ratio	End to End Delay	Throughput	Routing Overhead	Link Stability
P-OLSR [31]	✗	✓	✗	✗	✗	✗
ML-OLSR [32]	✓	✗	✓	✗	✗	✗
GPNC-SP [29]	✗	✗	✗	✗	✓	✓
Improved OLSR-ETX [30]	✓	✗	✓	✗	✓	✗
G-OLSR [71]	✓	✗	✓	✓	✓	✗
LCO-OLSR [72]	✓	✗	✓	✗	✓	✗
Note. ✓: used, ✗: Not used						

2.1.2 Reactive routing protocols

Reactive routing protocols identify on-demand routes to the destinations thereby providing latest routing information to the nodes for delivering the data. The following discussion presents reactive single path routing protocols available for FANETs.

Lei *et al.* [57] proposed a Link Availability Estimation based Reliable routing (LEBR) for aeronautical adhoc networks. A Semi-Markov Smooth mobility model had been proposed in this protocol to imitate the movement of UAVs in the sky. Using the mobility model, a probability density function of the relative speeds of two nodes was calculated and based on that, an estimation of link lifetime between the nodes was derived. This calculated link lifetime was used in the proposed link availability estimation based routing. LEBR is based on AODV protocol [12], but instead of hop count, it uses link availability value to identify a reliable path to the destination.

Biomo *et al.* [37] proposed a Modified-Reactive Greedy Reactive Routing (RGR) protocol, which employed the concept of reliable distance calculation in order to identify an optimal route to deliver packets to the destination. For identifying reliable distance, the source node recorded its current location, direction, velocity and time stamp from GPS and saved that information in RREQ packet and then, forwarded it to the destination. The destination node after receiving RREQ calculated its current location as well as the source node's current location and compared them in order to identify whether nodes were moving in the opposite or same direction. In case the nodes were moving in the same direction, Route Request (RREQ) was forwarded or Route Reply (RREP) was generated. Then reliable distance r was calculated using formula given in (2.1).

$$r = R - w * V'_{DS} \tag{2.1}$$

here, R is the transmission range of the node, w is a constant and V'_{DS} is a projection of relative velocity between source and destination.

Qingwen *et al.* [62] proposed an Adaptive Forwarding Protocol (AFP) for FANETs. The protocol used forwarding zone criteria based on forwarding probability to adaptively forward packets. Before forwarding a packet, any intermediate node calculated its forwarding zone criterion to verify its presence in the forwarding zone and if in forwarding zone, the packets were forwarded using forwarding probability, else packets were dropped. The nodes selected in the forwarding zone were required to have a larger distance to the last hop forwarder and closer to the destination, due to which the protocol reduced unnecessary rebroadcasts.

Yin *et al.* [35] proposed a Fountain-code based Greedy Queue and Position Assisted routing protocol (FGQPA) in which, first a Power Allocation and Routing (PAR) policy had been designed to minimize the impact of node queue backlog on packet forwarding delay. Then, a nearest-span routing policy had been defined within the PAR policy to minimize the packet forwarding delay further. For the experimental analysis purpose, the proposed protocol had been compared with Fountain-code based Greedy Position-Assisted (FGPA) routing protocol [73].

Luo *et al.* [74] proposed a Multiple Quality of Service Parameters based Routing Protocol (MQSPR) for FANETs. The protocol maintained sustained link connectivity and availability, resulting in a balanced link load and reduced end-to-end delay to provide a favourable network communication for civil aviation. In order to optimize these parameters, firstly, a mobility model had been proposed, which divided the aircraft movement into three phases, namely, speed up phase, middle smooth phase and slow down phase. Based on flight trajectory, flight schedule and node speed, it governed node movement in the air. For routing purpose, the protocol used route selection metrics as path availability period, residual path load capacity and path latency. In addition, route discovery advertisement broadcasting had been optimized in order to reduce network overhead. The performance of the protocol had been tested through comparative simulations against the routing protocols AODV and GPSR.

Zheng *et al.* [75] proposed an Adaptive Density-based Routing Protocol (ADRP) for flying Adhoc networks. The researchers extended AODV protocol to optimize its route discovery process by deriving route freshness information about the reverse path to source and the status of freshness information of the path to destination from destination sequence number included in RREQ. Authors further calculated the rebroadcast probability for RREQ rebroadcast by nodes based upon their number of neighbours. The mechanism allowed for a reduction in end-to-end delay and excessive rebroadcasts, and increased throughput.

Nour *et al.* [40] proposed a Bio-inspired On-demand Routing Protocol for Unmanned Aerial Vehicles. The protocol modified AODV routing protocol to include Boids of Reynolds, a method to virtually model the mobility pattern of a flock of birds and animals to depict the movement of UAVs in the air. The proposed protocols used three rules, namely separation (keeping minimal distance between neighbours to avoid collision), alignment (stay in common direction of movement by synchronizing speed with neighbours) and cohesion (approach center of the swarm by keeping close to neighbours), in order to keep nodes connected in the network.

Zheng *et al.* [36] formulated a Stable Ant-based Routing Protocol (SARP) in which the authors had used ant colony optimization to enhance the route discovery process and next hop selection. The authors had used stable value, link energy, and pheromone to select the next hop for packet forwarding, which resulted in the optimization of route discovery process. The stable value had been calculated using the inter-node distance between the current node and next hop nodes, and transmission range of the node. The pheromone deposition had been achieved using backward ANT (BANT) messages and forward ANT (FANT) messages, which are acting as route response and route request messages. To obtain neighbouring node information, a periodic hello message broadcast had been done. The simulations done using NS2 against AODV protocol showed that the proposed routing protocol performed better for the performance parameters namely packet delivery ratio, throughput, and normalised routing load.

Liu *et al.* proposed a Q-learning based routing protocol [76] in which the mechanism identified the optimal routes to the destination considering the minimum delay and energy consumption. The authors proposed a new exploration and exploitation procedure to enhance the routing performance. Nodes exchanged Hello packets periodically with neighbours to know the location, energy, arrival time, speed, and direction of movement. This information was kept in the neighbour table of each node and was used to know the network condition. For selecting the next hop, the neighbour associated with a link that satisfies the velocity condition is identified and the neighbour with maximum k-weighted Q-value is selected to form a route to the destination. Da Costa *et al.* proposed an improved Q-learning based routing protocol [77] in which they incorporated a reinforcement learning based Q-learning mechanism that considered the state and weight of the links for routing decision making. The newer the state, the higher the weight. Also, the mechanism considered the transmission quality of the link by considering the signal interference to noise ratio. It resulted in selecting the links with minimum noise levels. Peng *et al.* [78] in their research formulated a location aware routing mechanism which took into consideration the location, trajectory, and movement information of UAVs. The future position of the nodes was identified based on the trajectory information. This resulted in identifying the whole topology of the network in advance. For routing, if the source and the destination nodes were within the communication range of one another through intermediate nodes then Dijkstra's algorithm was used to compute the shortest path. Otherwise, future positions of the nodes were calculated which provided the delay of hypothetical links in the future. The node with the least delay value was considered as closest to the destination. Liang *et al.* proposed a path reliability and link monitoring repair [79] based routing in which the protocol calculated the weight values of all the communicating links to a node based on the link delay. The link with the maximum weight was chosen for data delivery. The mechanism continuously monitored the links for failure and if detected, it queried the neighbouring nodes for link availability to the destination. Zhang *et al.* proposed a packet arrival prediction routing [80] which focused on improving the reliability of transmission links. The protocol implemented the long short term memory (LSTM) model to estimate the packet arrival at UAVs. The routing decisions were optimized by the constraints based sorting approach which enabled fast routing decisions for packet transmissions. A topology-aware routing protocol [81] had been proposed by Arafat Muhammad Yeasir and Moh Sangman in which the researchers used two hop neighbour based topology control to establish a routing path considering the metrics of delay, node speed, location information, and energy. The inclusion of adaptive Q-learning allowed the protocol to adapt to rapid topology changes to allow sustained packet delivery among the nodes. Muthukumar *et al.* proposed a reduced latency routing protocol named Stability-based Energy- Efficient Link-State Hybrid Routing (S-ELHR) for FANETs [82]. The mechanism used a stability metric that considered the node energy usage, connection duration, and node degree to identify prospective nodes for data delivery between the source and the destination. The proposed protocol displayed better performance against OLSR and Energy Enhanced OLSR (EE-OLSR) routing protocols in terms of packet delivery, energy consumed, and delay parameters.

To present a summarized view of the discussed reactive routing protocols for FANETs, Table 2.4 highlights the salient features of the discussed reactive routing protocols, Table 2.5 pinpoints the strengths and weaknesses of discussed protocols and Table 2.6 provides information about the QoS parameters, namely, packet delivery ratio, packet loss ratio, end to end delay, throughput, routing overhead, and energy consumption used to evaluate the discussed protocols.

Table 2.4: Salient features of reactive routing protocols

Protocol Name	Salient Features of Reactive Routing Protocol
LEBR [57]	• Used link lifetime estimation of link availability among nodes from the calculation of probability density function of nodes' speed, to identify reliable links
Modified-RGR [37]	• Used modified RREQ packet to include current location, direction, velocity and timestamp of the source node that is further used by the destination node to verify that both the nodes are displacing in the common direction and then calculate reliable distance
AFP [62]	• Used adaptive forwarding probability based dynamic forwarding zone to deliver packets to the destination • Identified intermediate nodes with larger distance to last hop forwarder and closer to the destination
FGQPA [35]	• Used power allocation and routing mechanism to equalize queue backlog • Used nearest span routing to allow nodes with lesser queue backlog and nearer to the destination to receive packets from other nodes and forward them to next hop when available • Utilised node's future position to support the routing process

MQSPR [74]	• Used an improved mechanism for route discovery called forward the best advertisement (FBADV) that forwarded the best packets selectively in the network • Used a route selection mechanism which embedded QoS metrics namely path availability period, residual path load capacity and path latency in order to select an optimal route
ADRP [75]	• Modified the RREQ packet of AODV to include number of neighbours of source or forwarder in order to identify nodes with a lesser number of neighbours • Used source sequence number contained in RREQ in order to identify fresh information about the reverse path to source • Used destination sequence number in order to get the status of freshness information about the route to the destination so that the identified route could be accepted by source
BR-AODV [40]	• Introduced a control module named boids of reynolds into AODV protocol, for nodes to check their participation in one or more active paths and their displacement planning, in order to avoid path disconnection • Introduced an automatic ground base stations discovery mechanism in order to provide proactive associations to drones, and ground networks to serve real-time applications • Introduced UAV to UAV routing in a reactive manner and UAV to ground base station routing in a proactive manner

SARP [36]	• Introduced a stable next hop selection mechanism by including stable value, link energy and pheromone to elect the optimal next hop • The pheromone update helped in using the best path to deliver data to the destination
QMR [76]	• Utilized Q-learning to optimize delay and energy utilization of nodes through multi objective based optimization • Adjusted the learning rate of links and discount factor of nodes as per the nodes mobility in the network • Re-estimated neighbour relationships due to node mobility for optimal route calculations
Q-FANET [77]	• Used HELLO packets to update location information of nodes to keep the routing tables updated • Used greedy policy to maintain a balance between the exploration and exploitation for selection of the best path • Used improved Q-learning+ and Q-Noise+ mechnisms for better mobility consideration of nodes and channel quality for data transmission
FNTAR [78]	• Used location and trajectory information to identify the future position of the nodes • Used N-copy scheme to forward packets to link stable neighbour nodes

DSR-PM [79]	• The link monitoring mechanism ensured reporting of any path break along the communication route to allow swifter route repair • The route repair mechanism immediately identify a feasible alternative route from the nearby nodes to continue packet transmission. If not found, the source node initiates a route discovery again
PAPR [80]	• Used long short term memory to predict network load on UAV links in order to select links with lesser load • Routing decision factor allowed selecting an optimal path for data routing considering multiple factors
QTAR [81]	• The routing mechanism included Q-learning based decision making mechanism resulting in reliable communication • The two hop neighbour discovery mechanism recorded multiple node parameters to estimate node condition • Estimation of link duration resulted identifying link lifetime
S-ELHR [82]	• Topology discovery mechanism selected the relay nodes and a relay update message had been broadcasted to convey this information to all the nodes int he network • Source routing mechanism had been used for packet delivery which did not require maintaining routing table with any intermediate node

Table 2.5: Strengths and weaknesses of reactive routing protocols

Protocol Name	Strengths	Weaknesses
LEBR [57]	• Used link availability factor as optimal route selection metric to increase throughput • Reduced frequent link breakages in a highly dynamic environment	• End-to-end delay increased as nodes increased in the network
Modified-RGR [37]	• Reduced routing load and delay by restricting the scope of RREQ flooding	• Excessive RREQ discarding and increased route identification attempts could be observed if the reliable distance taken is too short, which would lead to increased routing overhead
AFP [62]	• Adaptive forwarding probability based dynamic forwarding zone criterion increased the packet delivery ratio of the network by decreasing packet collision between neighbours and reducing unnecessary rebroadcasts	• Energy consumption per received packet increased as node density increased, due to a greater number of nodes participating in the forwarding process

FGQPA [35]	• Power allocation and routing reduced cumulative network delay caused by queue backlog • Promiscuous mode helped in minimizing network overhead by eavesdropping neighbours to gather required information	• At lower transmission rate, transmission delay increased
MQSPR[74]	• FBADV process reduced the excessive route discovery advertisements flooding • The route selection mechanism reduced route congestion, end-to-end delay and packet loss rate by selecting stable and load balanced paths between nodes and ground station	• A relatively weak ground connectivity is observed as the node density decreased due to stringent internet gateway advertisement (IGWADV) forwarding policies, which imposed difficulties in path set up • With increased nodes in the network, routing overhead increased due to which, the packet delivery ratio decreased for the protocol

ADRP [75]	• Used adaptive forwarding probability to optimize route discovery efficiency • Used preferred retransmissions by nodes having lesser number of neighbours, in order to reduce end-to-end delay and minimize excessive broadcasts	• A periodic exchange of Hello packets among the neighbouring nodes had been incorporated in the protocol which could result in unnecessary energy utilization
BR-AODV [40]	• Mobility control module reduced down the attempts to discover new routes and allowed longer active path life maintenance for packet transmissions	• Packet drop rate increased with increase in background traffic per node
SARP [36]	• Ant colony optimization based next hop selection helped in avoiding collisions and contentions thereby increasing the data delivery • Reduced unnecessary rebroadcasting of route requests	• Routing overhead increased with increasing node density
QMR [76]	• Dynamic learning rate adjusted the Q-value quickly for optimizing delay and energy consumption of network • Optimal neighbour selection provided link stable packet delivery	Delay increased with increased data interval and node speed

Q-FANET [77]	• Q-learning+ mechanism reduced network delays by selecting neighbour nodes in a mobility aware manner • Q-Noise+ improved network transmission by considering signal to interference plus noise ratio for the channel quality of the network	• Increased data interval increased the delay of transmission slightly
FNTAR [78]	• GPS assisted motion sensing and positioning allowed improved future position calculation • Link stability due to location awareness allowed sustained connectivity with destination for data delivery	• With increasing nodes, the delay among nodes increased
DSR-PM [79]	• Continuous link monitoring by nodes allowed quick recovery of broken links resulting in effective data delivery among nodes • The route repair mechanism used link montioring information to effectively repair the broken links and reduced route reidentification from the source node	• Network overhead increased with increasing node speed

PAPR [80]	• The link prediction allowed selection of links with lesser traffic load for better data delivery • The optimization of routing selections using routing decision factor allowed selecting the most optimal route for effective data delivery	• With the increasing number of nodes, the packet delivery ratio decreased while delay increased
QTAR [81]	• The neighbour information maintained within every node helped in constructing a two hop neighbour based topology table providing the current status of nodes for selection as a route node for data forwarding • Q-learning mechanism dynamically adjusted itself with the dynamically changing UAVs resulting in a sustained route for data delivery	• With increased number of nodes, packet delivery ratio decreased
S-ELHR [82]	• A stability metric is used which consisted of link connectivity index, energy, and degree weight to estimate a stable link • Another factor named willingness has been used to decide upon readiness of a node for forwarding the data	• With increasing number of nodes, the routing overhead increased correspondingly

Table 2.6: QoS metrics used for reactive routing protocols

Protocol Name	Packet Delivery Ratio	Packet Loss Ratio	End to End Delay	Throughput	Routing Overhead	Energy Consumption
LEBR [57]	✗	✗	✓	✓	✓	✗
Modified-RGR [37]	✗	✗	✓	✗	✓	✗
AFP [62]	✓	✗	✓	✗	✗	✓
FGQPA [35]	✗	✗	✓	✗	✗	✗
MQSPR [74]	✓	✗	✓	✗	✓	✗
ADRP [75]	✓	✗	✓	✓	✓	✗
BR-AODV [40]	✗	✓	✓	✓	✗	✗
SARP [36]	✓	✗	✗	✓	✓	✗
QMR [76]	✓	✗	✓	✗	✗	✓
Q-FANET [77]	✓	✗	✓	✗	✗	✗
FNTAR [78]	✓	✗	✓	✗	✓	✗
DSR-PM [79]	✗	✓	✓	✓	✓	✗
PAPR [80]	✓	✗	✓	✗	✗	✗
QTAR [81]	✓	✗	✓	✗	✓	✓
S-ELHR [82]	✓	✗	✗	✗	✓	✓
Note. ✓: used, ✗: Not used						

2.1.3 Geographic/Position based routing protocols

Geographic routing protocols keep track of location information of nodes to record their location changes for effective delivery of data to the destinations. The following discussion provides description of geographic single path routing protocols for FANETs.

Wang *et al.* [63] proposed A-GR, a novel geographic routing protocol for FANETs. The protocol made use of the position and mobility information of the UAVs supplied by the Automatic Dependent Surveillance-Broadcast (ADS-B) system, to populate neighbour table and elect the next hop. Based on this information, the packets were forwarded to the destination. Each UAV consisted of an ADS-B unit on board for exchanging the node state information using a separate transceiver, which resulted in eliminating the network overhead for the actual transmission bandwidth of the adhoc network.

Lee *et al.* [42] proposed GCS-routing, a Ground Control System (GCS) controlled routing protocol. It followed a centralized routing approach where the deployment of UAVs, routing table calculation, routing information propagation among UAVs and routing information maintenance and updating was taken care of by GCS. For this purpose, the protocol used the geographic information and flight schedule of individual UAVs. This prevented UAVs from sending any kind of control information among them, saving the bandwidth. In addition, location prediction for the drones was easier for GCS due to the availability of the flight schedule in advance.

Gankhuyag *et al.* [83] proposed a novel directional routing scheme for flying adhoc networks. Based on AODV protocol, the proposed protocol utilized omnidirectional as well as directional transmissions by exploiting the location information of nodes, in the form of unicast and geocast routing. The RREQ packet was modified to contain the sender's position information, movement vector, minimum expected connection time and maximum risk value. On reception of RREQ packets at the destination, a utility value is calculated for each packet using path utility function and the packet with the highest value is selected, rest are discarded. Each node maintained a backward table for RREQ packet received from each previous node and used to send RREP packet back to the source using directional transmission. On receiving RREP, nodes store sender's information in their forwarding table so that it could be used to forward data to the destination.

Gankhuyag *et al.* [60] proposed a Robust and Reliable Predictive Routing Strategy for Flying Ad-hoc Networks, which used a combination of unicast and geocast routing by utilizing the trajectory and location information to route the data. In order to avoid unnecessary data loss and collision, the protocol incorporated the use of an omnidirectional and directional antenna in combination with dynamic angle adjustment for data transmission. The protocol also included a three-dimensional estimation method for predicting the location of intermediate nodes and then used directional transmission approach to forward data to them.

