# AN EFFICIENT MOBILITY MODEL AND ROUTING TECHNIQUE FOR SPARSE FLYING ADHOC NETWORK

A thesis submitted to the

*University of Petroleum and Energy Studies*

For the Award of

***Doctor of Philosophy***

*in*

***Computer Science and Engineering***

By

**JUHI AGRAWAL**

**September 2022**

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# DECLARATION

I declare that the thesis entitled **"An Efficient Mobility Model and Routing Technique for Sparse Flying Adhoc Network"** has been prepared by me under the guidance of Dr. Ravi Tomar, Associate Professor at the School of Computer Science, University of Petroleum and Energy Studies, and Dr. Monit Kapoor, Professor at Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab. No part of this thesis has formed the basis for the award of any degree or fellowship previously.


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**Date:**

# CERTIFICATE

I certify that **Juhi Agrawal** has prepared her thesis entitled **"An Efficient Mobility Model and Routing for Sparse Flying Ad-hoc Network",** for the award of Ph.D. degree at the University of Petroleum & Energy Studies, under my guidance. She has carried out work at the School of Computer Science, University of Petroleum & Energy Studies, Dehradun, India.

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# ABSTRACT

Unmanned aerial vehicles (UAVs) are widely used in both private and public sectors, particularly in post-natural disaster applications like search and rescue operations. In the Flying Ad Hoc Network (FANET), UAVs gather crucial data in a variety of formats, such as videos and photographs, from the disaster region and transmit it to the ground station (GS). The UAV quickly transmits the information it has collected to the GS so that rescue efforts can be carried out. A small number of UAVs are deployed for rescue operations when a rapid natural disaster affects a vast geographic area, resulting in intermittent or sparse networks. However, in highly dynamic UAV networks, packet forwarding is difficult because of unreliable links and sparse network.

The existing routing protocols that are designed for dense FANETs cannot be adopted directly for sparse FANETs. Most of the routing protocols available today are mainly designed for connected networks, so there is limited work focused on sparse networks. Traditional routing algorithms rely on flood-based strategies that cause high routing overhead. Some recently developed routing protocols employ greedy forwarding directly for routing in sparse FANETs, without considering delay as a significant limitation of disaster recovery operations.

This work introduces a new ferry mobility-based direction and time-aware greedy delay-tolerant routing (FM-DT-GDR) to transmit data to GS without delay following a disaster scenario in sparse FANETs. Once a beacon packet from the ferry is received, by comparing the distance between the GS

location and the ferry's anchor point location from the current node, the closest destination is determined and the search node transfers the data in accordance. If the beacon is not received by the search UAV, then the search UAV sends the data to GS using multi-hop communication.

Data from the search UAV is gathered by the ferry and sent to the GS. The availability of paths between the GS and the search UAV is significantly increased by the optimized ferry trajectory. Additionally, the FM-DT-GDR routing approach effectively chooses the forwarding node and transfers the data to the GS quickly. In the absence of neighbors, FM-DT-GDR switches to the data store, carry, and forward (SCF) mode.

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I would like to express my special thanks to my mother and brother for their blessings and encouragement during the period of study. My mother and my brother have been a source of inspiration and strength for me, enabling me to do this duty effectively; simply saying "thank you" is insufficient. My late father desired to see me pursue Ph.D., and he would be happy watching me somewhere from above, now when I conclude this.

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Last but not least, I would want to express my gratitude to MAA KAALI and MAHAKAAL for giving me the courage and knowledge to do this research.

Dehradun Juhi Agrawal

September 2022

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## LIST OF ABBREVIATIONS

| Acronym | Definition |
|---|---|
| FM-DT-GDR | A ferry mobility-based direction and time-aware greedy delay-tolerant routing |
| AN | Aerial Node |
| DTN | Delay tolerant network |
| DTN | Delay Tolerant Network |
| EED | End-to-End Delay |
| FANETs | Flying ad hoc networks |
| GMMM | Gauss-Markov Mobility Model |
| GeoDTN+Nav | Geographic DTN Routing with Navigator Prediction |
| GeoSaW | Geographic Spray and Wait |
| GPS | Global Positioning System |
| GPSR | Greedy Stateless Perimeter Routing |
| GS | Ground Station |
| LADTR | Location-Aided DTN routing |
| LAROD | Location-Aware Routing for Opportunistic DTN |
| MANETs | Mobile ad hoc networks |
| NH | Number of Hops |
| PDR | Packet Delivery Ratio |