Bujari *et al.* [84] formulated a Location-aware Waypoint based Routing Protocol GeoSaw, for air borne delay tolerant networks (DTN) in which the authors used location prediction of UAVs by exploiting their waypoint locations and current locations. For neighbour discovery, the protocol used local Hello message broadcast to keep a track of active neighbours. The waypoint information helped the protocol in predicting the future location of the nodes and the time when they reach that location. So, the sender node could wait for a particular node to reach the predicted location and then transmit the packets to it. The authors evaluated the performance of proposed protocol using The Opportunistic Network Environment (The One) simulation software. The performance metrics used for evaluation were packet delivery ratio, overhead ratio, and latency. The authors firstly compared the proposed protocol with existing DTN routing protocols namely Epidemic [85], Spray and Wait [86], First Contact [87], MaxProp [88] and the simulation results reflected that the proposed GeoSaw protocol achieved 100 percent average packet delivery ratio, similar to that of Epidemic and MaxProp routing protocols. Also, GeoSaw protocol reflected minimum overhead ratio as compared to other protocols with increasing number of nodes, whereas, in case of latency, GeoSaw performed second to Epidemic protocol. In the second case of performance evaluation, authors experiment with the protocol parameters namely allowed packet copies ranging from 1 to 3, and permission to retain or remove the packet copy in the sending node after packet forwarding. A total of six configuration combinations were formulated for the performance evaluation. Protocol showed promising results for packet delivery ratio for all the combinations except for single packet case. The overhead ratio increased with increase in the number of nodes for all the combinations except one copy with packet deletion configuration, while for latency, the protocol showed acceptable performance for all the cases except for copy with deletion combination. The authors mentioned the future scope as using some time to destination criteria for dynamic calculation of number of replicas in order to dynamically adapt the protocol's behaviour.

choi *et al.* [41] had presented a Geolocation-based Routing Protocol for FANETs in which the location information, direction of movement, and speed of UAVs were broadcasted over the network and the UAVs receiving this information stored it in their neighbour table. Based on this information, a neighbour closest to the destination was selected in a greedy manner for forwarding the packets. Moreover, for the selection of next hop forwarder node, the location prediction of the nodes was done using their direction of movement, speed, and time information. The researchers implemented the proposed protocol over the Internet Protocol (IP) layer in a test bed and demonstrated the execution of the protocol for multiple flying UAVs exchanging data and control information with each other, being controlled with help of commands issued by GCS for mission execution. In the task-adaptive framework-based routing [89] Chu *et al.* proposed a multi center election and member control methodology in which the mechanism elected master nodes that identified the skeleton of its cluster and then every master node shared this information among each other to converge the network. Based on this cluster information, the links were established among the nodes for data transmission.

To sum up the discussion about geographic routing protocols, Table 2.7 summarizes their salient features, Table 2.8 pinpoints their strengths and weaknesses and Table 2.9 provides information about the QoS parameters used to evaluate the discussed protocols.

Table 2.7: Salient features of geographic routing protocols

Protocol Name	Salient Features of Routing Protocol
A-GR [63]	• Used ADS-B system to get neighbour information such as node ID, position, velocity and altitude • Computed instantaneous flight time (IFT) using node position and mobility information in order to select next hop • Nodes available in the neighbour table were scanned to identify data forwarding node with best IFT value
GCS-Routing [42]	• Centralized routing mechanism controlled by ground control stations (GCS) • GCS fleet management module was used to track node position and movement schedule, and generate flight commands to nodes • Routing table management module initialized link cost for nodes and generated a combined routing table using Dijkstra's algorithm, to be distributed among nodes and maintained routing changes by tracking changes in node positions

DRS [83]	• Based on AODV, the RREQ packet was modified to include sender's location information, movement vector, minimum expected connection time and maximum risk value • For RREQ packets received at the destination, a utility value was calculated using path utility function, which used minimum expected connection time, hop count and risk value, and the packet with highest utility value was selected • RREP was sent back to the sender using backward table maintained by each node forwarding RRREQ • Route maintenance was done by using an omnidirectional transmission for node from which ACK was not received. If still ACK was not received, then a route error message was sent to the source and route discovery was re-initiated
GeoSaw [84]	• Used local Hello message broadcast to announce the presence of nodes in the neighbourhood • Used current location and path waypoints of nodes to predict their future location, and the time to reach that location, resulting in delivering the data to the nodes after reaching at that location
GRP [41]	• Used location information, node speed and direction of movement to prevent collision among UAVs, identify neighbour nodes, and next data forwarding neighbour in a greedy manner • Performed selection of next hop by predicting the location based on node speed, direction of movement, and time information.

RARP [60]	• Used modified RREQ packets to include sender's three-dimensional location trajectory information, movement vector, minimum expected connection time of RREQ path and maximum risk value • For next hop selection, utility information was calculated for all the RREQs received at the node and the RREQ with the best utility value was selected to be forwarded • Expected connection time was calculated for a link between the sender and the receiver from the information contained in their respective RREQs • An adaptive antenna with dynamic angle adjustment was used in order to mitigate near node and far node problem
SRS [89]	• Master nodes gathered the skeleton information of the network region which consisted of node position and cluster information • Skeleton information packets were used to update the skeleton information among the nodes in the network • The skeleton information helped in populating the routing table by identifying the most relevant gateway node for the intercommunication of nodes in different clusters and direct communication of nodes in case the nodes had been in the same cluster

Table 2.8: Strengths and weaknesses of geographic routing protocols

Protocol Name	Strengths	Weaknesses
A-GR [63]	• Reduced routing overhead by eliminating periodic hello beacon broadcasts and using different antennas to transmit data packets and ADS-B data	• Packet delivery ratio degraded when number of nodes increase beyond 50 nodes
GCS-Routing [42]	• Centrally managed ground control stations could estimate link cost from node location information, thus eliminating the requirement of any periodic control message broadcast, leading to reduced routing overhead • Ground control station kept a record of nodes' mobility schedules to be able to predict topology changes and link disconnections, thereby instantly reacting to reinstate them, in order to reduce route convergence time	• Failure in link estimations could be observed due to the presence of obstacles between the nodes • A momentary formation of transient loops could be observed during route updating process as the updated routing information could have been received by root node but its child nodes were yet to receive it

DRS [83]	• Used combined omnidirectional and directional transmissions, in order to reduce number of nodes involved in data transmission • A utility function, responsible to calculate utility values for RREQ considered minimum expected connection time to select a node that could exhibit sustained connection for a longer duration, hop count to select lesser number of intermediate nodes, and risk value to select nodes with least probability of failure during data transmission	• Very frequent directional changes by nodes could lead to greater route failures, in case of directional data transmissions
RARP [60]	• Use of the adaptive antenna with dynamic angle adjustment ensured successful data transmission majority of times • Alternate path set up maintained an alternate path before the expiry of the minimum expected connection time, to ensure sustained connectivity between sender and receiver • Local path repair mechanism ensured connectivity with all the nodes by using a combination of omnidirectional and directional transmissions in order to reduce service disruption time	• Very significant amount of control packets used to set up and maintain backward and forward tables • Increased node speed resulted in decreased average path lifetime

GeoSaw [84]	• Prediction of node location and time of reaching that location ensured successful delivery of data to that node for further relaying • Due to the precise node prediction of relaying nodes, GeoSaw showed 100 percent average packet delivery ratio, and acceptable values of overhead and latency	• With an increase in the number of nodes, the routing delay increased resulting in a deteriorated performance of the protocol
GRP [41]	• Selection of forwarding neighbour node in a greedy method allowed for the selection of most closest neighbour to the destination • Location prediction of next hop node helped in optimal forwarding of packets to the destination • Avoided local minima problem by issuing a route search message in a region towards the direction of the destination so that a node closer to the destination could be found	• The protocol could pose significant routing overhead to the network in case of highly dense FANETs due to broadcasting of the control information by the nodes

SRS [89]	• Dissemination of node position information through skeleton packets helped in identifying the most relevant nodes for packet delivery to destination • The updation of skeleton information resulted in direct communication of source and destination nodes present within a cluster	• Throughput and packet delivery ratio decreased with increased number of nodes

Table 2.9: QoS metrics used for geographic routing protocols

Protocol Name	Packet Delivery Ratio	Route Update Time	End to End Delay	Throughput	Routing Overhead	Network Disconnection Time	Route Setup Success Rate	Average Path Life Time
A-GR [63]	✓	✗	✓	✗	✓	✗	✗	✗
GCS-Routing [42]	✗	✓	✗	✓	✗	✓	✗	✗
DRS [83]	✗	✗	✗	✗	✗	✗	✓	✓
RARP [60]	✓	✗	✗	✗	✗	✓	✓	✓

GeoSaw [84]	✓	✗	✓	✗	✓	✗	✗	✗
GRP [41]	✗	✗	✗	✗	✓	✗	✗	✗
SRS [89]	✓	✗	✗	✓	✓	✗	✗	✗
Note. ✓: used, ✗: Not used								

2.1.4 Hierarchical routing protocols

Hierarchical routing protocols allow efficient management of densely populated networks by forming hierarchies or clusters of nodes in order to distribute communication load thereby providing effective routing of data within the network. The following discussion provides details of hierarchical single path routing protocols for FANETs.

Aadil *et al.* [45] proposed an Energy-aware Cluster based Routing (ECRNET) in flying adhoc networks. The authors proposed an energy-aware link-based clustering (EALC) model, which used k-means density clustering algorithm for selecting cluster heads. The model used a degree of the neighbourhood, energy level and distance to neighbours to select an optimal cluster head. A fitness value was defined for each node in the network and then sorted in reducing order. The node with the highest fitness value was elected as a cluster head and remaining nodes in its range were made its cluster members. For the rest of the nodes, again this procedure was repeated until all the nodes became a member of a cluster.

Khelifi *et al.* [90] proposed a Localization and Energy Efficient Data routing protocol (IMRL) for unmanned aerial vehicles. To initiate communication, the nodes communicated with their neighbours by sending communication requests. The anchor nodes receiving the requests replied with messages containing their own location and identification information. The nodes receiving replies identified Received Signal Strength Indicator (RSSI) values of replying nodes and selected three closest nodes with best RSSI values, and used an edge weight estimation mechanism to identify the weight of edges. These values were further used to calculate node location using the weighted centroid localization algorithm. Next, a cluster head was selected in two rounds. Firstly, a node with remaining energy higher than a threshold was selected as a cluster head. In the second round, utility function values were calculated for all the nodes and the one with the highest utility function value was selected as a cluster head. Finally, data from cluster members was delivered to the base station by cluster head.

Khan *et al.* [44] proposed a Bio-inspired Clustering Scheme for FANETs (BICSF) in which the authors used Glow worm swarm optimization technique to form energy aware clusters. The technique used residual energy and luciferin level of nodes to calculate fitness values and the node with the highest fitness value was elected as cluster head and the rest of the nodes become cluster members. Next, a Krill Herd inspired cluster management technique had been used in which the location of each node was updated in accordance with the location of cluster head and then a path detection function was used to find an optimal route for data delivery resulting in energy conservation of nodes. For cluster maintenance, a threshold energy had been defined for the cluster and the nodes whose residual energies were greater than equal to threshold energy were continued as cluster members, rest were declared dead. The performance evaluations of the proposed routing scheme were done using MATLAB against ant colony optimization and glow worm optimization, which revealed that BICSF performed better for cluster building time, cluster life time, energy consumption, and probability of successful delivery. Wu *et al.* [91] proposed a mobility prediction protocol in which a software defined network (SDN) based architecture had been proposed which used the Extended Kalman Filter (EKF) for estimation and prediction of node mobility. Then they proposed a directional particle swarm optimization algorithm to solve the FANET routing problems.

To end up the discussion about hierarchical routing protocols, Table 2.10 summarizes their salient features, Table 2.11 highlights their strengths and weaknesses and Table 2.12 provides information about the QoS parameters used to evaluate them.

Table 2.10: Salient features of hierarchical routing protocols

Protocol Name	Salient Features of Routing Protocol
ECRNET [45]	• Introduced an energy-aware link-based clustering (EALC) model which used k-means density clustering algorithm for optimal cluster head selection • Fitness values were calculated and sorted for each node, and node with maximum fitness value was elected as cluster head and nodes within its range were elected as cluster members • If the cluster head's fitness value falls below the threshold value, then all the nodes of that cluster were unclustered
IMRL [90]	• Node location estimation was done using weighted centroid localization algorithm • Cluster head was elected by using utility function calculation of nodes and the highest valued node was elected as cluster head • Next cluster head selection helped in optimizing the energy consumption by nodes in case the sink location was far away

BICSF [44]	• Used glow worm swarm optimization for cluster building which considered residual energy, and luciferin level of UAVs to calculate their fitness which allowed for electing cluster head and cluster members • Used krill herd inspired cluster management which used genetic operators namely cross over and mutation for optimal positioning of UAVs in cluster • Cluster management done in an efficient way by repetitive screening of UAVs for their remaining energies and the UAVs with energies below the threshold values were declared dead.
DPSO [91]	• Used Extended Kalman Filter to estimate and predict the mobility of nodes • Directional particle swarm optimization algorithm had been used to take the optimal routing decisions for efficient packet delivery

Table 2.11: Strengths and weaknesses of hierarchical routing protocols

Protocol Name	Strengths	Weaknesses
DPSO [91]	• Better mobility estimation of nodes due to the use of extended Kalman filter • The optimal routing decisions of directional particle swarm algorithm resulted in better values of throughput and packet delivery ratio	• Increased number of UAVs impacted the performance of protocol negatively in terms of packet delivery ratio and throughput

ECRNET [45]	• EALC enhanced the cluster lifetime and the energy consumption by selecting cluster heads based on energy level, distance to neighbours and degree of neighbourhood • EALC reduced the energy consumption of nodes by adjusting the transmission power of nodes as per operational requirements	• Erroneous transmission power adjustment of nodes could lead to faster energy depletion of cluster head
IMRL [90]	• Weighted centroid localization algorithm allowed for precise location estimation of nodes • Utility function value elected a cluster head with maximum surplus energy resulting in increased network lifetime • Selection of next cluster head optimized energy dissipation among nodes	• With an increase in network lifetime, the energy consumption of the proposed technique increased, as compared to existing techniques

BICSF [44]	• Glow worm swarm optimization introduced efficiency into the protocol by optimizing the cluster formation • Krill herd inspired cluster management ensured minimal dislocation of nodes from the cluster • Efficient cluster maintenance mechanism ensured adaptive cluster adjustments due to environmental changes and mobility of nodes	With increased node density of nodes, the cluster lifetime decreased due to frequently occurring topology changes

Table 2.12: QoS metrics used for hierarchical routing protocols

Protocol Name	Packet Delivery Ratio	Cluster Building Time	Cluster Lifetime	Energy Consumption	Throughput	Average Path Lifetime
ECRNET [45]	✗	✓	✓	✓	✗	✗
IMRL [90]	✓	✗	✗	✓	✗	✓
BICSF [44]	✓	✓	✓	✓	✗	✗
DPSO [91]	✓	✗	✗	✗	✓	✗
Note. ✓: used, ✗: Not used						

2.2 Multipath routing protocols for FANETs

Multipath routing is known for its reliable route identification and parallel data delivery enabling optimum utilization of resources thereby fulfilling the quality of service and quality of experience requirements for the traffic flows. It has helped the backbone networks in providing resilient communication by using diverse paths and splitting the traffic for spontaneous delivery of data to destinations. Due to the certain characteristics of multipath routing protocols like load balancing, congestion control, reliable communication, and maximum network resource utilization, it has become a prominent choice for high bandwidth consuming applications [92]. Not only in wired networks but the multipath routing has also shown its effectiveness for data delivery in wireless networks as well. In Network Coding based Multipath Cooperative Routing(NCMCR) [93], the protocol had exploited the multipath packet forwarding capability for delivering data in batches for low earth orbit satellite communications. Two algorithms were incorporated into the protocol, namely, source-based and destination-based multipath cooperative routing algorithms, which manage the traffic delivery in a dynamic and cooperative manner. A No-Stop-Wait acknowledgement mechanism had been devised to handle the acknowledgements in an efficient way thereby increasing the network throughput. The experimental analysis of the protocol proved its efficiency against the existing routing protocols. Further efforts have been made to enhance the multipath routing algorithms to adapt to inherent characteristics of wireless networks for efficient data delivery like network utility maximization mechanism had been formulated in [94] in which the authors had developed a hop by hop rate control algorithm for multipath routing in communication networks. They proved the effectiveness of routing mechanism in terms of total effective rate and aggregate effective utility over the conventional hop-by-hop rate control and end-to-end rate control with multipath networks. In another study [95], the authors had surveyed network utility maximization framework based on congestion control for multipath transmission networks. Here, firstly a detailed description of cross-layer design and optimisation based resource assignment had been presented focusing on congestion control and then congestion control frameworks had been discussed focusing on elastic and inelastic traffic. Finally, cross-layer multipath congestion control algorithms had been discussed focusing upon flow control and energy reduction.

Extending the advancements in multipath routing techniques, similar kind of routing solutions have emerged for FANETs as well. The following discussion describes multipath routing protocols available for FANETs by dividing them categorically based upon their routing mechanism into proactive routing, geographic routing, and reactive routing protocols, describing their features, characteristics which affect their route identification, data delivery and route maintenance procedures.

2.2.1 Proactive routing protocols

Proactive multipath routing protocols for FANETs have modified their basic table driven route identification mechanism to accommodate multipath identification feature in order to provide fail safe and resilient data delivery among the highly dynamic flying nodes. The following discussion provides insight into recently developed proactive multipath routing protocols for FANETs.

Yin *et al.* [96] had proposed a Network Coding based OLSR Multipath transmission scheme for FANETs in which the authors had used Random Linear Network Coding (RLNC) to encode multiple data blocks into packets and then forwarding them to next nodes which further follow the same procedure. The MPR selection method of OLSR had been improved to use greedy algorithm which used recent time stamps values of Hello messages received from nodes for the selection of MPRs. Route calculation took place when a route request got transmitted between nodes and then using the node-disjoint method, multipath routes were constructed out of it. If multipath calculation was not possible using node-disjoint method then link-disjoint method was used and if the same happened for link-disjoint method then joint multipath routing was used. The performance of the proposed protocol was tested for parameters namely successful delivery ratio, end to end delay, and normalised transmission overhead, for which the routing mechanism displayed better performance as compared to its peers.

Secinti *et al.* [97] proposed a UAV Network Management Protocol in which the interconnected UAVs had been deployed as OpenFlow switches managed by a centralised controller operated from a remote location using the OpenFlow v1.5 southbound protocol. Initially, Experimenter messages were used to acquire the 3D position and channel availability information of UAVs to know about their network topology. Then an estimated transmission time (ETT) was calculated for each link using packet error rate and data rate of the communication channel. Afterward, these ETT values were used by disjoint Dijkstra algorithm with vertex splitting method to identify all the possible path between UAVs. Then these identified paths were conveyed by OpenFlow controller to the UAVs using modify state message which populated the flow tables and configured group action buckets. In case of link breakage, the instructions were issued by the controller to the UAV to refer to a different action bucket for selecting an alternate route. To eliminate any possibility of signal jamming, a γ value had been used as a multiplier value which was defined as a natural exponential function of intersecting signal ranges of UAVs on separate paths. This γ value was multiplied to the UAVs having intersecting links so as to increase their ETT values in order to avoid their selection as a potential communication link so as to avoid any jamming attacks from disrupting the communication. The protocol's performance tests revealed its efficiency in terms of average outage rate but the performance got degraded for average end to end delay because of its efforts of eliminating the intersecting UAV links.

To summarize the discussion, Table 2.13 highlights the salient features, Table 2.14 pinpoints the strengths and weaknesses and Table 2.15 provides information about the QoS parameters used for evaluating the protocols.

Table 2.13: Salient features of proactive routing protocols

Protocol Name	Salient Features of Routing Protocol
NC-OLSR [96]	• Used RLNC to encode multiple data blocks into packets • Optimised MPR selection mechanism by selecting MPRs with recent Hello message time stamp • Performed multipath calculation using three different methods with a priority of node-disjoint method $>$ link-disjoint method $>$ joint multipath routing
SD-UAVA [97]	• Used experimenter message to acquire information about 3D node location, channel availability and topology information • Used estimated transmission time by Dijkstra algorithm to identify multiple routes between UAVs • Selected UAVs with disjoint links in order to avoid link intersection

Table 2.14: Strengths and weaknesses of proactive routing protocols

Protocol Name	Strengths	Weaknesses
NC-OLSR [96]	• Use of network coding enhanced the reliability of data transmission over wireless channel by increasing the throughput • Reduced multiple route discovery attempts by identifying multiple routes in a single route discovery attempt • Improved MPR selection ensured longer availability of MPRs for communication	• Routing load of NC-OLSR increased in case of lowest node velocity due to increased values of network coding operation co-efficients
SD-UAVA [97]	• Experimenter messages helped in tracking the exact situation of nodes to be elected in the routing process • Availability of disjoint paths in the action buckets allowed for quick route recovery • Link intersection avoidance mechanism resulted in prevention of possibility of signal jamming attack	• Average end-to-end delay increased while removing intersecting links of UAVs

Table 2.15: QoS metrics used for proactive routing protocols

Protocol Name	Packet Delivery Ratio	Packet Loss Ratio	End to End Delay	Throughput	Routing Overhead	Link Stability
NC-OLSR [96]	✓	✗	✓	✗	✓	✗
SD-UAVA [97]	✗	✓	✓	✗	✗	✗
Note. ✓: used, ✗: Not used						

2.2.2 Reactive routing protocols

Reactive routing protocols have adapted themselves to identify multiple on demand routes to the destination for reliable delivery of data with lesser network outage times. The following discussion describes reactive multipath routing protocols for FANETs.

Zhai *et al.* [98] proposed a Rapid Re-establish Temporally Ordered Routing Algorithm (RTORA). The researchers extended the link reversal mechanism of TORA [14] by using a height mechanism with it, in order to reduce control overhead and reinstate the broken route quickly. The mechanism allows only source nodes to update a broken route. After a UPD or CLR is received by the nodes, the link-status list and the height list of neighbours is updated. In case of the existence of a downlink, nothing is done. Else, the link reversal mechanism is executed to identify a feasible route. The experimental evaluation of the protocol displayed improved performance for average end-to-end delay and routing overhead.

Another protocol named Link Stability Estimation-based Preemptive Routing (LEPR) protocol [99] had been proposed in which the authors had used GPS information to formulate a link stability metric which included link quality (ratio of forward and reverse delivery of packets among pair of nodes), safety degree (closeness of nodes i,j in terms of communication range and euclidean distance), and mobility prediction factor (using instantaneous relative speed and direction of movement between nodes i,j) to decide upon disjoint paths for data delivery. The protocol showed reliable performance against AODV and DSR in NS3 simulator when tested for packet delivery ratio, end to end delay, route discovery frequency, and routing overhead.

Pu [100] had proposed a Jamming Resilient Multipath Routing Protocol JarmRout which aimed at preventing any jamming attack, network disruptions, and localized failures.The protocol utilised three factors namely estimation of link quality, estimation of traffic load and spatial distance measurement to find neighbour node links with best link quality, least traffic load and sufficiently separated in terms of spatial distance. The route identification process initiated with finding an already stored route in the routing table and if not available, an RREQ packet was broadcasted. The neighbours processed and forwarded the packets by replacing the node id, position coordinates, quality of link and network load values if the received packets' link quality, traffic load and position coordinates were inferior to itself. Otherwise the received RREQ was forwarded as it is. And once all the requests had reached the destination, the destination node selected two distinct paths to reach the source node with optimal parametric values. The performance of the protocol was tested by changing the number of nodes and jammers for parameters namely packet delivery ratio, data delivery latency, communication outage rate, and energy consumed. The protocol performed well for all the performance metrics except for energy consumed because of the control packet transmissions for multiple paths.

To present a summarized view of the discussed reactive routing protocols for FANETs, Table 2.16 highlights the salient features of the discussed reactive routing protocols, Table 2.17 pinpoints the strengths and weaknesses of discussed protocols and Table 2.18 provides information about the QoS parameters used to evaluate the discussed protocols.

Table 2.16: Salient features of reactive routing protocols

Protocol Name	Salient Features of Reactive Routing Protocol
RTORA [98]	• Used height mechanism and link reversal mechanism to reinstate lost routes • The height mechanism allowed only source node to perform link reversal
LEPR [99]	• Used GPS information to track the location of nodes • Used the quality of link, degree of safety, and movement prediction to evaluate link stability of nodes
JarmRout [100]	• Used link quality estimation, traffic load estimation and spatial distance measurement metrics to identify best neighbours for route discovery • Destination used two different paths to send reply to the source node in order to avoid any jamming attack

Table 2.17: Strengths and weaknesses of reactive routing protocols

Protocol Name	Strengths	Weaknesses
LEPR [99]	• Used link stability metric to ensure a reliable route discovery • Used semi proactive route maintenance mechanism to identify an alternative path proactively before the primary path could go down	• End-to-end delay and route discovery frequency increased with increase in node speed
RTORA [98]	• Reduced routing overhead by allowing only source node to perform route updates • Reduced network delay by avoiding congestion due to control packet flooding	• Due to the high dynamicity of nodes, delay could be introduced into route re-establishment process due to pure reactive nature of the protocol
JarmRout [100]	• Used spatially disjoint multiple paths so as to avoid probability of disruption, leading to greater data delivery • Spatially disjoint paths avoided the scenarios of contention between neighbouring nodes for channel access	• High energy consumption was recorded due to the transmission of packets over two paths

Table 2.18: QoS metrics used for reactive routing protocols

Protocol Name	Packet Delivery Ratio	Packet Loss Ratio	End to End Delay	Throughput	Routing Overhead	Energy Consumption
RTORA [98]	✗	✗	✓	✗	✓	✗
LEPR [99]	✓	✗	✓	✗	✓	✗
JarmRout [100]	✓	✓	✓	✗	✗	✓
Note. ✓: used, ✗: Not used						

2.2.3 Geographic/Position based routing protocols

Location aided routing protocols have exploited the location information of flying nodes to identify multiple paths to the destination, providing efficient data delivery in the scenarios of high node mobility. The following literature describes the geographic multipath routing mechanisms for FANETs.

A Cross-layer Link quality and Geographical-aware beaconless opportunistic routing protocol (XLinGO) [101] had focused on enhancing simultaneous multiple video transmission over FANETs. The protocol worked using contention based forwarding in which the source UAV used broadcasting to send video packets to its neighbouring nodes. The video packet header included the location information of source node. The neighbour nodes divided the forwarding region into negative progress area (NPA) and positive progress area (PPA). PPA was the area with neighbour nodes nearer to the destination than source. For deciding which neighbour node would forward data, every node in PPA calculated a dynamic forwarding delay (DFD) and threshold energy and the node with least DFD value and energy sufficiently above threshold energy would forward the packet. The relay nodes were selected based on the metrics namely link quality, progress value (number of nodes till the destination) and queue length (packets stored in interface queue) and the node with best values of these metrics was selected for packet relaying. The protocol's performance had been evaluated using OMNET++ simulator [102] for the parameters structural similarity of video vs. link quality, structural similarity of video vs. frame recovery, and structural similarity vs. mobility, which revealed better performance for XLinGO as compared to other protocols.

To sum up the discussion about geographic routing protocols, Table 2.19 summarizes their salient features, Table 2.20 pinpoints their strengths and weaknesses and Table 2.21 provides information about the QoS parameters used to evaluate the discussed protocols.

Table 2.19: Salient features of geographic routing protocols

Protocol Name	Salient Features of Routing Protocol
XLinGO [101]	• Used broadcasting based packet forwarding to the source node • Divided the data forwarding area into negative progress area and positive progress area in order to find nodes closer to the destination • Selected nodes with least values of dynamic forwarding delay and higher values of threshold energy to forward packets

Table 2.20: Strengths and weaknesses of geographic routing protocols

Protocol Name	Strengths	Weaknesses
XLinGO [101]	• Selecting forwarding nodes with least dynamic forwarding delay and higher threshold energy ensured successful forwarding of packets • Selecting relay nodes with better values of link quality, progress value, and queue length metrics ensured successful packet relaying	• Contention based forwarding mechanism of source nodes could result in delayed availability of communication channel

Table 2.21: QoS metrics used for geographic routing protocols

Protocol Name	Packet Delivery Ratio	Route Update Time	End to End Delay	Throughput	Routing Overhead	Network Disconnection Time	Route Setup Success Rate	Average Path Life Time
XLinGO [101]	✓	✗	✗	✗	✗	✗	✗	✗
Note. ✓: used, ✗: Not used								

Apart from the discussion done above for the routing protocols of FANETs, there have been other correlated advancements noticed in the domain. Anicho *et al.* [103] in their paper had discussed how UAV routing protocols and UAV autonomy algorithms exhibited conflicting characteristics for their operation in adhoc mode as well as infrastructure operational mode. The authors had at first discussed how topology changes affect the routing in autonomous and multi-UAV cooperative networks. Then the authors talked about the UAV autonomy algorithms and their conflicting behaviour with respect to routing algorithms. The authors had proposed an integration interface for UAV routing and autonomy algorithm in which the routing algorithm shared link status information with UAV autonomy algorithm in order to adjust UAV movements for sustained connectivity and data transmissions. Bujari *et al.* [104] had presented a comparison of topology based and location based routing over 3D Internet of Things (IoT) involving drones, other moving vehicles, and sensors. The authors selected the popular topology based routing protocols namely DSDV, AODV, and DSR and compared them with position based protocols namely Greedy-Face-Greedy (GFG) [105], Greedy-Random-Greedy (GRG) [106], and Depth First Search (DFS) [107] for their performance evaluation using the parameters of delivery ratio, path dilation and delivery time. The simulation results revealed that DSDV and GFG are not favourable choices for data delivery in IoT applications. AODV and DSR showed good data delivery rates but they exhibited a high level of delay. So, they are not favourable for real-time data delivery in IoT applications.

Finally, to summarize the findings discovered from the in-depth study of existing literature, a comparative analysis of the protocols has been tabulated in Table 2.22 highlighting their differences in route identification mechanisms, packet forwarding techniques, methods of storing routing information and any supporting information required for routing.

Table 2.22: Comparative analysis of FANET routing protocols

Routing Protocols	Characteristics of FANET Routing Protocols														
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
P-OLSR [31]	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
ML-OLSR [32]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
GPNC-SP [29]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
Improved OLSR-ETX [30]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
LEBR [57]	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
Modified-RGR [37]	✓	✗	✗	✗	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗
AFP[62]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗	✗	✗
FGQPA [35]	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✗	✗	✗	✗
MQSPR [74]	✓	✗	✗	✗	✗	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗
ADRP [75]	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗

BR-AODV [40]	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗
SARP [36]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗
A-GR [63]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗
GCS-Routing [42]	✓	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗
DRS [83]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
RARP [60]	✓	✗	✓	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
GeoSaw [84]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗
GRP [41]	✓	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗
IMRL [90]	✓	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✓
ECRNET [45]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
BICSF [44]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✓	✗
NC-OLSR [96]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
SD-UAVA [97]	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗
RTORA [98]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗

LEPR [99]	✗	✓	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
JarmRout [100]	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
XLinGO [101]	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
G-OLSR [71]	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗
LCO-OLSR [72]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
QMR [76]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
Q-FANET [77]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
FNTAR [78]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
RLPR [108]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
DSR-PM [79]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
DPSO [91]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
PAPR [80]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗
QTAR [81]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗
SRS [89]	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	✓	✗
S-ELHR [82]	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗

In Table 2.22 the column labels P1 denotes Single path Forwarding, P2 denotes Multi Path Forwarding, P3 denotes Link Prediction, P4 denotes Location Prediction, P5 denotes Mobility Prediction, P6 denotes Selective Forwarding, P7 denotes Greedy Forwarding, P8 denotes Location Aided, P9 denotes Infrastructure Based, P10 denotes On demand Route Discovery, P11 denotes Table Driven Route Discovery, P12 denotes Swarm Intelligence, P13 denotes Nature Inspired, P14 denotes Cluster Based, P15 denotes Fuzzy Logic Based. The labels ✓denotes used, and ✗denotes Not used.

2.2.4 Chapter Summary

This chapter discusses the existing research done by various researchers in the field of adhoc routing in FANETs. The chapter arranges routing protocols under different categories. For each category, the chapter discusses respective routing mechanisms associated with the core functionality of FANET routing protocols. The discussion attempts to provide insights into the salient features of each routing mechanism, strengths and weaknesses of each routing mechanism, and the QoS metrics based on which the performance of routing protocols have been evaluated. Finally, an exhaustive comparison of all the routing protocols has been summarized in the tabular form highlighting the various route identification mechanisms adopted by the protocols to find and recover routes for flying nodes communicating in adhoc manner. The chapter provides in-depth insights into the kind of routing protocol suitable for various routing scenarios and the drawbacks and performance issues impacting the routing performance of the protocols.

Chapter 3

Evaluation of Existing Routing Protocols for FANETs

The evolution of flying adhoc networks happened as an extension to the existing mobile adhoc network routing protocols. The existing MANET routing protocols were used for routing of UAVs in FANETs. The shortcomings in MANET routing protocols led to the development of improved routing protocols for FANETs. For the purpose of identifying a MANET routing protocol with the best performance for routing in FANETs, this chapter discusses the simulation based evaluation of existing routing protocols for FANET routing. To test the performance of various existing routing mechanisms, routing protocols exhibiting different categories of route identification mechanisms have been selected so as to exhaustively evaluate the data delivery capability and efficiency of these protocols. The first protocol selected for the evaluation is the Adhoc On-demand Distance Vector (AODV) routing protocol. AODV is a reactive routing protocol which uses the on-demand route discovery mechanism to identify the routes when needed. The mechanism uses route request and route reply packets for exchanging the control information related to route identification and route recovery. The second protocol considered for evaluation is the Optimised Link

State Routing (OLSR) protocol. OLSR is a proactive routing protocol in which every node stores the network information for all the nodes with itself and keeps on updating it at regular intervals. The route identification is supported by the multi point relays and link states in order to select the best route for packet delivery. Its table driven routing mechanism allows it to route the data in an efficient manner. The next routing protocol used for the evaluation is the Adhoc On-demand Multipath Distance Vector (AOMDV)routing. AOMDV is a multipath routing protocol which ensures identifying multiple feasible paths for delivering the packets. The next protocol considered for evaluation is the Zone Routing Protocol (ZRP). ZRP is a hybrid routing protocol which utilizes both proactive routing and reactive routing schemes for effective packet delivery. The protocol divides the routing region into multiple zones where the intra-zone routing is done in a proactive manner while the inter-zone routing is done in a reactive manner. The protocols under evaluation have been simulated to analyse their performance in terms of various Quality of Service (QoS) metrics such as Packet Delivery Ratio (PDR), Average End to End Delay (EED), average throughput, and normalized routing load (NRL). These metrics help in analysing the effectiveness of existing routing protocols for routing packets in FANETs.

3.1 Simulation and Analysis

Evaluating the performance of different routing protocols with varied routing decision making mechanisms can allow for identifying a routing mechanism with acceptable packet delivery in FANETs. To analyse the performance of various routing mechanisms, exhaustive simulations have been performed using Network Simulator-2 (NS-2), a discrete event simulator. NS-2 is a network simulator developed primarily to support simulations of adhoc networks and has all the major adhoc routing protocols implemented in it. So, this simulator becomes a suitable choice for experimenting with adhoc routing protocols for data routing. The protocols have been simulated using the scenarios with variations in node speed and number of nodes. Table 3.1 enlists the simulation parameters used for the evaluation of MANET protocols for routing in FANETs.

Table 3.1: Simulation parameters for the evaluation of existing routing protocols

Parameter	Value
Number of UAV nodes	10,20,30,40,50,60,70,80,90,100
Simulation area	2000 x 2000 x 2000 m^3
Mobility model	3D Random Waypoint Mobility Model
Minimum node speed	5m/s
Maximum node speed	10m/s
Traffic type	Constant bit rate
Antenna type	Omnidirectional
Simulation time	600 sec.

In the first performance analysis, the protocols under consideration have been evaluated for packet delivery ratio in terms of node density. The simulations revealed that with increasing number of nodes, the packet delivery ratio increased initially but after a certain increase in node density, the packet delivery ratio started decreasing due to packet loss happening as a result of frequent link breakages. Out of the compared protocols, the AODV protocol outperformed the rest of the protocols despite an increase in the node density as shown in Figure 3.1.

In the performance analysis of protocols for routing load versus node density, initially the routing load was moderate as the protocols identified the routes for lesser number of nodes. As the node density increased in the scenario, the routing load for the protocols started increasing gradually. It is evident from Figure 3.2 that AOMDV and ZRP exhibited maximum routing load while OLSR exhibited minimum routing load. AODV produced moderate level of routing load even with increasing node density.

In the analysis of end to end delay versus node density, AOMDV and OLSR exhibited

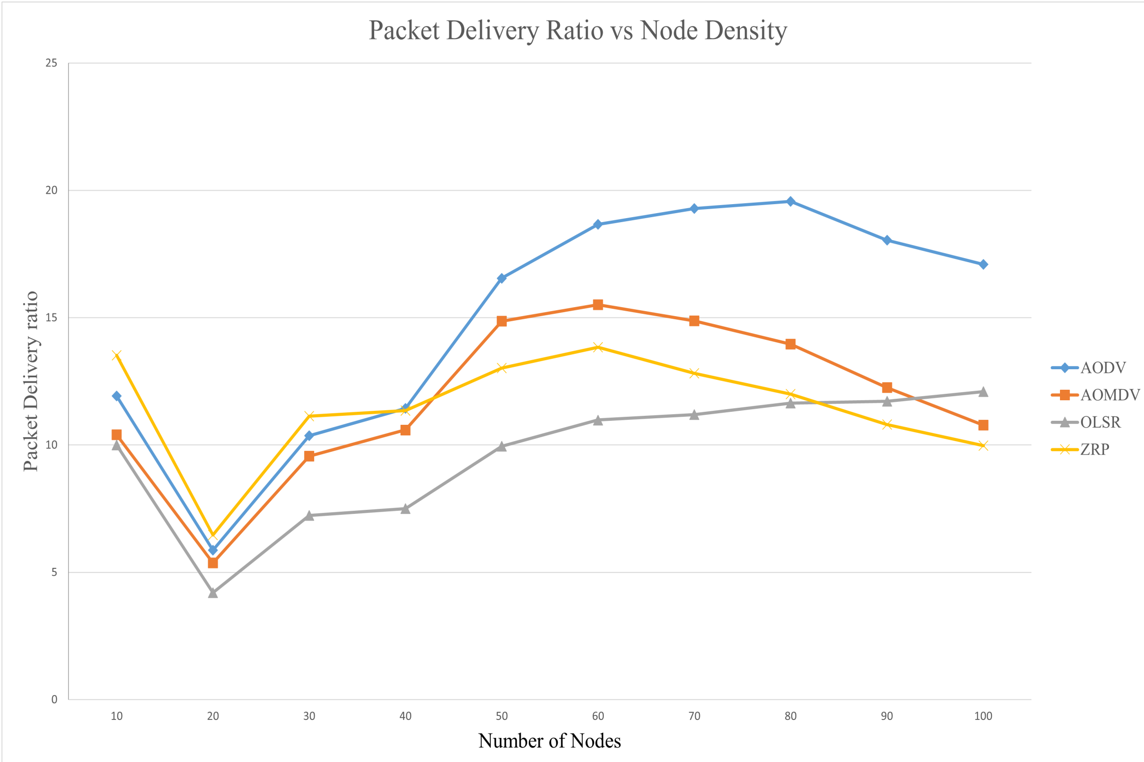


Figure 3.1: Analysis of packet delivery ratio in terms of node density.

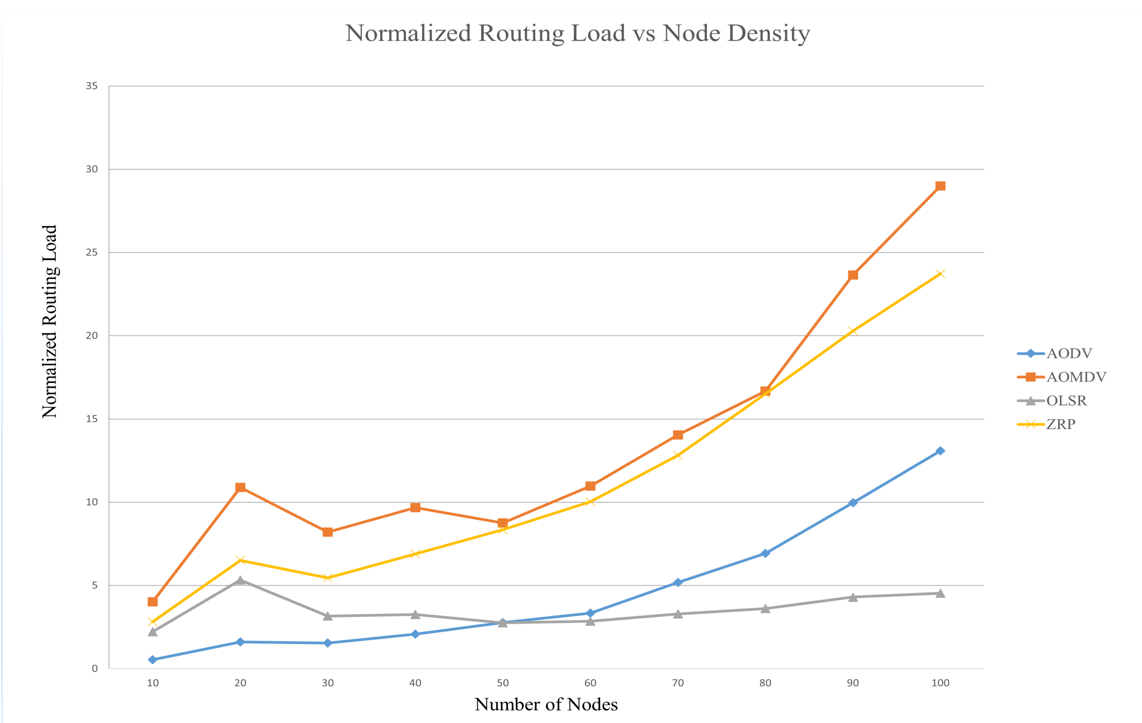


Figure 3.2: Analysis of normalized routing load in terms of node density.

lesser delay for the initial number of nodes but the delay values for AOMDV increased drastically after a marker of 60 nodes while OLSR continued its efficiency in keeping lower delay values. While ZRP exhibited the second highest delay in delivering the data, AODV experienced moderate levels of delay even with increased number of nodes as shown in Figure 3.3.