| | |
|---|---|
| PPRZM | Paparazzi mobility model |
| QoS | Quality of Service |
| RM | Random Movement |
| RWP | Random Waypoint |
| RoI | Region of Interest |
| RERR | Route error |
| RREP | Route reply |
| RREQ | Route request |
| RO | Routing Overhead |
| S&W | Spray and Wait |
| SCF | Store Carry and Forward |
| 3-D | Three-dimensional |
| UAVs | Unmanned aerial vehicles |
| VANETs | Vehicular ad hoc networks |

## SYMBOLS AND INTERPRETATION

| Symbols Used | Interpretation |
|---|---|
| $U_i$ | 1-hop neighbor UAV |
| $U_i$ | 1-hop neighbors of $U_s$ |
| $0.8C_r$ | 80% of the communication range of the node. |
| U | Candidate nodes obtained after applying the threshold |
| $V_c$ | Current speed |
| $P_d$ | Data packet |
| $\lvert x_i - x_d \rvert$ | Distance between destination (d) and neighbor node (i) |
| $d_{si}$ | Distance between sender node and neighbor node |
| $J_t(d)$ | Distance cost |
| F | Ferry |
| GS | Ground station |
| $V_{max}$ | Maximum speed |
| $T_{travel\_min}$ | Neighbor node that takes minimum travel time out of all the nodes |

| | |
|---|---|
| $T_{travel\_min}(U_i)$ | Node after applying threshold which takes minimum travel time |
| $d(U_i)$ | Node located at the shortest distance from the destination. |
| -1 | Node moving in the opposite direction of the destination |
| $U_{travel\_min}$ | Node with minimum travel time |
| n | Number of candidate nodes found after applying a threshold |
| $n(U_i)$ | Number of neighbors of the source node |
| US | Search UAV |
| $J_t(v)$ | Speed cost |
| $\Delta$ | Threshold value |
| $T_{travel\_i}$ | Travel time a neighbor node takes to arrive destination |
| $T_{travel\_s}$ | Travel time a source node takes to reach the destination |
| $T_{travel\_i\_s}$ | Travel time of source node and neighbor nodes to reach the destination |
| A | Value of simulation x-axis |

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# TITLE OF THE THESIS

***AN EFFICIENT MOBILITY MODEL AND ROUTING TECHNIQUE FOR SPARSE FLYING ADHOC NETWORK***

# CHAPTER 1

# INTRODUCTION AND MOTIVATION

The exponential boom of the telecommunication era has introduced all types of information and communication technology (ICT) applications into our lives [1-2]. A few years ago, communication over the wire was an important part of our lives. After that, the internet was introduced and bit transmission became possible. Shortly thereafter, the Wi-Fi revolution gave rise to cellular devices that could be controlled remotely and exchange data with other devices without reliable and fast centralized management or infrastructure. The result is known as a Mobile Ad-hoc Network (MANET) [3-5]. MANET is a self-sustaining, decentralized, and self-organizing network of mobile nodes.

Unmanned Aerial Vehicles (UAVs), also known drones, are of particular interest. The use of UAVs in all facets of life has grown dramatically during the past ten years [6-9].UAVs may carry out a variety of functions, leading to the development of several beneficial applications like Internet access and phone calls while also improving the evaluation of the ground end user's happiness, or what is known as Quality of Experience (QoE) [10].

Our daily lives are affected by recent advancements in wireless technology, particularly given the prevalence of inexpensive Wi-Fi wireless interfaces and other gadgets like global positioning systems, sensors, etc [11-13]. UAVs are a result of all these cutting-edge technologies. Numerous civilian and military applications, like rescue team coordination [9-13], border surveillance [14-16], and autonomous tracking [17-20], have appeared since the launch of the Flying Ad-hoc Network (FANET).