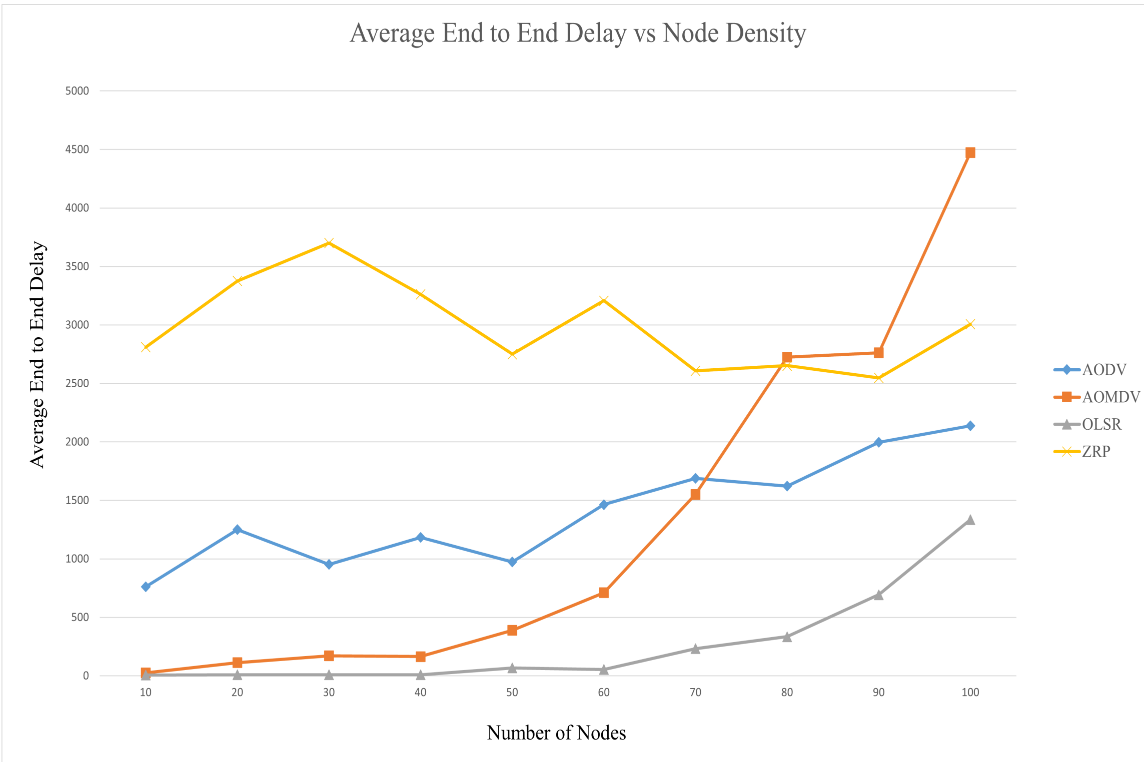


Figure 3.3: Analysis of average end to end delay in terms of node density.

The analysis of throughput versus node density reflected the better efficiency of AODV routing protocol in terms of successful packet delivery as compared to other routing protocols. While the initial throughput values were similar for AODV, AOMDV, and ZRP, the OLSR showed weaker throughput with lesser number of nodes. With increasing number for nodes, the throughput values for all the protocols increased gradually but AODV showed the best throughput efficiency as shown in Figure 3.4.

From the analysis, it has been evident that the reactive on demand AODV protocol proved

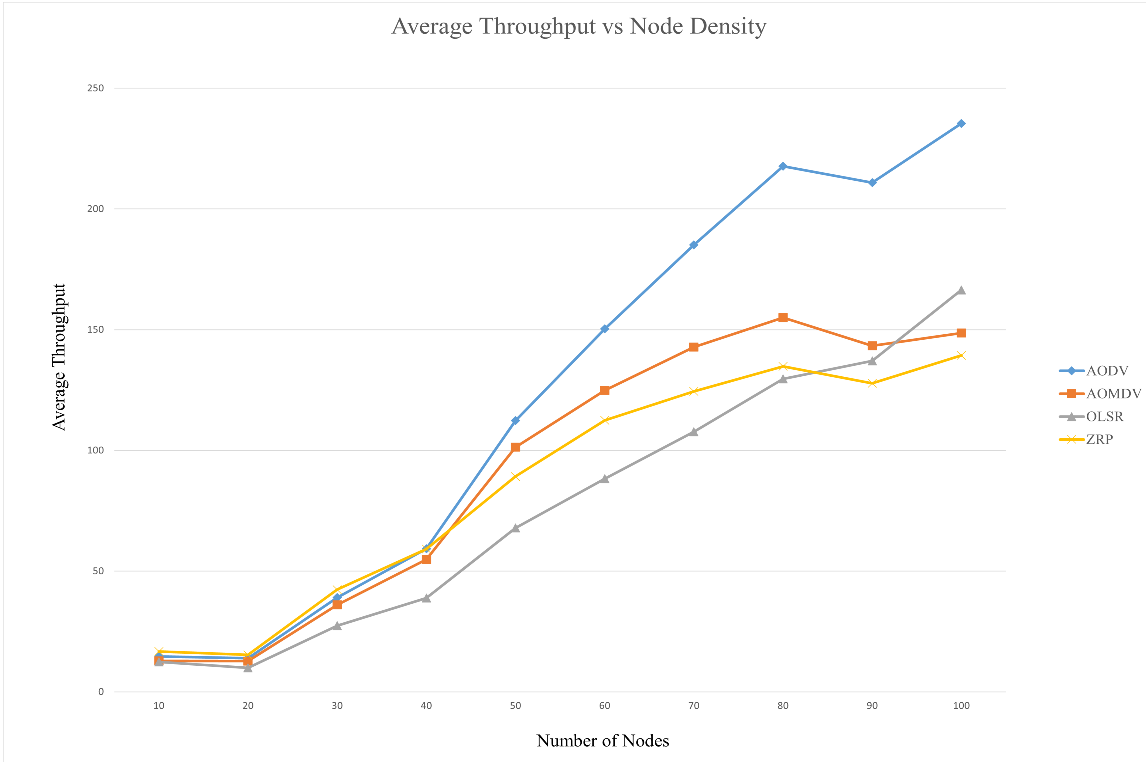


Figure 3.4: Analysis of throughput in terms of node density.

its effectiveness in providing the maximum throughput and packet delivery ratio with reasonable values of end to end delay and routing load. The link state OLSR protocol has been able to reduce the average end to end delay and normalized routing load to the minimum level. This analysis has been instrumental in deciding upon a type of routing mechanism to choose for further research work.

3.2 Chapter Summary

This chapter discusses the simulation based performance analysis of existing MANET routing protocols used for FANET routing. To analyse the performance of various routing mechanisms, exhaustive simulations have been performed using Network Simulator-2 (NS-2), a discrete event simulator. The protocols tested in the experimentation have been Adhoc On-demand Distance Vector (AODV), Adhoc On-demand Multipath Distance Vector

(AOMDV), Optimised Link State Routing (OLSR), and Zone Routing Protocol (ZRP). The protocols have been simulated using the scenarios with variations in node speed and number of nodes. The evaluation of the protocols has been done using the parameters, namely, packet delivery ratio, normalized routing load, average end to end delay, and average throughput. The analysis revealed the effectiveness of the reactive on demand AODV protocol in providing the maximum throughput and packet delivery ratio while the link state OLSR protocol has been able to reduce the average end to end delay and normalized routing load to the minimum level. This analysis has been instrumental in deciding upon a type of routing mechanism to choose for further research work.

Chapter 4

Proposed Quality of Service Aware Routing Protocol (QARP) for FANETs

This chapter provides the details of the proposed Quality of Service Aware Routing Protocol for FANETs. The proposed QARP protocol incorporates the functionality of firefly algorithm in the route discovery process to identify least delay incurring neighbour nodes for packet delivery to the destination. The Gaussian Quantum Particle Swarm Optimization (GQPSO) algorithm has been incorporated to identify a least delay route for packet delivery. A suitable network scenario has been depicted in which the proposed protocol could be a feasible solution for data routing among the UAVs in adhoc mode. Then a detailed discussion on the methodology of the proposed QARP protocol has been done.

4.1 Network Model for the Proposed FANET Routing Protocol

Flying adhoc networks have evolved to be used in various application scenarios where the human reachability is quite difficult. FANETs have shown their effective implementations in the scenarios like border surveillance, traffic monitoring, crop monitoring etc. where the tasks have been completed effectively with least effort by the autonomously flying UAVs. Routing protocols have been instrumental in the successful execution of the tasks by the FANETs. To evaluate the performance of the proposed routing protocol, a scenario of an agriculture field has been considered in which the UAVs have been deployed to monitor and analyse the status of the crop like plant condition and soil condition parameters. The information related to different parameters is recorded using the cameras mounted on the UAVs. The captured information is transmitted among the autonomous randomly flying UAVs using omni directional antennas so that it can finally reach the destination node. The proposed protocol is focusing on optimizing the exchange of data among the flying nodes so that a near to real time transmission of information could take place and the farmers can take action for the benefit of crops based upon the data received from the UAV adhoc network. For the experimentation, let's consider a set of UAVs $N_i = N_1, N_2, N_3, ..., N_n$, where n is the total number of UAVs deployed within a scenario of $area = X \times Y \times Zm^3$. The UAVs move randomly and communicate with each other thereby exchanging the control information packets and data packets among themselves while flying within their respective communication ranges. All the UAVs exchange data using node disjoint links in full duplex mode. A scenario depicting the same has been visualized in Figure 4.1.

The network model prominently consists of a network of UAV nodes flying over the field and communicating among themselves using the wireless communication links represented

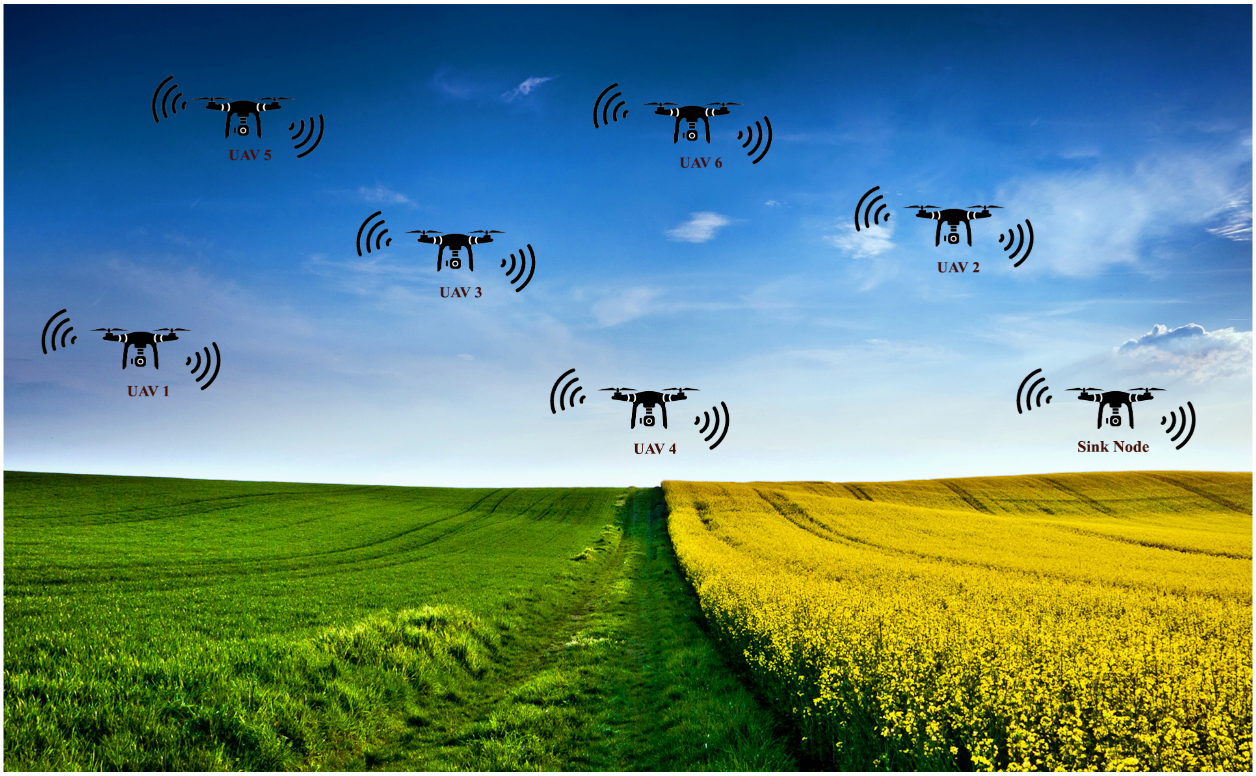


Figure 4.1: A group of UAVs monitoring the crops over a field.

as

$$G = (U, L), \tag{4.1}$$

where G represents a network of UAVs communicating in adhoc mode, U is a set of UAVs, and L is the wireless links established among the UAVs.

For transmitting a data packet from source node U1 to the destination node U2 where U1,U2 ε U, a communication path is required to be established using a set of links between U1 and U2. The path containing the set of links could be defined as

$$Path(U1, U2) = (U1, r_1, r_2, ..., r_n, U2), \tag{4.2}$$

where r_n is the relay node ($r_1, r_2, ..., r_n \varepsilon$ U), and the wireless communication between two adjacent nodes is represented by the link $l_1, l_2, ..., l_n \varepsilon L$.

The FANET considered in this scenario consists of UAVs flying and moving dynamically due to which the communication links among them change frequently over time. So the FANET in this scenario could be considered as a time varying network as represented in equation 4.3.

$$G(t) = (U(t), L(t)) \tag{4.3}$$

where t denotes the time, G(t) denotes a network of UAVs as a function of time, U(t) denotes set of UAVs operating as a function of time, and L(t) denotes the wireless links operating as a function of time.

The network model also includes some assumptions and relevant notations which have been used to mathematically formulate the proposed protocol as discussed further.

4.1.1 Assumptions

The following assumptions are considered while executing the proposed protocol within a FANET.

1. All the autonomously flying UAVs are of the same or similar type in terms of their form factor and flying capabilities.
2. All the UAVs have uniform resource availability and same communication range for inter-UAV communication.
3. All the UAVs communicate using IEEE 802.11 wireless network technology in full duplex mode and are equipped with Global Positioning Systems (GPS) for location awareness.

4.1.2 Notations

Table 4.1 provides information about the notations used in the proposed routing protocol. These notations have been used in the various mathematical functions and algorithms to denote specific terminologies.

Table 4.1: Notations used in the proposed routing protocol

N	Number of UAVs
i	Node number
j	Node number
n	Maximum iterations
Node_delay	Delay of communication among UAVs
t	Iteration counter
X_i^t	Position of $node_i$ at t^{th} iteration
X_{inew}	New position of node
β_0	Attraction constant
γ	Absorption coefficient
α	Randomness strength 0-1 (highly random)
N_{di}	Node delay
N_{pi}	Node position
N_{dinew}	Updated node delay
pbest_i	Personal best (one hop neighbour of a node with least delay)
gbest	Global best (global best delay values of all the nodes in the direction of destination in ascending order.)
La	Local attractor
δ	Adaptive shrinkage factor
ϕ	Random number generated out of normal distribution in the range 0,1
G	Random number taken from the range 1,3

4.2 Methodology of the Proposed Quality of Service Aware Routing Protocol for FANET

Nature inspired meta heuristic algorithms have shown their efficiency in solving complex problems with inherent dynamicity. These algorithms are able to optimize the adaptation of freely moving communicating nodes within a network. To develop a delay aware efficient routing protocol, a nature inspired firefly algorithm has been incorporated into the route discovery mechanism of the QARP protocol. The basic principle of the algorithm lies in the concept of adapting the placement of fireflies closer to the one with the highest brightness. Based on this principle, the proposed algorithm utilizes the minimum delay among the neighbouring nodes with respect to a reference node to decide upon the candidate nodes considered for route discovery. The functioning of the delay aware routing protocol is briefed as follows.

1. In the initialization phase, for each one hop neighbour of a node, the transmission delay and position information is identified.

2. The firefly algorithm is used to optimize the position of the nodes to minimize the one hop delay.

3. For each node, the least delay one hop neighbour is identified.

4. Then using the modified Gaussian Quantum Particle Swarm Optimization algorithm, the nodes' delay is optimized by adjusting the position of the nodes.

5. Finally, the least delay nodes are used for delivering the data to the destination.

6. In case of route failure, an alternate node is identified for the node causing the route failure from the list of least delay neighbours in the direction of the destination. If no alternate node is available, then the route discovery is started from the point of failure.

4.2.1 Delay Awareness in Route Discovery

In the initialization of the proposed routing mechanism, each node identifies its one hop neighbours through the exchange of hello messages. The hello message contains the location information of the node. In this way, each node comes to know about the current location and delay of its one hop neighbour. Due to the on-demand execution of the protocol, the route discovery initiates as and when a route is required to be established. For this purpose, a Route Request (RREQ) packet is broadcasted to every one hop neighbour of each node to cover the whole network with RREQ packets. Every subsequent node receiving an RREQ packet will either forward the packet to the next nodes if it does not have a direct route to the destination, or it will respond with a Route Reply (RREP) if it is the neighbour of the destination node. The firefly algorithm optimizes the location of each one hop neighbour of a node to identify a node with the least delay to the destination using equation 4.4 [109].

$$X_i^{t+1} = X_i^t + \beta_0 e^{-\gamma r_{ij}^2}(X_j^t - X_i^t) + \alpha_t \varepsilon_i^t \tag{4.4}$$

where X_i^{t+1} represents the updated position of node i, X_i^t represents the current node position, t is iteration counter, $\beta_0 e^{-\gamma r_{ij}^2}$ represents attractiveness constant which is defined by the brightness values of two fireflies with respect to each other, β is the attraction factor, $X_j^t - X_i^t$ is the distance between node j and i, α_t is a constant parameter with the value ranging from $0 \leq \alpha_t \leq 1$, and ε_i^t is a random number drawn from uniform distribution at time t.

The pseudo code for the route discovery process is given in Algorithm 1.

The route discovery process mentioned in Algorithm 1 discusses the execution of the procedure as explained below.

1. In the step 1, each UAV node N_i initializes itself.

2. In the step 2, each node N_i identifies the transmission delay and node position of its one hop neighbour by exchanging the HELLO packets.

3. In step 3, the route discovery procedure initiates. The source node transmits RREQ

Algorithm 1 Pseudo code for route discovery procedure of quality of service aware routing protocol

1: Initialize the UAV nodes $N_i = 1, 2, 3, ..., n$
2: For each node N_i identify the transmission delay and position of each one hop neighbour by exchanging the HELLO packets
3: Initiate Route Discovery by sending RREQ packets from a source node to its one hop neighbours
4: For every packet received at a node
5: **while** $Iteration \leq n$ **do**
6:     **if** Source_address, Packet_id found in the route cache **then**
7:         Drop RREQ packet
8:     **else**
9:         **if** Node_address==Destination_address **then**
10:             Send an RREP packet containing node position and delay back to the source using the reverse route
11:         **else**
12:             Forward the packet to its one hop neighbours
13:         **end if**
14:     **end if**
15:     **for** All the one hop neighbours of a node N_i with a route to destination **do**
16:         **if** $Node\_delay_i > Node\_delay_j$ **then**
17:             Update node position using equation 4.4
18:         **end if**
19:         Rank nodes based upon node delay N_{di} and node position N_{pi}
20:     **end for**
21: **end while**

packets to its one hop neighbours. The neighbours subsequently forward the RREQ packets to their one hop neighbours and so on.

4. In steps 4 to 7, for every RREQ packet received by a node, If a node is receiving a duplicate RREQ which is identified by matching the Source_address and Packet_id, then the RREQ packet is dropped.

5. In steps 8 to 10, If a node receiving the RREQ packet is the destination itself, then the node creates an RREP packet which contains the destination node position and transmission delay to reach the source and the packet is forwarded towards the source using the upstream path.

6. In steps 11 to 14, if the node receiving the RREQ is not the destination node then the packet is forwarded from one node to its one hop neighbours and so on until the destination is reached. The forwarded RREQ packet contains the node position and transmission delay of the forwarding node.

7. In the steps 15 to 16, for all the one hop neighbours of a node with route to the destination, compare the data delivery delay of the nodes among each other.

8. In step 17 to 18, update the positions of one hop neighbours using equation 4.4 to optimize the data delivery delays to the destination.

9. In steps 19 to 21, rank the nodes based on the least data delivery delay to the destination

Finally, the mechanism provides a list of nodes capable of delivering data to the destination with the least delay. A flow chart depicting the flow of instructions is shown in Figure 4.2.

4.2.2 Delay Awareness in Route Establishment

After the route discovery process completes successfully, the proposed routing protocol initiates the optimal route establishment process in which the mechanism attempts to identify the route with the least delay to deliver the data. The optimal route is identified by optimizing the node positions which further helps in identifying the intermediate nodes with the least delay for end to end delivery of data. The pseudo code defining the route establishment process is given in Algorithm 2.

The stepwise explanation of the route establishment process is given below.

1. In step 1, the route establishment procedure receives the list of nodes with the least delay N_{di} and their corresponding node positions N_{pi} for each node from the route discovery procedure.