The monitoring of agriculture and farms, the discovery of oil fields, the production of films, and many more private uses are also available [21–24]. These kinds of applications demand considerable backing from many academic fields as well as the focus and interest of scientists. However, other solutions can be more expensive to operate and slower to deploy.

UAVs expand the communication era from two-dimension (2-D) to three-dimensional (3-D) space. UAVs are autonomous flying nodes that can operate in a variety of environments due to their movements, sensory, and communication capabilities. In recent years, UAVs have become very popular due to their ability to collaborate with other UAVs and forward collected information to the ground station (GS). The UAVs can be used independently without human intervention with the growth of Global Positioning System (GPS) technology [25-30].

Hence, various research groups have begun to acknowledge the potential of UAVs in military surveillance [31], environmental surveillance [32,33], and search and rescue operations [34]. UAVs in disaster recovery operations help in locating people in distress or potential danger, that are lost or unable to maneuver in risky zones after a disaster [35]. The usage of UAVs for search and rescue applications is typically much cheaper than helicopters or manned aircraft [36,37]. The below figure depicts the overall scenario in FANETs.

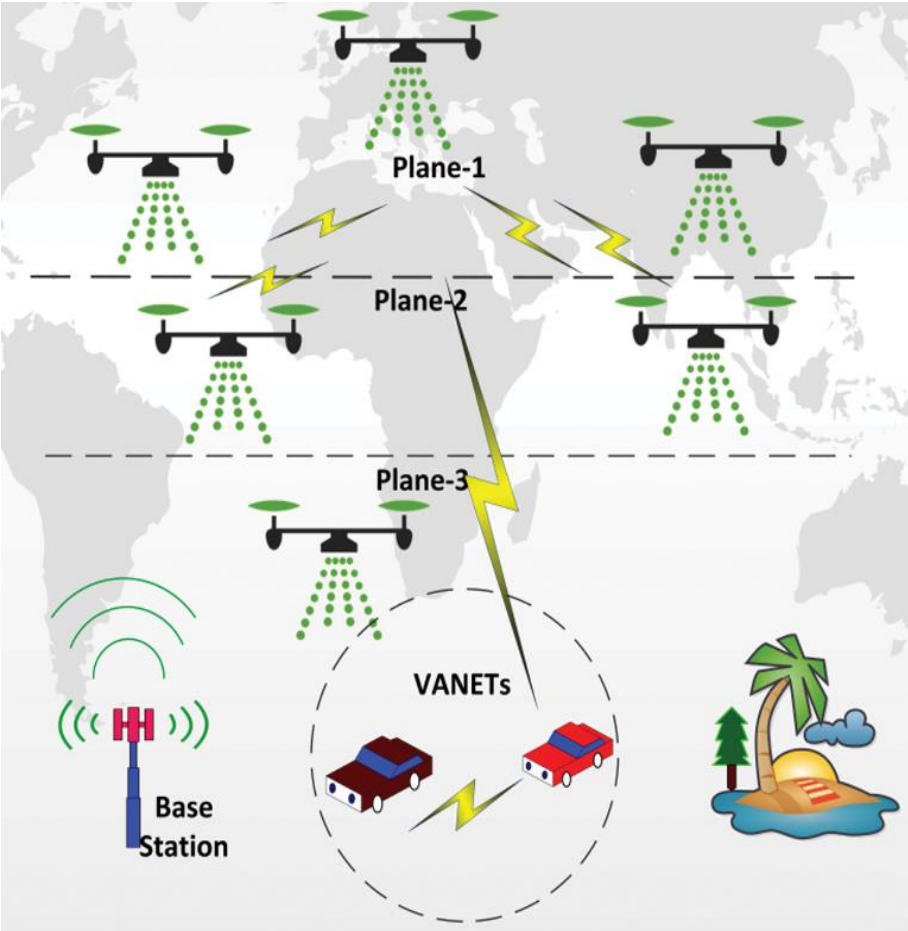


Figure 1.1: Overall FANET Scenario.

In addition, to search for missing persons, it can also be used to identify potential hazards in search areas before ground teams are dispatched. However, due to the fast movement of UAVs and the sparse nature of FANETs in search and rescue operations, many challenges like routing, etc. can be faced while sending the data to GS.