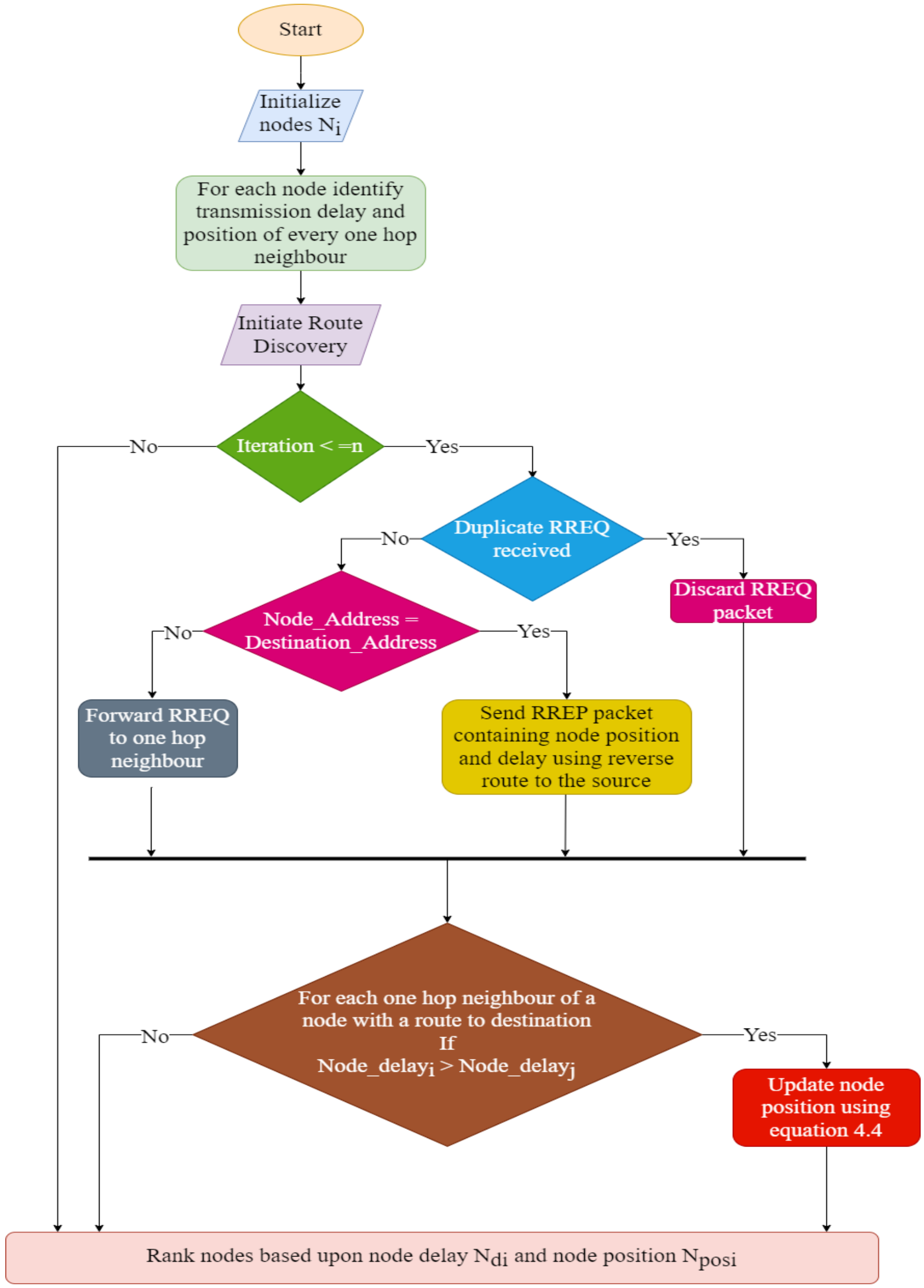


Figure 4.2: Flow of instructions in route discovery process.

2. Step 2 initializes the value of the personal best variable $pbest_i$ for a node as N_{di}.

3. Step 3 initializes the value of the global best variable gbest as min(N_{di}).

4. In steps 4 to 5, for all one hop neighbours of a node in the direction of the destination,

Algorithm 2 Pseudocode for route establishment procedure of quality of service aware routing protocol

1: From the route discovery procedure, get node delay N_{di} and node position N_{pi}
2: Initialize pbest_i = N_{di}
3: Initialize gbest = min(N_{di})
4: **while** $Iteration \leq n$ **do**
5:     For all one hop neighbours of a node in the direction of the destination, calculate the new position of node X_{inew} towards the destination using equation 4.5
6:     Calculate the new delay N_{dinew} of data delivery to the destination.
7:     **if** $N_{dinew} < N_{di}$ **then**
8:         update $N_{di} = N_{dinew}$
9:         $pbest_i$ = N_{di}
10:         Calculate min(N_{di})
11:         **if** min(N_{di}) $<$ gbest **then**
12:             Update gbest = min(N_{di})
13:         **end if**
14:     **end if**
15:     Using gbest populate routing table and start data transmission
16: **end while**

calculate the new position of node X_{inew} towards the destination using equation 4.5.

5. In steps 6 to 7, Identify the new delay of nodes for data delivery to the destination. compare the newly calculated delay N_{dinew} with the older one N_{di} and check whether it is less than the older delay or not.

6. In step 8, if the newer delay N_{dinew} is less than the older delay N_{di} then update the value of N_{di} with N_{dinew}.

7. In step 9, update the $pbest_i$ with N_{di}.

8. In step 10 calculate the minimum of N_{di} as min(N_{di}).

9. In steps 11 to 13, compare the min(N_{di}) with gbest. If min(N_{di}) is less than gbest then update the gbest with min(N_{di}).

10. In step 15, using gbest populate the routing table and start data transmission.

The pbest primarily defines the personal best delay value of one hop neighbours of a node in the direction of the destination and gbest defines the global best delay values of all the nodes in the direction of the destination in ascending order. The GQPSO algorithm calculates the optimized position X_{inew} of the nodes using the location update equation 4.5 [110].

$$X_{inew} = La_i - \delta|mbest - X_i| \log\left(\frac{1}{G}\right) \tag{4.5}$$

Here, La_i is the local attractor which is defined in equation 4.6, δ is the adaptive shrinkage factor used to optimize the convergence of the algorithm as defined in equation 4.10. This factor affects the searching and convergence of the algorithm as a smaller value of δ will result in a local convergence and a larger value of δ will result in delayed convergence of the algorithm, mbest is the mean of personal best and its mathematical relation is defined in equation 4.11. This parameter is used to enhance the global searching ability among the flying nodes, X_i is the previous position of the node, and G is an absolute random number generated from a normal distribution out of a range of (0,1) as defined in equation 4.12.

$$La_i = (C_1 \times \phi_i \times pbest_i + C_2 \times (1 - \phi_i) \times gbest \tag{4.6}$$

here, C_1 and C_2 are the social and cognitive constants, pbest_i is the personal best variable which is defined in equation 4.7 and gbest is the global best value which is defined mathematically in equation 4.8, ϕ is defined in equation 4.9 as an absolute value of a random number derived from the normal distribution in the range of 0,1.

$$pbest_i = N_{di} \tag{4.7}$$

here, N_{di} is defined as the one hop neighbours of a node with the least delay towards the destination.

$$gbest = min(N_{di}) \tag{4.8}$$

here, $min(N_{di})$ is defined as a set of nodes with the least delay towards the destination forming an end to end route for data delivery.

$$\phi = abs(rand(0,1)) \tag{4.9}$$

$$\delta = (\omega_2 - \omega_1)\left(\frac{itermax - iter}{itermax}\right) + \omega_1 \tag{4.10}$$

here, ω_1 and ω_2 are constants whose values are 0.5 and 1. iter and itermax refer to the current iteration and maximum iterations.

$$mbest = \frac{1}{n}\sum_{i=1}^{n} pbest_i \tag{4.11}$$

here $pbest_i$ is the personal best value of the node.

$$G = abs(rand(0,1)) \tag{4.12}$$

After the positions of the nodes are updated, the one hop neighbours with the least delay N_{dinew} to a node in the direction of the destination are again identified and compared with existing delay value N_{di}. If the new value is lesser than the previous one, the node with least delay replaces the previous node. Thus for every node in the direction of the destination, a list of one hop neighbour nodes with the least delay in the direction of the destination is formed. The routing procedure can choose a set of nodes with the least delay towards destination and start delivering the data. Figure 4.3 depicts a flowchart representing the same.

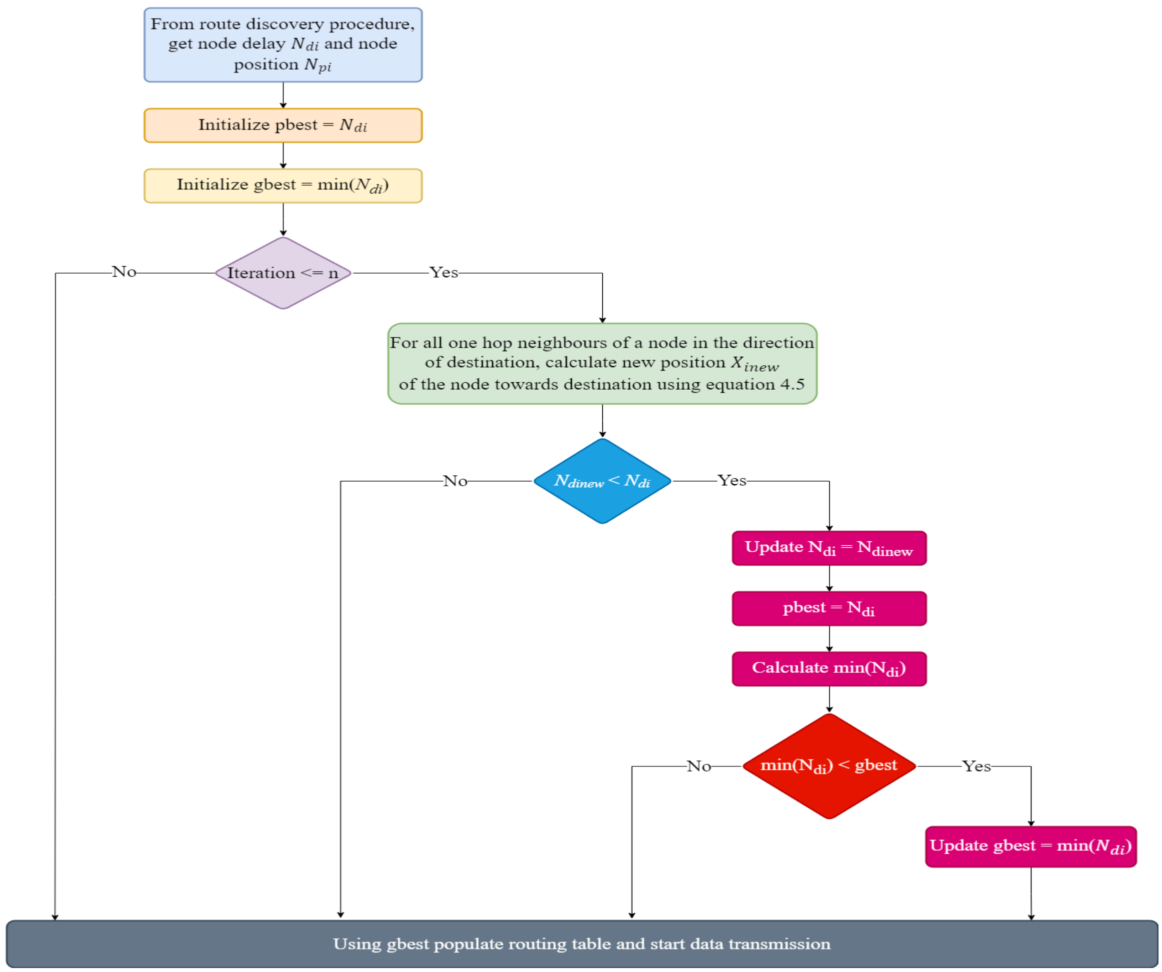


Figure 4.3: Flow of instructions in the route establishment process.

The combination of two heuristic algorithms provide effective routing among the flying nodes by ensuring the least delay incurring routes for packet delivery. Both, the firefly algorithm and GQPSO algorithms have shown their efficiency in solving similar kind of problems due to which they became suitable for proposing this routing protocol. Also, the location information aids in the identification of the currently available optimal nodes for forming the subsequent routes.

4.3 Chapter Summary

This chapter proposes an efficient quality of service aware routing protocol for FANETs. The protocol uses a combination of firefly algorithm and GQPSO algorithm to provide effective least delay packet delivery to the destination. The assumptions have been considered for the execution of this proposed protocol. To mathematically formulate the proposed protocol, the mathematical notations have been defined. The chapter further discusses the methodology of the proposed FANET routing protocol which describes the functionality of the protocol getting optimized in two different phases. In the first phase of route discovery, the nature inspired Firefly algorithm optimizes the position of the nodes to allow the identification of prospective nodes for effective data delivery to the destination. In the second phase, the modified Gaussian Quantum Particle Swarm Optimization algorithm identifies the least delay incurring nodes to the destination out of the nodes identified in the previous phase and chooses intermediate nodes with least delay in data delivery to the destination. So, the delay awareness in the route discovery and route establishment allows for optimal packet transmission to the destination in the network of UAVs.

Chapter 5

Results and Discussion

This chapter discusses the performance evaluation of the proposed QARP protocol. The performance evaluation provides insights into the effectiveness of the proposed routing protocol for packet delivery in terms different quality of service parameters. The performance evaluation helps in identifying the efficiency of the protocol for optimal utilization of the resources. The proposed QARP protocol has been compared with other existing routing protocols namely MA-DP-AODV [111], MDA-AODV [112], MDRMA [113].The baseline for selecting these protocols for experimental evaluation is that the AODV protocol and its optimized variants have been proven to perform efficiently in the highly dynamic environment of mobile nodes. Selecting these optimized variants of AODV protocol will allow us to exhaustively test our proposed routing mechanism for various performance metrics.

5.1 Performance Evaluation Metrics

The simulation based performance evaluation of the proposed protocol has been done in order to evaluate its efficiency and effectiveness for packet delivery in terms of various performance evaluation metrics, namely, packet delivery ratio, delay, throughput, routing overhead, and energy consumed. The definition of the performance evaluation metrics has been provided below.

- **Packet Delivery Ratio**: This metrics identifies the ratio of the total number of successfully received packets in comparison to the total number of sent packets. The mathematical relation used for the calculation of packet delivery ratio is defined in equation 5.1.

$$PDR = \sum_{i=1}^{n} \frac{N_{pr}}{N_{ps}} \tag{5.1}$$

  where N_{pr} is the number of packets successfully received at the destination and N_{ps} is the number of packets sent by the source and n is the total number of packets.

- **Delay**: This metric tells the amount of delay incurred in transmitting the packets from source to the destination. The delay includes the processing delay, propagation delay, and queuing delay. The mathematical relation used to calculate delay is defined in equation 5.2.

$$Delay = \sum_{i=1}^{n} \frac{D_{pr} + D_{pg} + D_{q}}{N_{pr}} \tag{5.2}$$

  where D_{pr} is the processing delay, D_{pg} is the propagation delay, D_q is the queuing delay, and N_{pr} is the total number of successfully received packets.

- **Throughput**: This metric determines the number successfully received packets at the destination per unit time. The throughput value is represented in kilobits per second (kbps). The mathematical relation for the same is defined in equation 5.3.

$$Throughput = \sum_{i=1}^{n} \frac{N_{pr}}{T_r - T_s} \tag{5.3}$$

where N_{pr} is the total number of successfully received packets at the destination, T_r is the time when the packet is received at the destination, and T_s is the time when packet left the source.

- **Routing Overhead**: This metric defines a ratio of total number routing packets sent to the total number of successfully received packets. The mathematical relation for this metric is defined in equation 5.4.

$$RoutingOverhead = \sum_{i=1}^{n} \frac{N_{rp}}{N_{pr}} \tag{5.4}$$

where N_{rp} is the total of routing control packets and N_{pr} is the total number packets successfully received at the destination.

- **Energy Consumed**: This metric defines the amount of energy consumed for the delivery of packets from the source to the destination. The mathematical relation for this metric is defined in equation 5.5.

$$EnergyConsumed = \sum_{i=1}^{n} \frac{E_t - E_r}{N_{pr}} \tag{5.5}$$

where E_t is the energy of the node at the time of transmission of packet, E_r is the energy value of the node when the packet is successfully received at the destination, and N_{pr} is the total packets successfully received at the destination.

These performance metrics helped in evaluating the capability of proposed routing protocol for delivering packets in FANETs.

5.2 Simulation Results

The exhaustive simulations have been performed to comprehensively analyse the behaviour of the proposed protocol through the variation of different parameters namely node density, packet transmission rate, and number of connections for data transmission. The metrics used for performance evaluation are delay, routing overhead, throughput, packet delivery ratio, and energy consumed. For simulation purpose, a discrete event simulator Network Simulator-2.35 has been used which is an open source network simulator freely available for use under the GNU GPL license. The simulation parameters used for the evaluation and comparison of the protocols are listed in Table 5.1.

Table 5.1: Simulation parameters.

Parameter	**Value**
Number of UAV nodes	100, 125, 150, 175, 200
Number of active data connections	20,25,30,35,40
Packet transmission rate	4,8,12,16,20 packets/sec.
Mobility model	3D Random Waypoint mobility model
Traffic type	Constant bit rate traffic
Packet Size	500 bytes
Minimum node speed	0 m/s
Maximum node speed	50 m/s
Interface queue	Priority queue
Simulation area	4000 x 4000 x 4000 m^3
Simulation time	600 seconds

5.2.1 Performance Evaluation in Terms of Varying Node Density

Let's discuss the effect of varying node density on the performance of the proposed protocol. An increase in the number of nodes in a dynamically changing adhoc network results in slow convergence of the network that leads to an increased delay in delivering the packets. Our proposed protocol has attempted to cater to this issue by using the nature inspired firefly algorithm. The algorithm identifies the least delay one hop neighbours of a node in the direction of the destination. This helps in identifying the nodes with the least delay to deliver the packets to the destination. The heuristic of the algorithm is further augmented by using the GQPSO algorithm which takes the nodes identified by the firefly algorithm, applies its location optimization to them, and then evaluates the delay. Finally, the nodes with the least delay in delivering packets to the destination are identified and data delivery is initiated. As shown in Figure 5.1, it is evident that the delay incurred by the proposed QARP protocol is significantly lesser than the rest of the protocols.

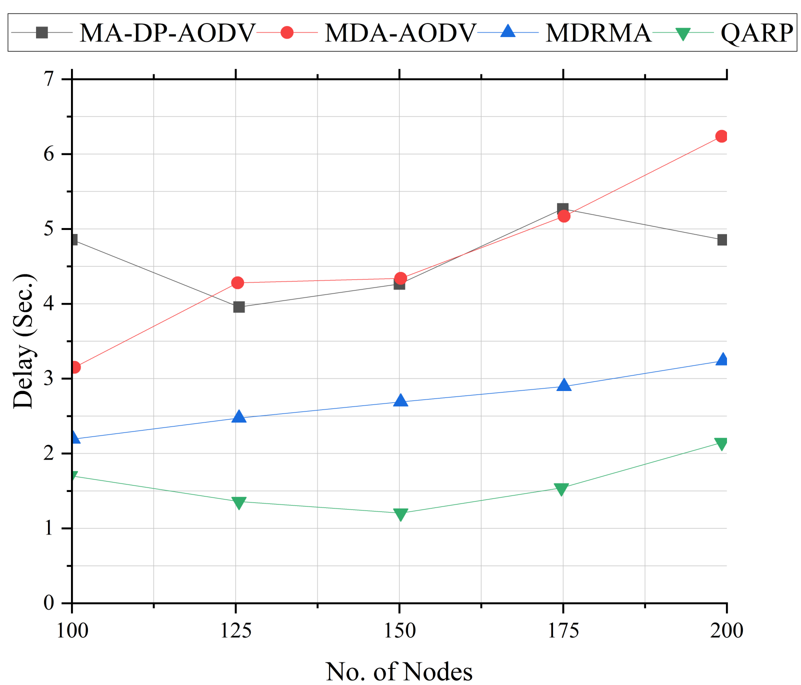


Figure 5.1: Impact of node density on delay

The increase in node density has also impacted the packet delivery ratio of the protocols under evaluation. With the increased number of nodes entering into a dynamic adhoc network the possibility of path formations increases due to the ample availability of nodes. The proposed QARP protocol in Figure 5.2 has shown a similar behaviour where with an increasing number of nodes the packet delivery ratio increased gradually showing a significant improvement over the rest of the protocols in comparison.