Search and rescue UAVs can be deployed relatively quickly and easily in such situations where time is of the essence, and first responders can avoid danger [38-40].

In addition, to search for missing persons, it can also be used to identify potential hazards in search areas before ground teams are dispatched. However, due to the fast movement of UAVs and the sparse nature of FANETs in search and rescue operations, many challenges like routing, etc. can be faced while sending the data to GS.

## 1.1 FLYING AD-HOC NETWORKS (FANETs)

UAVs are highly helpful in surveillance [41], search, and rescue operations [42,43], surveillance of forest fire [44], reconnaissance applications [45,46], etc. UAVs can likely be equipped with many new technologies like GPS, infrared cameras, sensors, and communication systems [47]. The UAV can be controlled via a fully autonomous onboard computer or remotely controlled by an operator from a GS.

The advent of GPS and other localization technologies has made UAVs autonomous [48,49]. Different names are used to designate these networks as below:

- Unmanned Aerial Vehicles network [50] ;
- Drone Ad-hoc Network (DANET) [51,52];
- Aerial Communication Network [53];
- Airborne network [54,55].

The figure below shows the general scenario of sparse FANETs.

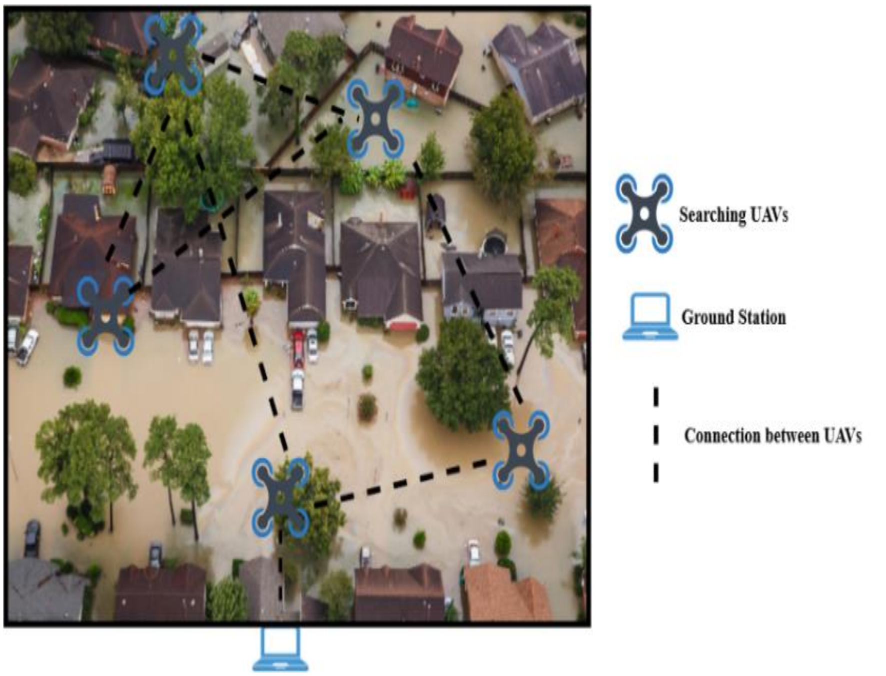


Figure.1.2: Sparse FANET generation in flood like situation.

Thus, multiple UAVs form a FANET and continue to collect data in the form of videos, and images from the target area, coordinate with each other and utilize multi-hop communication to send data to the GS [56-60].

Multi-UAV networks can provide more interconnection between UAVs which greatly improves network performance compared to single UAV systems [61,62]. Real-world UAV scenarios may include cases where the UAVs are not always connected to or able to communicate with the GS, resulting in significant transmission delays [63-66]. The figure shown below depicts the single and multi-UAV scenarios.

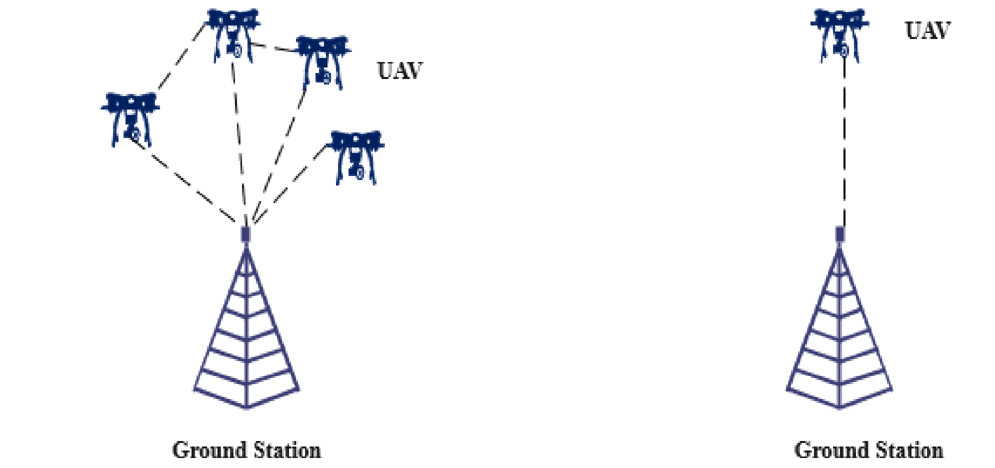


Figure 1.3: Two scenarios in FANETs.

The network might not be completely connected with a low node density and significant UAV mobility, therefore a contemporaneous path between nodes can not be assumed to exist [67]. This class of networks is called sparse FANETs, which is a type of delay/disruption tolerant network (DTN) [68-69].

The sparse FANETs result in recurring link failures that make the design of routing protocol more difficult. Position-based routing, topology-based routing, and other existing routing protocols all require that there be at least one absolute path between to the destination, which may be appropriate for dense or completely connected networks. Therefore, such routing protocols are not capable of efficiently forwarding packets in partially connected or sparse, or intermittent networks [70]. Therefore, it is of paramount importance to create an efficient and flexible routing protocol that is routable in discrete FANETs.

The direct application of routing protocols does not work with sparse FANETs. DTNs offers several solutions for sparse networks because they store, carry, and forward (SCF) the data packets until a suitable neighbor is found [71-75]. These routing protocols are made for highly mobile and sparse networks with very low UAV density, like sparse FANETs [76,77]. To overcome the problem of sparse networks or network segmentation, the DTN routing scheme allows messages to be buffered using the SCF mechanism [78-80].

However, existing DTN routing protocols have many issues that need to be addressed, like low packet delivery, high routing overhead, and high delay due to flooding schemes, especially in real-time applications. A new solution to DTN-based routing schemes is to include UAV position information in the routing decisions.

## 1.2 FLYING AD-HOC NETWORKS (FANETs) Vs. VEHICLE AD-HOC NETWORKS (VANETs) Vs. MOBILE AD-HOC NETWORKS (MANETs)

FANETs are a subclass of traditional ad-hoc networks like VANETs and MANETs, but the nodes in these networks differ in speed, node type, topology, and configuration. FANET differs from traditional MANETs in several key ways. A FANET can be termed as a specific set of highly mobile UAVs containing UAVs that generalize topologies from two-dimension (2D) to three-dimension (3D). Figure 1.4 shows MANET [81], VANET [82], and FANET [83] diagrams. This new field of research attracting many researchers and becoming increasingly found in real-life applications [84].