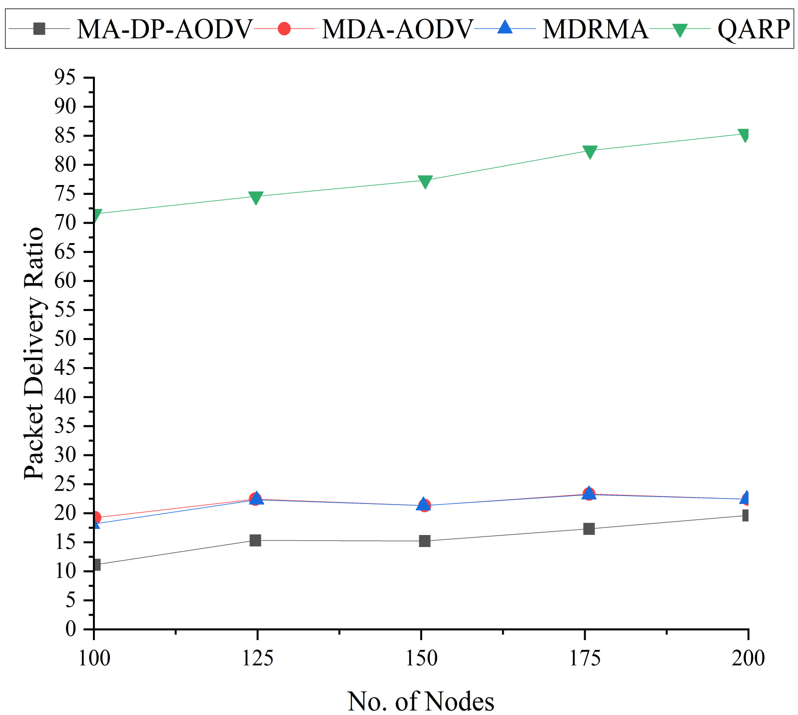


Figure 5.2: Impact of node density on packet delivery ratio.

While evaluating the effect of node density on the routing overhead, it is observed that the increased node density adds to the routing overhead. As could be seen in Figure 5.3, the routing overhead has increased with the increase in the number of nodes. Still, the proposed QARP protocol has managed to perform well. Although, with the increase in the number of nodes, the routing overhead has increased for every protocol but the proposed QARP protocol has incurred the least routing overhead among all.

Increased node density has also shown its impact on the throughput of the network. With increased node density, more number nodes were involved in the successful transmission of packets to the destination. As seen in Figure 5.4 the increasing number of nodes results in increased throughput of all the routing mechanisms. Although the increment in the throughput for the other routing mechanisms varied marginally, our proposed QARP protocol showed significantly better performance.

Energy consumption has also been a major challenge for efficient routing of data among the flying nodes. Increased node density has shown its impact on the energy utilization by the routing mechanisms to find the feasible routes for data delivery. The proposed routing mechanism utilised its nature inspired heuristics to efficiently consume energy of nodes for effective packet delivery. As seen in Figure 5.5 the energy utilization for other routing protocols increased linearly while the proposed routing mechanism consumed the least amount of energy for efficient packet delivery among nodes.

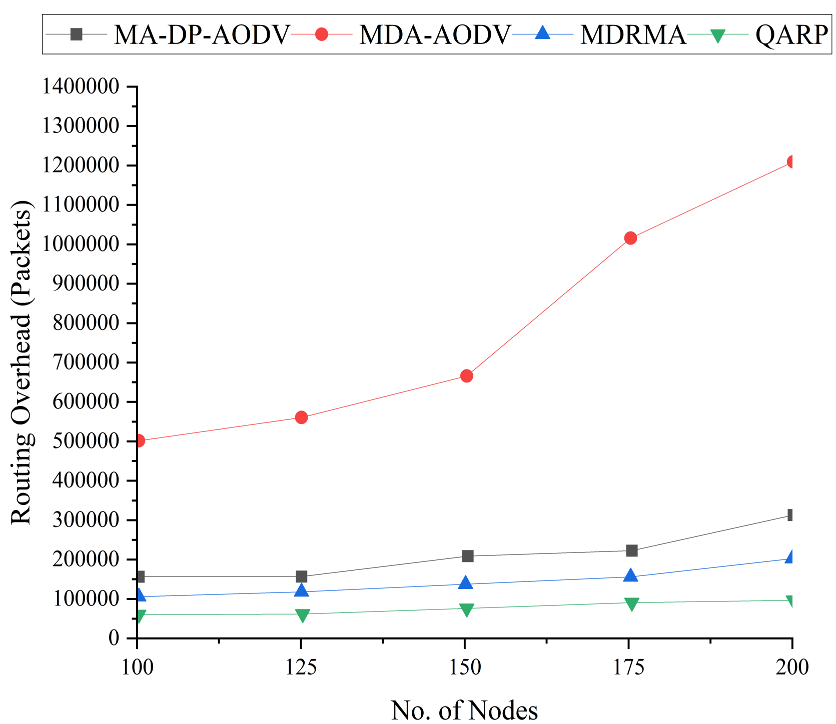


Figure 5.3: Impact of node density on routing overhead.

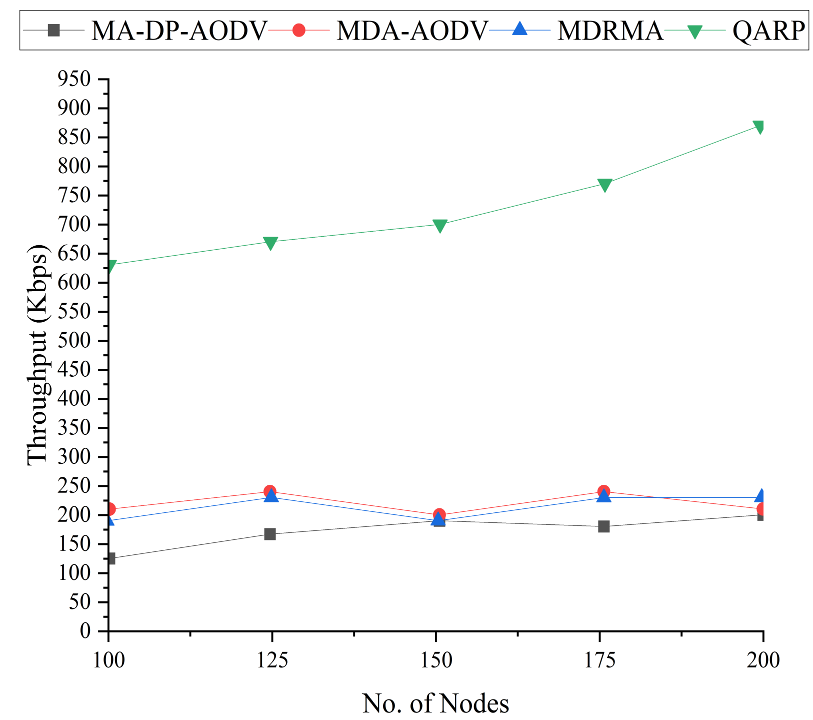


Figure 5.4: Impact of node density on throughput.

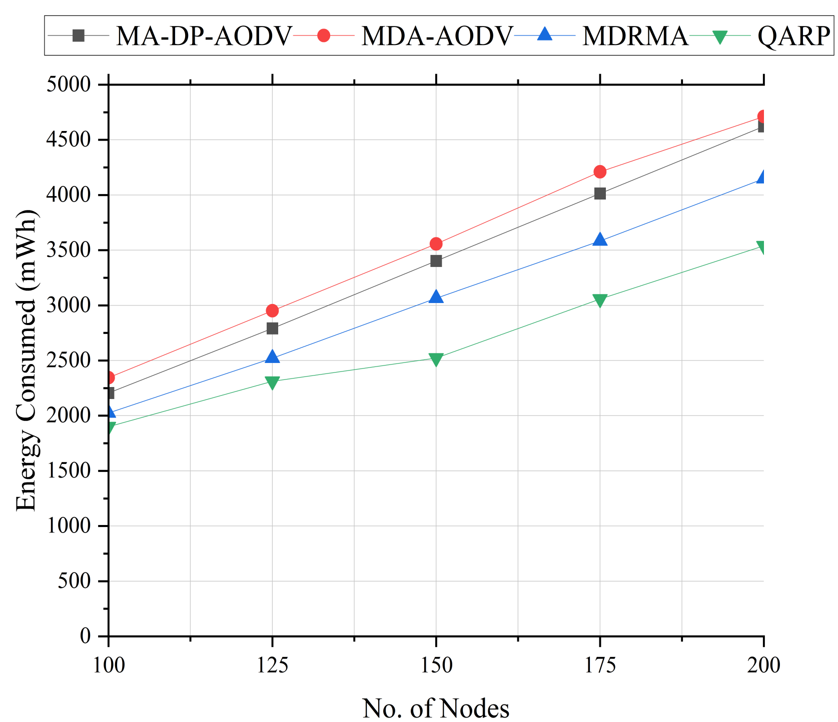


Figure 5.5: Impact of node density on energy consumption.

5.2.2 Performance Evaluation in Terms of Varying Data Flows

A discussion on the impact of data flow on the performance of FANET routing is done here. The increased number of data connections among the nodes increases the flow of packets within the network. This results in the network being more sensitive to performance degradations due to node movements and path breaks. The dynamic location changes, flying speed variation, and change in the direction of movement of nodes affect the data delivery performance of the network. To reduce the effect of these factors, the proposed QARP protocol utilizes the dynamic adapting ability of nodes introduced by the hybrid operation of firefly and GQPSO algorithms which select the most optimal nodes for data delivery with the sustained probability of packet transmission to the destination. As shown in Figure 5.6, the proposed QARP protocol has shown significant improvements in the transmission delay of packets to achieve increased data flows in the network. Although the delay has increased with the increase in data flows but the nodes have been delivering packets to the destinations without affecting the actual communication.

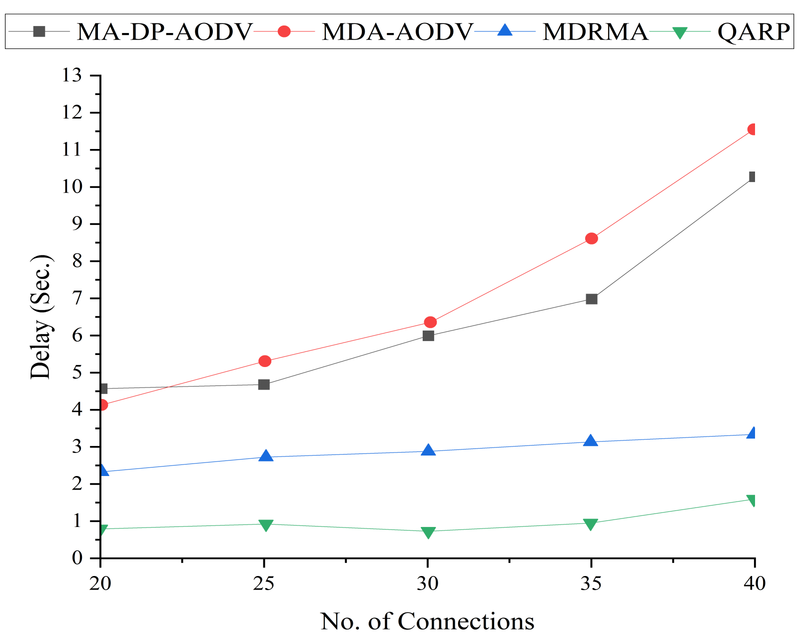


Figure 5.6: Impact of the number of data flows on delay.

The packet delivery ratio of the network is also influenced by the increase in data flow in the network. The proposed QARP protocol has shown its effectiveness in handling the increased packet flows by adjusting the UAV nodes to provide continuous delivery of data to the destination nodes. As shown in Figure 5.7, the QARP protocol has shown significant improvement in terms of packet delivery ratio delivering enhanced packet throughput for UAV adhoc network as compared to other UAV adhoc routing protocols.

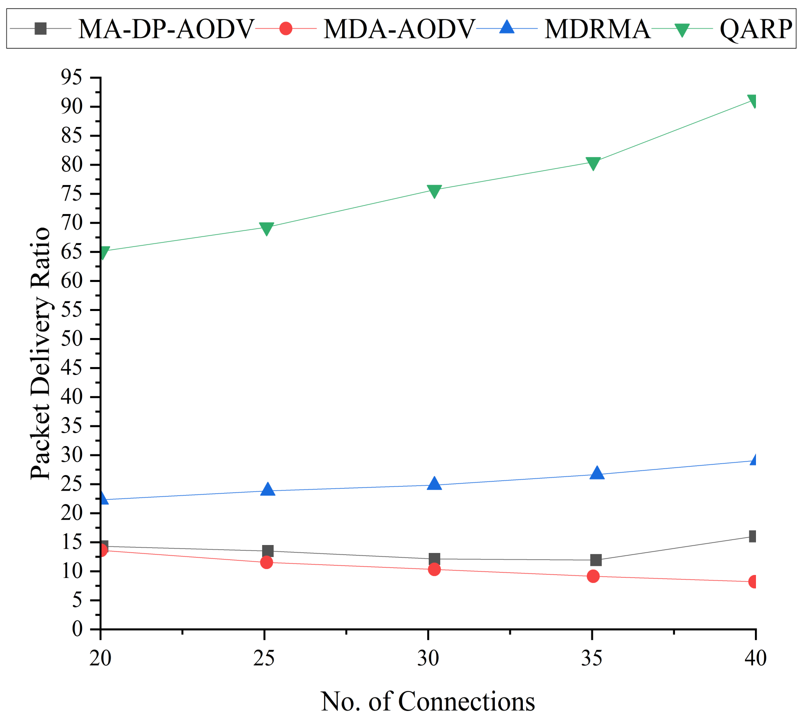


Figure 5.7: Impact of the number of data flows on packet delivery ratio.

The increased data flow in the UAV adhoc network also alters the routing overhead induced by the routing protocols. The frequency of UAV nodes dynamically entering and exiting the data delivery route forces the routing protocol to utilize the route discovery packets to reinstate the data transmission. The proposed QARP protocol takes care of this constraint as the hybrid nature inspired heuristic based algorithms promptly patches the missing node and the network continues with data transmission. As shown in Figure 5.8, the proposed QARP introduced minimal routing overhead in the network with the increasing data flows thereby allowing for effective utilization of bandwidth for actual data communication.

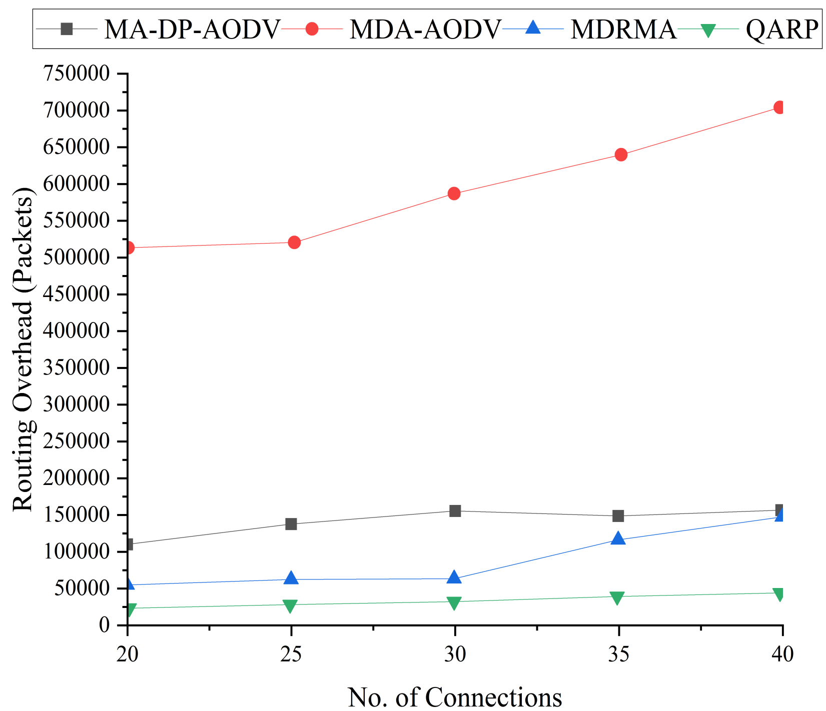


Figure 5.8: Impact of the number of data flows on routing overhead.

The increased data flow has also impacted the throughput of the routing protocols. As seen in Figure 5.9, the throughput of the proposed protocol is significantly higher as compared to the existing protocols. The delay aware meta heuristics of QARP have succeeded in providing the least delay nodes to deliver the data in a highly dynamic environment.

Increased data flow has also showed its impact on the energy consumption of nodes for packet delivery. As seen in Figure 5.10, the proposed routing mechanism has optimised the utilization of node energy by consuming the minimum possible amount of energy for delivering data over multiple data connection among the nodes. The delay awareness in the route discovery and routing table population has allowed the usage of minimum delay incurring routes for packet delivery resulting in reduced energy consumption by nodes.

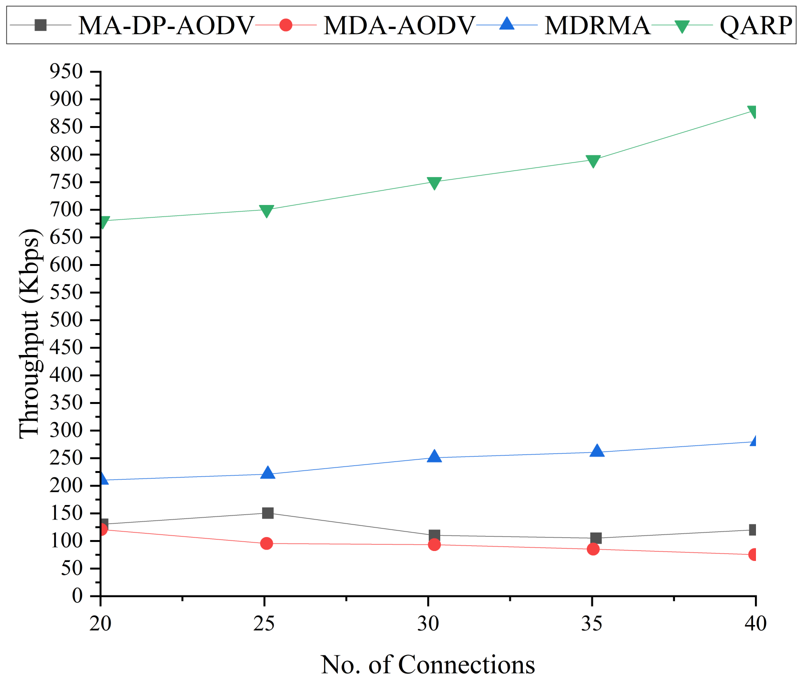


Figure 5.9: Impact of the number of data flows on throughput.

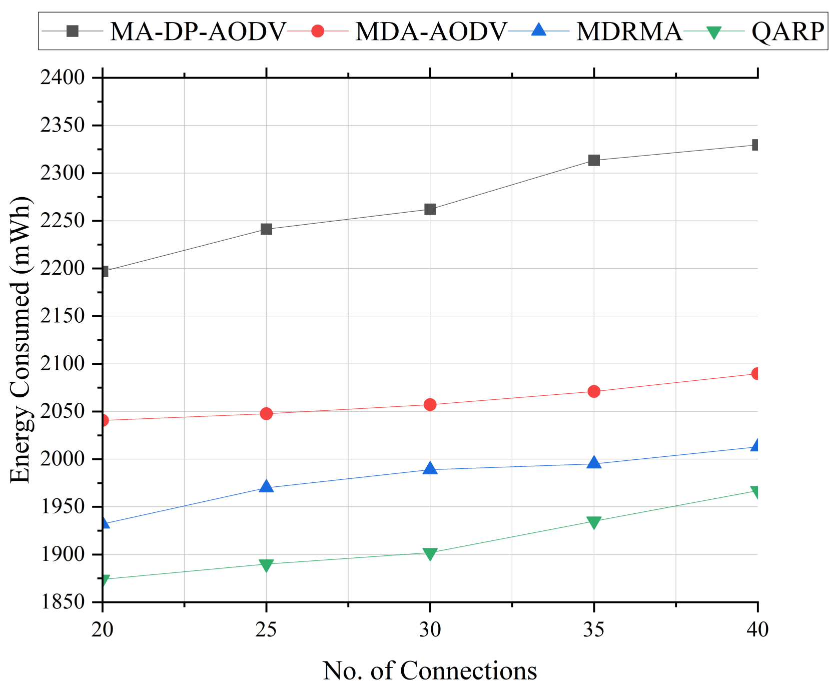


Figure 5.10: Impact of the number of data flows on energy consumption.

5.2.3 Performance Evaluation in Terms of Varying Packet Flows

A discussion on the effect of varying packet flow on the dynamically moving UAVs in the adhoc network is done. The dynamicity of the network results in frequent path changes. In the case of reactive routing protocols, the characteristic of on-demand route discovery of a broken link can cause the packets to be accumulated in the nodes' interface queues waiting for a feasible link to continue data transmission. This results in the network getting congested leading to a drop in the network performance. The proposed protocol has attempted to take care of this drawback by using the location information and the delay information of nodes forming inter-node links to identify the most sustainable links for delivering the data to the destination. As shown in Figure 5.11, the proposed QARP protocol performed reasonably by keeping the delay values lower as the packet transmission rate increased in the network as compared to other protocols.

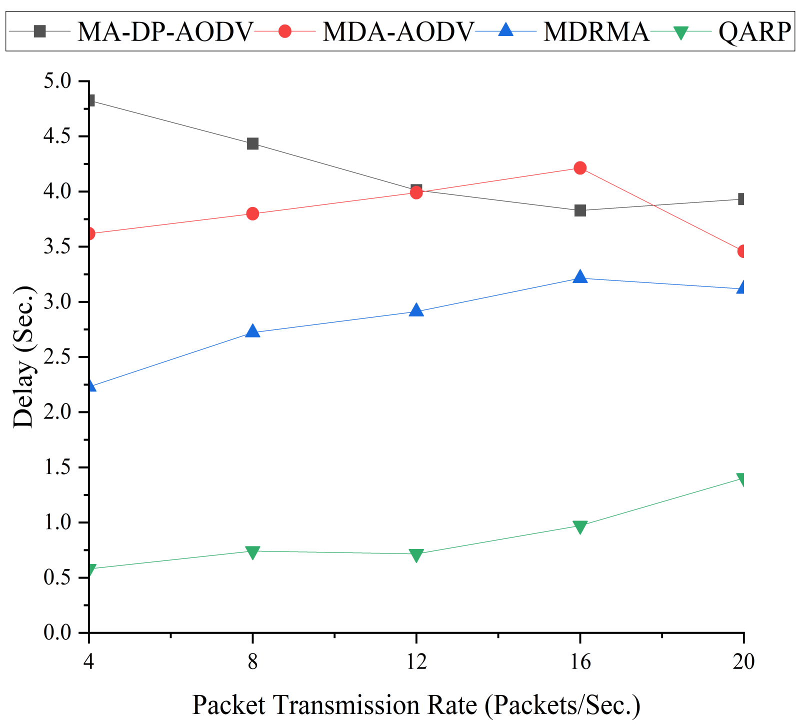


Figure 5.11: Impact of packet transmission rate on delay.

The packet transmission rate can also impact the performance of the network in terms of packet delivery ratio. With an increased packet transmission rate, the network delivers more data to the destination which results in increased throughput and packet delivery ratio. As shown in Figure 5.12, as the packet transmission rate is increasing, the packet delivery ratio for the proposed QARP routing protocol is increasing. Due to the inclusion of nature inspired heuristics in the data routing decision making, the proposed protocol has shown significant improvement in performance as compared to MA-DP-AODV, MDA-AODV, and MDRMA routing protocols.

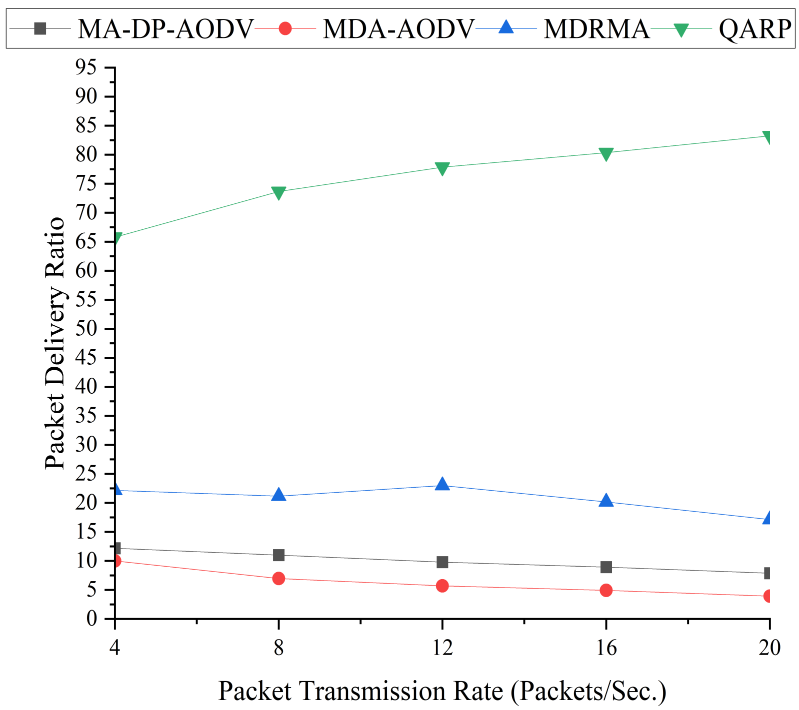


Figure 5.12: Impact of packet transmission rate on packet delivery ratio.

The higher packet transmission rate could increase routing overhead in case of frequent route failures as the broken routes for different destinations are required to be reidentified and reinstated. By the time routes are reidentified, the packets waiting to be delivered are accumulated in the interface queues of intermediate nodes. As shown in Figure 5.13 the proposed routing protocol QARP has kept the routing overhead lower by quickly adapting the network to route breakages since the GQPSO algorithm can identify the alternate nearest nodes to the destinations efficiently thereby allowing the data to be delivered to the destination nodes.

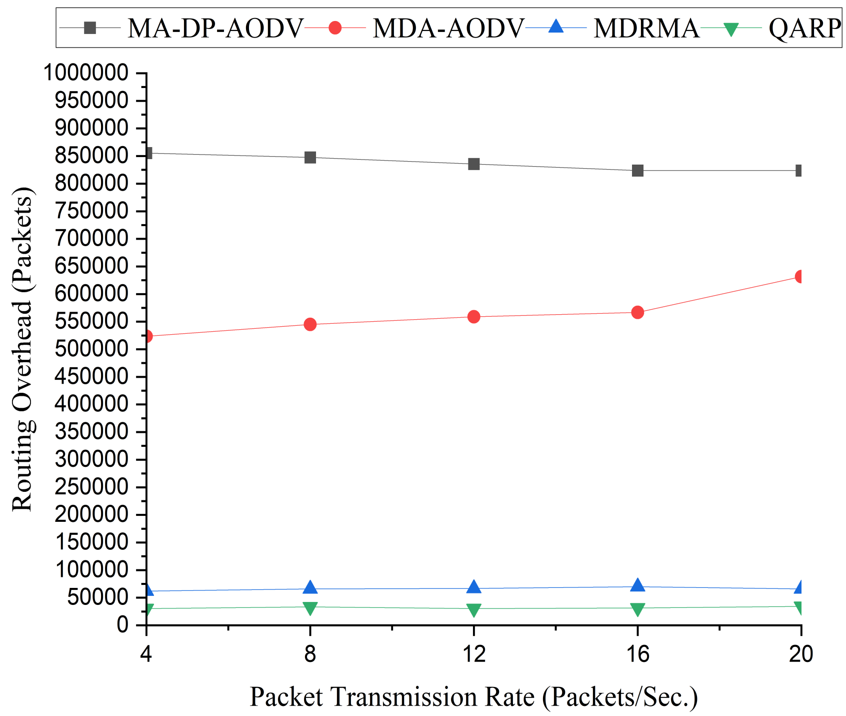


Figure 5.13: Impact of packet transmission rate on routing overhead.

The variation of the packet transmission rate has also impacted the throughput of the network. With an increased packet transmission rate, the throughput of the network increased. Due to the inclusion of meta heuristic behaviours, the proposed QARP protocol outperformed the remaining protocols under tests as seen in Figure 5.14.

The varying packet transmission rate has also shown its impact on the energy consumption of the nodes in a time varying network. As seen in Figure 5.15 the energy consumption is increasing for all the routing protocols with increasing packet transmission rate while the proposed QARP consumed the minimum amount of energy among all the routing mechanisms showing an optimal performance for packet delivery among flying nodes. The optimization could be attributed to the nature inspired heuristics catering to the dynamicity of the FANETs.

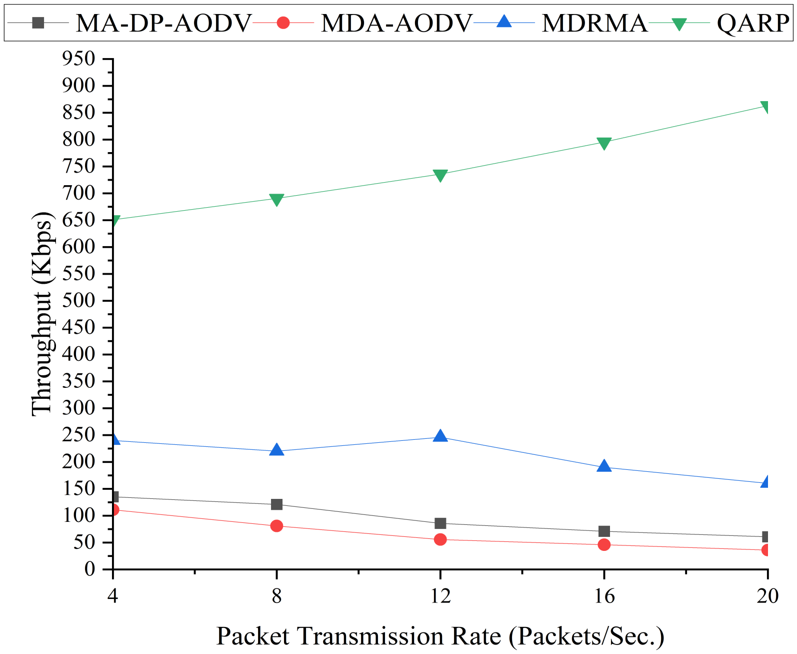


Figure 5.14: Impact of packet transmission rate on throughput.

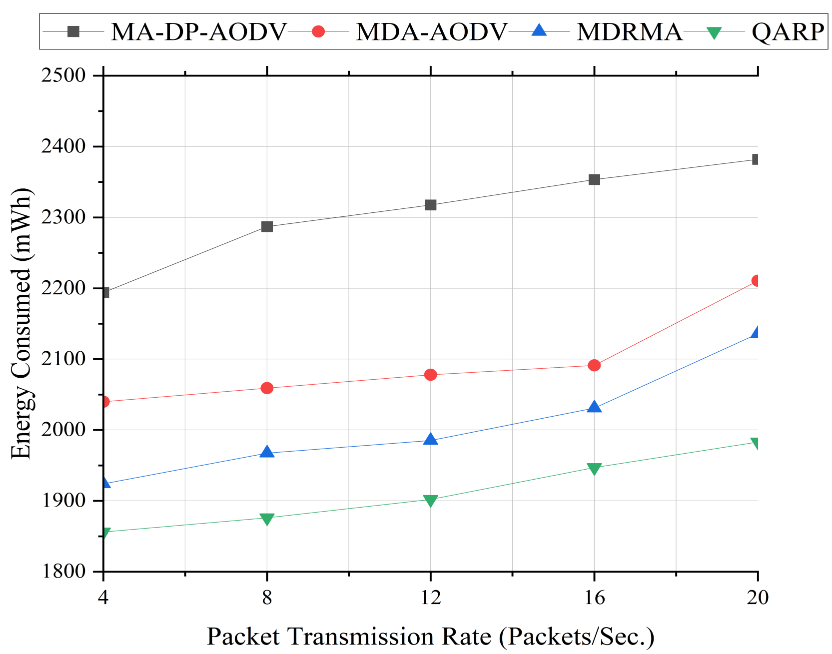


Figure 5.15: Impact of packet transmission rate on energy consumption.

5.3 Chapter Summary

This chapter discusses the performance evaluation of the proposed QARP routing protocol in comparison to the other existing routing protocols. For the purpose of experimentation, the discrete event simulator Network Simulator-2.35 has been used. The simulation parameters included varied number of nodes, varied number of links, varied packet transmission rates, and varying node speeds in order to evaluate the performance of the proposed routing protocol against the existing protocols exhaustively. The protocols have been evaluated for their performance in terms of delay, packet delivery ratio, routing overhead, throughput, and energy consumed with respect to number of connections, packet transmission rate, and number of nodes. The proposed routing protocol outperformed the rest of the protocols in terms of all the performance parameters.

Chapter 6

Conclusions and Future Scope

6.1 Conclusions

This thesis has been composed on the theme of proposing an optimal routing protocol for flying adhoc networks considering the quality of service parameters. The initial part of the thesis introduces the concept of adhoc networks and adhoc routing in a detailed manner. A detailed discussion on the characteristics and features of FANETs has been done so as to differentiate them from the MANETs and VANETs. To study the problem domain, a detailed discussion on the existing routing protocols for FANETS has been done highlighting their salient features, strengths, weaknesses, and quality of service parameters used for their evaluation. A simulation based evaluation of existing adhoc routing protocols namely AODV, AOMDV, OLSR, and ZRP has been done considering the scenarios of varying node speed and node density. The simulation results identified AODV as a routing scheme exhibiting optimal data delivery with reasonable values of delay and overhead. This analysis provided a direction to develop an optimal routing mechanism for FANETs. Also, the conclusion drawn from the detailed literature review helped in identifying the research gaps to be considered for further research. Based on the identified research gaps, the development of

Quality of Service Aware Routing Protocol for FANETs has been done considering the reduction of communication delays and overhead as its primary goal. A network model for the proposed QARP protocol has been discussed mentioning the nodes' arrangement and nodes' communication in the adhoc network. Considering some limited assumptions, a detailed methodology of the proposed QARP protocol has been discussed explaining its neighbour discovery and route identification mechanism. The proposed QARP protocol incorporates the heuristics of nature inspired Firefly algorithm to optimize the route discovery process by identifying the least delay incurring neighbour nodes in the direction of the destination which serve as input for optimizing the route establishment process. A delay aware route establishment process further augments the delay optimization by selecting the least delay incurring intermediate nodes to deliver the packets from source to destination by utilizing the heuristics of Gaussian Quantum Particle Swarm Optimization algorithm. This heuristic based routing mechanism has handled the FANET dynamics really well by showing optimal performance in terms of packet delivery ratio, routing overhead, throughput, delay, and energy consumed for different simulation scenarios of varied node density, varied packet transmission rates, and a varied number of connections. The proposed QARP protocol out performed the existing routing protocols for all the performance metrics as its efficient delay aware routing mechanism has been able to effectively deliver the packets to the destinations with least delay.

6.2 Future Scope

Quality of service guarantees for a highly dynamic adhoc network is challenging to fulfil. Due to frequent topology changes, node position changes, link breakages, and node disconnections, providing reliable routing paths for data delivery are difficult for adhoc routing protocols. In an attempt to address this issue, a Quality of Service aware routing protocol has been proposed in this thesis. Although the proposed QARP protocol tried to address the prominent challenges in the delivery of packets among the flying UAVs but due to the inherent dynamicity of FANETs, framing a perfect solution for data routing among adhoc flying nodes is challenging. The future directions for this research could be the inclusion of multipath load balancing in designing a routing protocol for FANETs. The usage of machine learning algorithms could also be a feasible choice for packet delivery in FANETs provided that the learning mechanism can adapt to the changing dynamics of the network quickly. The usage of effective route prediction and node position prediction mechanisms can also help in optimizing packet delivery in FANETs as handling the frequent location changes, topology changes, and travel speed changes is a challenge.

Bibliography

[1] S. Hayat, E. Yanmaz, and R. Muzaffar, "Survey on Unmanned Aerial Vehicle Networks for Civil Applications: A Communications Viewpoint," *IEEE Communications Surveys and Tutorials*, vol. 18, no. 4, pp. 2624–2661, 2016.

[2] H. Shakhatreh, A. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, "Unmanned Aerial Vehicles: A Survey on Civil Applications and Key Research Challenges," *arXiv preprint arXiv:1805.00881*, pp. 1–58, 2018.

[3] A. Otto, N. Agatz, J. Campbell, B. Golden, and E. Pesch, "Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey," *Networks*, no. February, pp. 1–48, 2018.

[4] O. K. Sahingoz, "Networking models in flying Ad-hoc networks (FANETs): Concepts and challenges," *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 74, no. 1-2, pp. 513–527, 2014.

[5] M. T. Hyland, R. O. Baldwin, and M. A. Temple, "Simulation-based Performance Evaluation of Mobile Ad Hoc Routing Protocols in a Swarm of Unmanned Aerial Vehicles," *Advanced Information Networking and Applications Workshops*, vol. 2, no. May, pp. 3–10, 2007.

[6] B. N. Cheng and S. Moore, "A comparison of MANET routing protocols on airborne tactical networks," *Proceedings - IEEE Military Communications Conference MILCOM*, 2012.

[7] M. Jean-Aime, R. Gilles, and L. Nicolas, "Emulation-Based Performance Evaluation of Routing Protocols for Uaanets," *Communication Technologies for Vehicles: 8th International Workshop, Nets4Cars/Nets4Trains/Nets4Aircraft 2015, Sousse, Tunisia, May 6-8, 2015. Proceedings*, pp. 227–240, 2015.

[8] K. Singh and A. K. Verma, "Experimental analysis of AODV, DSDV and OLSR routing protocol for flying adhoc networks (FANETs)," in *Proceedings of 2015 IEEE International Conference on Electrical, Computer and Communication Technologies, ICECCT 2015*, pp. 1–4, 2015.

[9] S. Thounhom and T. Anusas-amornkul, "The Study of Routing Protocols for UAVs using Paparazzi Mobility Model with Different Altitudes," in *Proceedings of the 2016*

International Conference on Communication and Information Systems - ICCIS '16, pp. 106–111, 2016.

[10] C. E. Perkins and P. Bhagwat, "Highly dynamic Destination-Sequenced Distance-Vector routing (DSDV) for mobile computers," *ACM SIGCOMM Computer Communication Review*, vol. 24, no. 4, pp. 234–244, 1994.

[11] P. Jacquet, P. Mühlethaler, T. H. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc networks," *Proceedings. IEEE International Multi Topic Conference, 2001. IEEE INMIC 2001. Technology for the 21st Century.*, pp. 62–68, 2001.

[12] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc on-demand distance vector (AODV) routing," *RFC 3561*, vol. July, 2003.

[13] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," *Mobile Computing*, pp. 153–181, 1996.

[14] V. Park and M. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," *Proceedings of INFOCOM '97*, vol. 3, pp. 1405–1413, 1997.

[15] Z. J. Haas, M. R. Pearlman, and P. Samar, "The zone routing protocol (zrp) for ad hoc networks," 2002.

[16] J. Moy, "OSPF Version 2," 1998.

[17] S. Balandin, S. Andreev, and Y. Koucheryavy, *Simulation-Based Comparison of AODV, OLSR and HWMP Protocols for Flying Ad Hoc Networks*. Springer International Publishing, 2014.

[18] J. D. Camp and E. W. Knightly, "The IEEE 802.11s extended service set mesh networking standard," *IEEE Communications Magazine*, vol. 46, no. 8, pp. 120–126, 2008.

[19] B. Karp and H. Kung, "GPSR: Greedy Perimeter Stateless Routing for wireless networks," *ACM MobiCom*, pp. 243–254, 2000.

[20] M. Iordanakis, D. Yannis, K. Karras, G. Bogdos, G. Dilintas, M. Amirfeiz, G. Colangelo, and S. Baiotti, "Ad-hoc routing protocol for aeronautical mobile ad-hoc networks," *Fifth International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, pp. 1–5, 2006.

[21] K. Liu, J. Zhang, and T. Zhang, "The clustering algorithm of UAV networking in near-space," *ISAPE 2008 - The 8th International Symposium on Antennas, Propagation and EM Theory Proceedings*, pp. 1550–1553, 2008.

[22] R. L. UstLidowski, B. E. Mullins, and R. O. Baldwin, "A novel communications protocol using geographic routing for swarming UAVs performing a search mission," in *7th Annual IEEE International Conference on Pervasive Computing and Communications, (PerCom 2009)*, pp. 1–7, 2009.

[23] A. Alshabtat, L. Dong, J. Li, and F. Yang, “Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks,” *Journal of Electrical and Computer Engineering*, vol. 6, no. 1, pp. 48–54, 2010.

[24] C. Zang and S. Zang, “Mobility prediction clustering algorithm for UAV networking,” *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, pp. 1158–1161, 2011.

[25] R. Shirani, M. St-hilaire, T. Kunz, Y. Zhou, J. Li, and L. Lamont, “Combined Reactive-Geographic Routing for Unmanned Aeronautical Ad-hoc Networks,” pp. 820–826, 2012.

[26] L. Lin, Q. Sun, J. Li, and F. Yang, “A novel geographic position mobility oriented routing strategy for UAVs,” *Journal of Computational Information Systems*, vol. 2, no. 8, pp. 709–716, 2012.

[27] K. Saifullah and K. I. Kim, “A new geographical routing protocol for heterogeneous aircraft Ad Hoc Networks,” in *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, pp. 1–9, 2012.

[28] Y.-B. Ko and N. b. c. d. Vaidya, “Location-aided routing (LAR) in mobile ad hoc networks,” *Wireless Networks*, vol. 6, no. 4, pp. 307–321, 2000.