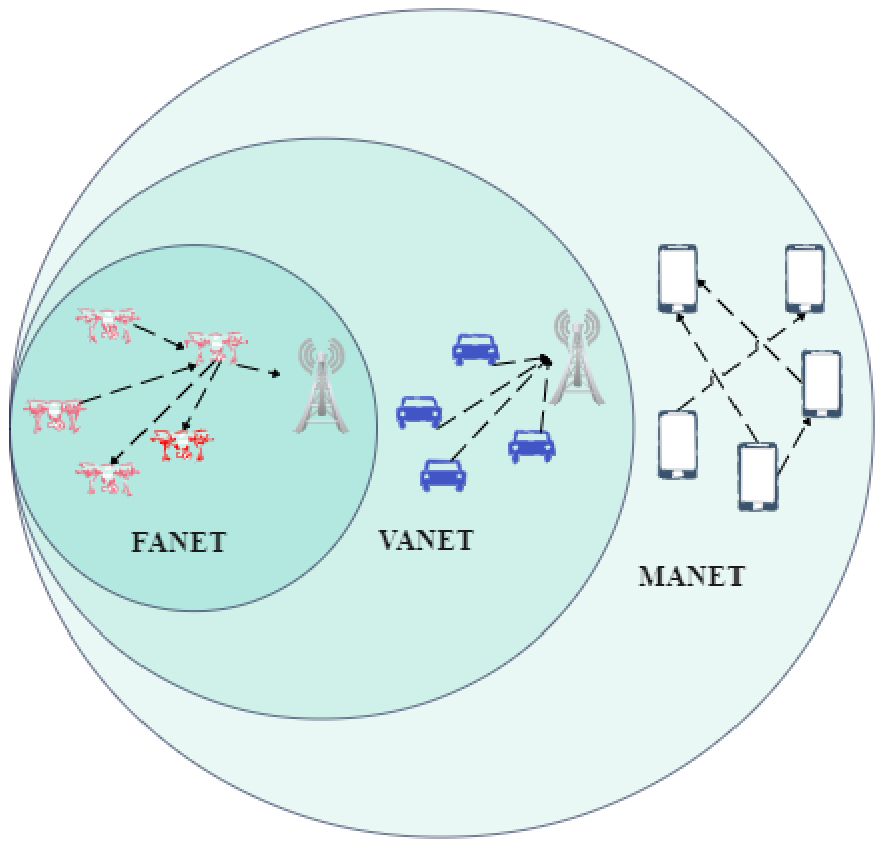


Figure 1.4: diagrammatic representation of MANET, VANET, FANET.

The difference between MANET, VANET, and FANET is described in detail below:

### 1.2.1 Mobility

UAV mobility is generally higher than MANET nodes. The rapid movement of nodes causes network fragmentation, resulting in frequent disruption of network connections. MANET node's movement is usually limited to ground artifacts, whereas FANET allows UAVs to traverse freely in the 3D area [86]. This additional independence of FANET requires efficient routing protocols that can offset the impact of mobility while conserving resources [87,88]. The collision between UAVs is an important consequence of UAV mobility and in some situations can be very important in unique missions involving autonomous UAVs [89,90].

### 1.2.2 Topology

The UAV's ability to fly creates scenarios where the UAVs are not placed on a flat surface and can fly at a certain height. With the growing popularity of UAVs, for the first time, practical applications of these three-dimensional networks are conceivable. On the other hand, this is a very tricky situation, especially when you think about how packets are routed [91,92].

### 1.2.3 Battery Consumption

Since the nodes participating in the network are battery-operated devices, power management is a major problem affecting the lifespan of the network. Also, unlike traditional ad-hoc networks like VANETs and MANETs, FANET consumes more power due to the propeller/rotor running on the node. As a result, we need power-efficient routing protocols that make gadgets work and extend the lifespan of the network [93].

### 1.2.4 Localization

The position of nodes in FANET can be obtained using a variety of modern positioning systems, including GPS, and other proximity-based accuracy technologies. In general, MANET devices use GPS to locate positioning devices, but in some MANET environments (indoor, underwater, urban, etc.) the GPS signal strength satellites may not be sufficient. However, due to the nature of UAVs, it is best to use GPS to determine the node’s location [94].

### 1.2.5 Radio Propagation

A radio signal's proximity to the terrain has an impact. A source and a destination frequently have no line of sight as MANET nodes are so near to the ground, which lowers the reliability of radio propagation. UAVs can instead fly at a fixed altitude, which lessens or even eliminates the appearance of landscape artifacts and ensures line-of-sight. The 802.11 standards, however, have demonstrated poor performance in aerial settings [24]. This is a result of network connectivity limitations brought on by channel interferences and the unique network dynamics of UAV-to-UAV and UAV-to-ground communications. In reality, the radiation pattern of antennas is torus-shaped rather than spherical, making communication between UAVs that are positioned one on top of the other challenging.

A comparison table of MANET, VANET, and FANET is shown in Table 1.1.

Table 1.1: Comparison between MANETs, VANETs, and FANETs.

| Parameters | FANET | VANET | MANET |
|---|---|---|---|
| **Node speed** | Low to high (6-460)km/h | Medium to high (20-130) km/h | Lower (6 km/h) |
| **Level of Mobility** | 3D, Either random or predefined | 2D, Random | 2D, Random |

| | | | |
|---|---|---|---|
| **Topology change** | Slow, fast, and stationary | Dynamic, Unpredictable | Liner movement but more progressive than VANET |
| **Propagation model** | Air | Ground | Ground |
| **Energy constraints** | High | Low | Medium |
| **Wireless technology** | 802.11a/b/ac/s/n/p | 802.11 p | 802.11 a/b/g/n |
| **Localization** | GPS / AGPS | GPS / AGPS | GPS |

## 1.3 APPLICATIONS OF FANETs

FANET provides a flexible, low-maintenance environment that makes it very useful for many potential applications, as depicted in the Figure 1.5.

This section discusses the potential applications of FANET such as forest fire detection and monitoring, agricultural management, load transportation, search and rescue (SAR) operations, environmental sensing, relaying network, and reconnaissance and patrolling.

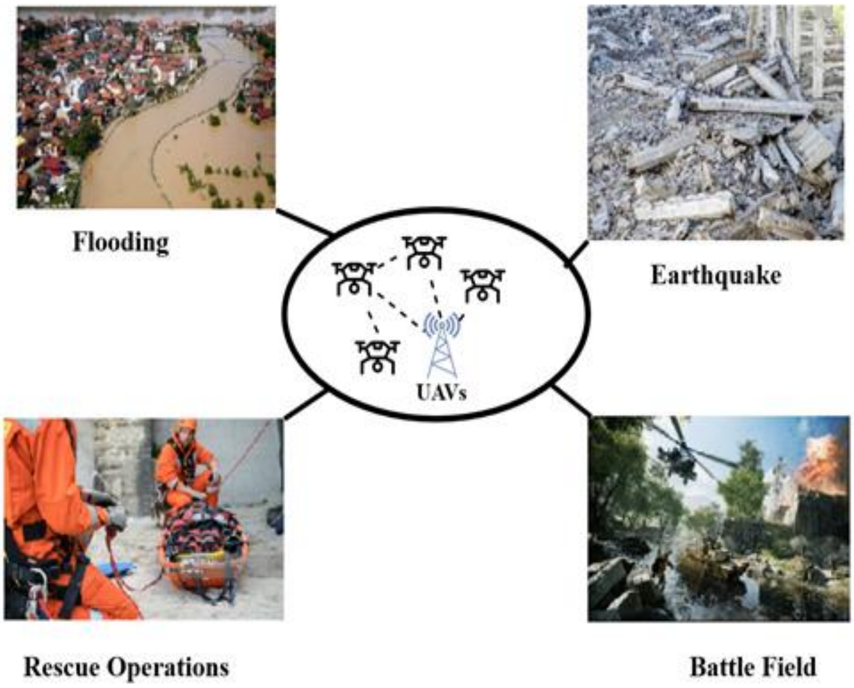


Figure 1.5: Application scenario of FANETs.

### 1.3.1 Forest Fire Detection and Monitoring

Forest-fire fighting activity is expensive. The cost of operating and maintaining aircraft helicopters and training personnel is enormous. Also, firefighters are at great risk. According to a report from the US Forest Service [95], between 2006 and 2016, approximately 24% of firefighter deaths were due to aircraft and helicopter crashes. In 2017, the US Los Angeles Fire Department (LAFD) announced plans to use UAVs to detect and monitor wildfires [71, 96].

### 1.3.2 Traffic and Urban Monitoring

Traffic monitoring is also an application that allows FANET to work extensively and update complex surveillance infrastructure. Historically, these operations were performed using fixed cameras. However, drones appear to be ideal for these situations as they can communicate between UAVs or infrastructure to get an accurate image of the urban environment at a specific location. Multiple cameras and sensors can be added to UAVs to provide an overview of the various situation and safety scenarios of road and rail networks, as well as the ground rescue team at this location. In [100-102], a vehicle carrying multiple UAVs was designed to help form a chain of connected UAVs using multi-link dialogue, increasing the variety of surveillance tasks.