[29] Q. Lin, H. Song, X. Gui, X. Wang, and S. Su, “A Shortest Path Routing Algorithm for Unmanned Aerial Systems based on Grid Position A Shortest Path Routing Algorithm for Unmanned Aerial Systems based on Grid Position,” *Journal of Network and Computer Applications*, vol. August, no. 1-10, 2017.

[30] P. Xie, “An enhanced olsr routing protocol based on node link expiration time and residual energy in ocean fanets,” in *2018 24th Asia-Pacific Conference on Communications (APCC)*, pp. 598–603, IEEE, 2018.

[31] S. Rosati, K. Kruzelecki, L. Traynard, and B. Rimoldi, “Speed-aware routing for UAV ad-hoc networks,” *2013 IEEE Globecom Workshops, GC Wkshps 2013*, pp. 1367–1373, 2013.

[32] Y. Zheng, Y. Wang, Z. Li, L. Dong, Y. Jiang, and H. Zhang, “A mobility and load aware OLSR routing protocol for UAV mobile ad-hoc networks,” *2014 International Conference on Information and Communications Technologies (ICT 2014)*, pp. 1.019–1.019, 2014.

[33] M. H. Tareque, M. S. Hossain, and M. Atiquzzaman, “On the Routing in Flying Ad hoc Networks,” *Federated Conference on Computer Science and Information Systems (FedCSIS), 2015*, vol. 5, pp. 1–9, 2015.

[34] K. Singh and A. K. Verma, “Flying Adhoc Networks Concept and Challenges,” *Encyclopedia of Information Science and Technology, Fourth Edition*, pp. 6106–6113, 2017.

[35] C. Yin, Z. Xiao, X. Cao, X. Xi, P. Yang, and D. Wu, "Enhanced Routing Protocol for Fast Flying UAV Network," *2016 IEEE International Conference on Communication Systems (ICCS)*, pp. 1–6, 2016.

[36] X. Zheng, Q. Qi, Q. Wang, and Y. Li, "A stable ant-based routing protocol for flying ad hoc networks," in *2017 4th International Conference on Machinery, Materials and Computer (MACMC 2017)*, Atlantis Press, 2018.

[37] J. D. M. M. Biomo, T. Kunz, and M. St-Hilaire, "Routing in unmanned aerial ad hoc networks: A recovery strategy for Greedy geographic forwarding failure," *IEEE Wireless Communications and Networking Conference, WCNC*, pp. 2236–2241, 2014.

[38] G. Di Caro, F. Ducatelle, and L. M. Gambardella, "AntHocNet: An adaptive nature-inspired algorithm for routing in mobile ad hoc networks," *European Transactions on Telecommunications*, vol. 16, no. 5, pp. 443–455, 2005.

[39] H. F. Wedde, M. Farooq, T. Pannenbaecker, B. Vogel, C. Mueller, J. Meth, and R. Jeruschkat, "BeeAdHoc," *Proceedings of the 2005 conference on Genetic and evolutionary computation - GECCO '05*, p. 153, 2005.

[40] N. E. H. Bahloul, S. Boudjit, M. Abdennebi, and D. E. Boubiche, "Bio-inspired on demand routing protocol for Unmanned Aerial Vehicles," *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, pp. 1–6, July 2017.

[41] S.-C. Choi, H. R. Hussen, J.-H. Park, and J. Kim, "Geolocation-based routing protocol for flying ad hoc networks (fanets)," in *2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN)*, pp. 50–52, IEEE, 2018.

[42] J. Lee, K. Kim, S. Yoo, A. Y. Chung, J. Y. Lee, S. J. Park, and H. Kim, "Constructing a reliable and fast recoverable network for drones," in *2016 IEEE International Conference on Communications, ICC 2016*, pp. 0–5, 2016.

[43] M. Bahr, "Proposed routing for IEEE 802.11s WLAN mesh networks," *Proceedings of the 2nd annual international workshop on Wireless internet - WICON '06*, pp. 5–es, 2006.

[44] A. Khan, F. Aftab, and Z. Zhang, "Bicsf: Bio-inspired clustering scheme for fanets," *IEEE Access*, vol. 7, pp. 31446–31456, 2019.

[45] F. Aadil, A. Raza, M. F. Khan, M. Maqsood, I. Mehmood, and S. Rho, "Energy Aware Cluster-Based Routing in Flying Ad-Hoc Networks," *Sensors*, vol. 18, pp. 1–16, 2018.

[46] N. A. Khan, N. Jhanjhi, S. N. Brohi, R. S. A. Usmani, and A. Nayyar, "Smart traffic monitoring system using unmanned aerial vehicles (uavs)," *Computer Communications*, vol. 157, pp. 434–443, 2020.

[47] A. Nayyar, B.-L. Nguyen, and N. G. Nguyen, "The internet of drone things (iodt): future envision of smart drones," in *First International Conference on Sustainable Technologies for Computational Intelligence: Proceedings of ICTSCI 2019*, pp. 563–580, Springer, 2020.

[48] K. Telli, O. Kraa, Y. Himeur, A. Ouamane, M. Boumehraz, S. Atalla, and W. Mansoor, "A comprehensive review of recent research trends on unmanned aerial vehicles (uavs)," *Systems*, vol. 11, no. 8, 2023.

[49] S. Bharany, S. Sharma, S. Bhatia, M. K. I. Rahmani, M. Shuaib, and S. A. Lashari, "Energy efficient clustering protocol for fanets using moth flame optimization," *Sustainability*, vol. 14, no. 10, 2022.

[50] M. Atif, R. Ahmad, W. Ahmad, L. Zhao, and J. J. P. C. Rodrigues, "Uav-assisted wireless localization for search and rescue," *IEEE Systems Journal*, vol. 15, no. 3, pp. 3261–3272, 2021.

[51] D. Khan, P. Ball, and G. Childs, "A cross layer design approach for multi-hop mobile ad hoc networks," *The Mediterranean Journal of Computers and Networks (MEDJCN)*, vol. 3, no. 3, pp. 91–99, 2007.

[52] M. Kumar, S. Mittal, and A. K. Akhtar, "Energy efficient clustering and routing algorithm for wsn," *Recent Advances in Computer Science and Communications (Formerly: Recent Patents on Computer Science)*, vol. 14, no. 1, pp. 282–290, 2021.

[53] V. Sehrawat and S. K. Goyal, "Naisep: Neighborhood aware clustering protocol for wsn assisted iot network for agricultural application," *Wireless Personal Communications*, vol. 130, no. 1, pp. 347–362, 2023.

[54] I. Bekmezci, O. K. Sahingoz, and c. Temel, "Flying Ad-Hoc Networks (FANETs): A survey," *Ad Hoc Netw.*, vol. 11, pp. 1254–1270, May 2013.

[55] Q. Sang, H. Wu, L. Xing, and P. Xie, "Review and comparison of emerging routing protocols in flying ad hoc networks," *Symmetry*, vol. 12, no. 6, pp. 1–24, 2020.

[56] B. N. Cheng and S. Moore, "A comparison of MANET routing protocols on airborne tactical networks," in *Proceedings - IEEE Military Communications Conference MILCOM*, 2012.

[57] L. Lei, D. Wang, L. Zhou, X. Chen, and S. Cai, "Link availability estimation based reliable routing for aeronautical ad hoc networks," *Ad Hoc Networks*, vol. 20, pp. 53–63, 2014.

[58] S. G. Manyam, S. Rathinam, S. Darbha, D. Casbeer, Y. Cao, and P. Chandler, "GPS Denied UAV Routing with Communication Constraints," *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 84, no. 1-4, pp. 691–703, 2016.

[59] A. Mukherjee, V. Keshary, K. Pandya, and N. Dey, *Flying Ad hoc Networks: A Comprehensive Survey*, vol. 701. Springer Singapore, 2018.

[60] G. Gankhuyag, A. P. Shrestha, and S.-J. Yoo, "Robust and Reliable Predictive Routing Strategy for Flying Ad-hoc Networks," *IEEE Access*, vol. 3536, no. c, pp. 1–1, 2017.

[61] W.-s. Jung, J. Yim, and Y.-b. Ko, "QGeo: Q-Learning based Geographic Ad-Hoc Routing Protocol for Unmanned Robotic Networks," *IEEE Communications Letters*, vol. 7798, no. c, pp. 1–1, 2017.

[62] W. Qingwen, L. Gang, L. Zhi, and Q. Qian, "An adaptive forwarding protocol for three dimensional Flying Ad Hoc Networks," in *ICEIEC 2015 - Proceedings of 2015 IEEE 5th International Conference on Electronics Information and Emergency Communication*, pp. 142–145, 2015.

[63] S. Wang, C. Fan, C. Deng, W. Gu, Q. Sun, and F. Yang, "A-GR: A novel geographical routing protocol for AANETs," *Journal of Systems Architecture*, vol. 59, no. 10 PART B, pp. 931–937, 2013.

[64] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, and L. Lamont, "The performance of greedy geographic forwarding in unmanned aeronautical Ad-Hoc networks," in *Proceedings - 2011 9th Annual Communication Networks and Services Research Conference, CNSR 2011*, pp. 161–166, 2011.

[65] A. Sathyan, N. D. Ernest, and K. Cohen, "An Efficient Genetic Fuzzy Approach to UAV Swarm Routing," *Unmanned Systems*, vol. 4, no. 2, p. 1650001, 2015.

[66] V. A. Maistrenko, L. V. Alexey, and V. A. Danil, "Experimental estimate of using the ant colony optimization algorithm to solve the routing problem in FANET," *2016 International Siberian Conference on Control and Communications (SIBCON)*, pp. 1–10, 2016.

[67] E. Yakici, "Solving location and routing problem for UAVs," *Computers and Industrial Engineering*, vol. 102, no. October, pp. 294–301, 2016.

[68] A. V. Leonov, "Modeling of bio-inspired algorithms AntHocNet and BeeAdHoc for Flying Ad Hoc Networks (FANETs)," *13th International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE)*, vol. 02, pp. 90–99, 2016.

[69] A. V. Leonov, "Application of bee colony algorithm for FANET routing," in *International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM*, vol. 2016-Augus, pp. 124–132, 2016.

[70] S. Rosati, K. Kruzelecki, G. Heitz, D. Floreano, and B. Rimoldi, "Dynamic Routing for Flying Ad Hoc Networks," *Transactions on Vehicular Technology*, vol. 65, no. 3, pp. 1690–1700, 2014.

[71] H. Ali, S. ul Islam, H. Song, and K. Munir, "A performance-aware routing mechanism for flying ad hoc networks," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 1, pp. 1–17, 2021.

[72] Q. Zhu, Z. Zhou, J. Yang, and Z. Fu, "An Optimized Routing OLSR Protocol with Low Control Overhead for UAV Ad Hoc Networks," *American Journal of Networks and Communications*, vol. 10, no. 1, pp. 6–12, 2021.

[73] Y. Zhu, Q. Huang, J. Li, and D. Wu, "Design and evaluation of airborne communication networks," in *2015 Seventh International Conference on Ubiquitous and Future Networks*, pp. 277–282, 2015.

[74] Q. Luo and J. Wang, "Multiple QoS Parameters Based Routing for Civil Aeronautical Ad Hoc Networks," *IEEE Internet of Things Journal*, vol. 4662, no. c, pp. 1–1, 2017.

[75] X. Zheng, Q. Qi, Q. Wang, and Y. Li, "An adaptive density-based routing protocol for flying Ad Hoc networks," *AIP Conference Proceedings*, vol. 1890, 2017.

[76] J. Liu, Q. Wang, C. T. He, K. Jaffrès-Runser, Y. Xu, Z. Li, and Y. J. Xu, "QMR:Q-learning based Multi-objective optimization Routing protocol for Flying Ad Hoc Networks," *Computer Communications*, vol. 150, pp. 304–316, 2020.

[77] L. A. L. da Costa, R. Kunst, and E. Pignaton de Freitas, "Q-FANET: Improved Q-learning based routing protocol for FANETs," *Computer Networks*, vol. 198, no. September 2020, p. 108379, 2021.

[78] J. Peng, H. Gao, L. Liu, Y. Wu, and X. Xu, "FNTAR: A Future Network Topology-aware Routing protocol in UAV networks," *IEEE Wireless Communications and Networking Conference, WCNC*, vol. 2020-May, 2020.

[79] Q. Liang, T. Lin, F. Wu, F. Zhang, and W. Xiong, "A dynamic source routing protocol based on path reliability and link monitoring repair," *Plos One*, vol. 16, no. 5, p. e0251548, 2021.

[80] M. Zhang, C. Dong, P. Yang, T. Tao, Q. Wu, and T. Q. S. Quek, "Adaptive Routing Design for Flying Ad Hoc Networks," *IEEE Communications Letters*, vol. 14, no. 8, pp. 1–1, 2022.

[81] M. Y. Arafat and S. Moh, "A Q-Learning-Based Topology-Aware Routing Protocol for Flying Ad Hoc Networks," *IEEE Internet of Things Journal*, vol. 9, no. 3, pp. 1985–2000, 2022.

[82] M. Muthukumar, R. Rangasamy, I. Hussain, and S. A. AlQahtani, "Energy efficient green routing for uavs ad-hoc network.," *Intelligent Automation & Soft Computing*, vol. 37, no. 1, 2023.

[83] G. Gankhuyag, A. P. Shrestha, and S.-j. Yoo, "A Novel Directional Routing Scheme for Flying Ad-hoc Networks," *2016 International Conference on Information and Communication Technology Convergence (ICTC)*, pp. 593–597, 2016.

[84] A. Bujari, C. T. Calafate, J. C. Cano, P. Manzoni, C. E. Palazzi, and D. Ronzani, "A location-aware waypoint-based routing protocol for airborne DTNs in search and rescue scenarios," *Sensors (Switzerland)*, vol. 18, no. 11, pp. 1–14, 2018.

[85] A. Vahdat and D. Becker, "Epidemic routing for partially connected ad hoc networks," *Technical Report*, vol. 27708, no. CS-200006, pp. 1–14, 2000.

[86] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait: an efficient routing scheme for intermittently connected mobile networks," in *Proceedings of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking*, pp. 252–259, ACM, 2005.

[87] S. Jain, K. Fall, and R. Patra, *Routing in a delay tolerant network*, vol. 34. ACM, 2004.

[88] J. Burgess, B. Gallagher, D. D. Jensen, B. N. Levine, *et al.*, "Maxprop: Routing for vehicle-based disruption-tolerant networks.," in *Infocom*, vol. 6, Barcelona, Spain, 2006.

[89] Z. Chu, Z. Ye, J. Zhao, L. He, and I. Rasheed, "Novel Framework-Based Routing for Task-Adaptive Mobile Networks of Unmanned Aerial Vehicular," *Electronics (Switzerland)*, vol. 11, no. 3, 2022.

[90] F. Khelifi, A. Bradai, K. Singh, and M. Atri, "Localization and Energy-Efficient Data Routing for Unmanned Aerial Vehicles: Fuzzy-Logic-Based Approach," *IEEE Communications Magazine*, vol. 56, no. 4, pp. 129–133, 2018.

[91] Q. Wu, M. Zhang, C. Dong, Y. Feng, Y. Yuan, S. Feng, and T. Q. Quek, "Routing protocol for heterogeneous FANETs with mobility prediction," *China Communications*, vol. 19, no. 1, pp. 186–201, 2022.

[92] S. K. Singh, T. Das, and A. Jukan, "A Survey on Internet Multipath Routing and Provisioning," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, pp. 2157–2175, 2015.

[93] F. Tang, H. Zhang, and L. T. Yang, "Multipath Cooperative Routing with Efficient Acknowledgement for LEO Satellite Networks," *IEEE Transactions on Mobile Computing*, vol. 18, no. 1, pp. 179–192, 2019.

[94] O. León, J. Hernández-Serrano, and M. Soriano, "Network Utility Maximization in Multipath Lossy Wireless Networks," *International Journal of Communication Systems*, vol. 23, no. 5, pp. 633–652, 2015.

[95] Q. V. Pham and W. J. Hwang, "Network Utility Maximization-Based Congestion Control over Wireless Networks: A Survey and Potential Directives," *IEEE Communications Surveys and Tutorials*, vol. 19, no. 2, pp. 1173–1200, 2017.

[96] J. Yin, L. Wang, C. Han, and Y. Yang, "Nc-olsr: A network coding based olsr multipath transmission scheme for fanets," in *2017 4th International Conference on Systems and Informatics (ICSAI)*, pp. 1007–1012, IEEE, 2018.

[97] G. Secinti, P. B. Darian, B. Canberk, and K. R. Chowdhury, "SDNs in the Sky: Robust End-to-End Connectivity for Aerial Vehicular Networks," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 16–21, 2018.

[98] Z. Zhai, J. Du, and Y. Ren, "The Application and Improvement of Temporally Ordered Routing Algorithm in Swarm Network with Unmanned Aerial Vehicle Nodes," *The Ninth International Conference on Wireless and Mobile Communications*, no. c, pp. 7–12, 2013.

[99] X. Li and J. Yan, "Lepr: Link stability estimation-based preemptive routing protocol for flying ad hoc networks," in *2017 IEEE Symposium on Computers and Communications (ISCC)*, pp. 1079–1084, IEEE, 2017.

[100] C. Pu, "Jamming-resilient multipath routing protocol for flying ad hoc networks," *IEEE Access*, vol. 6, pp. 68472–68486, 2018.

[101] D. Rosário, Z. Zhao, T. Braun, E. Cerqueira, A. Santos, and I. Alyafawi, "Opportunistic routing for multi-flow video dissemination over flying ad-hoc networks," in *Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014*, pp. 1–6, IEEE, 2014.

[102] A. Varga, "Omnet++," in *Modeling and tools for network simulation*, pp. 35–59, Springer, 2010.

[103] O. Anicho and P. B. Charlesworth, "Conflicts in Routing and UAV Autonomy Algorithms for Ad-hoc & Infrastructure-based UAV Networks," *Australian Journal of Telecommunications and the Digital Economy*, vol. 6, no. 4, pp. 96–108, 2018.

[104] A. Bujari, C. E. Palazzi, and D. Ronzani, "Comparing Routing Protocols over a 3D IoT," *Proceedings of the Eighteenth ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pp. 304–305, 2018.

[105] H. Frey and I. Stojmenovic, "On delivery guarantees of face and combined greedy-face routing in ad hoc and sensor networks," in *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking*, MobiCom '06, (New York, NY, USA), pp. 390–401, ACM, ACM, 2006.

[106] R. Flury and R. Wattenhofer, "Randomized 3d geographic routing.," in *InfoCom*, vol. 8, pp. 1508–1516, IEEE, 2008.

[107] I. Stojmenovic, M. Russell, and B. Vukojevic, "Depth first search and location based localized routing and QoS routing in wireless networks," *Proceedings of the International Conference on Parallel Processing*, vol. 2000-Janua, pp. 173–180, 2000.

[108] Q. Usman, O. Chughtai, N. Nawaz, Z. Kaleem, K. A. Khaliq, and L. D. Nguyen, "A Reliable Link-Adaptive Position-Based Routing Protocol for Flying ad hoc Network," *Mobile Networks and Applications*, vol. 2910, pp. 0–1, 2021.

[109] S. Łukasik and S. Żak, "Firefly algorithm for continuous constrained optimization tasks," in *Computational Collective Intelligence. Semantic Web, Social Networks and Multiagent Systems: First International Conference, ICCCI 2009, Wrocław, Poland, October 5-7, 2009. Proceedings 1*, pp. 97–106, Springer, 2009.

[110] S. Coelho, “Expert Systems with Applications Gaussian quantum-behaved particle swarm optimization approaches for constrained engineering design problems,” *Expert Systems With Applications*, vol. 37, no. 2, pp. 1676–1683, 2010.

[111] K. A. Darabkh, M. S. Judeh, H. Bany Salameh, and S. Althunibat, “Mobility aware and dual phase AODV protocol with adaptive hello messages over vehicular ad hoc networks,” *AEU - International Journal of Electronics and Communications*, vol. 94, pp. 277–292, 2018.

[112] A. Swidan, H. B. Abdelghany, R. Saifan, and Z. Zilic, “Mobility and Direction Aware Ad-hoc on Demand Distance Vector Routing Protocol,” *Procedia Computer Science*, vol. 94, no. MobiSPC, pp. 49–56, 2016.

[113] K. A. Darabkh, M. G. Alfawares, and S. Althunibat, “MDRMA: Multi-data rate mobility-aware AODV-based protocol for flying ad-hoc networks,” *Vehicular Communications*, vol. 18, p. 100163, 2019.

List of Publications

1. Atul Malhotra and Sanmeet Kaur, ”A Comprehensive Review on Recent Advancements in Routing Protocols for Flying Adhoc Networks”, *Transactions on Emerging Telecommunications Technologies* , Wiley, 2019. (IF 3.6).
   DOI:10.1002/ett.3688

2. Atul Malhotra and Sanmeet Kaur, ”QARP: A Quality of Service Aware Routing Protocol for FANETs”, *International Journal of Communication Systems*, Wiley, 2024. (IF 2.1).
   DOI: 10.1002/dac.5723