### 1.3.3 Agricultural Management

Agricultural production management must control the suitability of crops in the context of precision agriculture which covers all methods and strategies for monitoring all types of agriculture (state of crops, soil, moisture, etc.) using information technology [103]. Manned aircraft are used in this field, but to overcome the problem of spatial and temporal resolution, the concept of a small network of a group of autonomous drones is more accurately considered. Data on plant satisfaction, buoyancy, and other important parameters are available in minutes so you can take precise action. The UAV takes off from a specific location and automatically follows a designated course, periodically filming the area.

### 1.3.4 Load Transportation

There is a lot of interest in using UAVs to deliver and transport commodities. The United Arab Emirates said in 2014 that they intended to use UAVs to transmit official documents to the general population, such as passports, identity cards, and licenses. Amazon Prime Air [71] successfully delivered its first UAV package to Cambridge, England in 2016. The payload capacity of the UAV, which is used in each of these applications to deliver cargo, is what determines how much cargo can be moved.

### 1.3.5 Search and Rescue (SAR) Operations

As part of SAR operations, UAVs typically search for or locate targets on the ground. The traditional context is the rescue of victims from inaccessible or dangerous places after a natural disaster like an earthquake, hurricane, tsunami, etc [97]. The FANET speeds up the search and rescue operation and provides an autonomous and decentralized communication system [98]. FANET was first used in search and rescue operations during Hurricane Katrina in 2005, the Nepal earthquake in April 2015, and the Fukushima disaster in 2011 [99].

### 1.3.6 Reconnaissance and Patrolling

UAVs that fly in a stationary mode are frequently used for the first line of defense patrols to watch over a particular area. Images of items and sites of interest that are dispersed over large areas may be collected as part of surveillance tasks. UAVs occasionally need to keep an eye on a certain target or area, similar to how ground forces typically patrol an area regularly for security, inspection, and observation. For instance, a swarm of UAVs can spot illicit border crossings as well as unintentional human disruptions, such as those involving guns and drugs [38].

Another situation is when UAVs work together for a mission with unexpected trajectories to conduct reconnaissance over a region to find ground units [39]. UAV usage in tactical scenarios has severe restrictions on communication and coordination latency, in contrast to the urban or civilian environment. The complexity required for FANETs, such as Tactical Edge Networks, is likewise impacted by this [40, 41].

## 1.4 RESEARCH ISSUES AND CHALLENGES

Though a FANET differs slightly from traditional VANETs, and MANETs, the underlying concept is the same: dynamic nodes are added as needed. As a result, while facing additional challenges, some problems in a FANET are as significant as in a VANET. UAV deployment over a specific terrestrial network is always a difficult undertaking. Although various studies have been done to raise the productivity of systems with flying nodes, there are still various issues that need to be looked into.

### 1.4.1 Routing

It is far more difficult to route data between UAVs in a FANET than it is in MANETs with low portability mobility circumstances [18]. Topology changes show that routing tables need to be dynamically changed. In FANET, the majority of metric calculations made by traditional routing algorithms are disregarded to provide a reliable connection between UAVs. Due to FANET's extremely high mobility, route reliability is also a significant concern. Although the authors in [104] offered a dependable routing protocol, it is necessary to ensure that such routing strategies are appropriate for use in FANET.

Accordingly, a new study area is required to compute routing metrics [30-35, 49,51-54], create effective routing algorithms, and build network models to create an adaptive and responsive ad hoc model.

### 1.4.2 Path Planning

Coordination and participation between UAVs are two of the most critical variables to boost a FANET's effectiveness in large-scale mission territory and multi-UAV operations. In such circumstances, each UAV must alter its course, and new ones should be incrementally computed. To arrange the FANET nodes for structuring the clusters of UAVs, new techniques or algorithms are necessary.

### 1.4.3 Quality of Service (QoS)

A FANET can be used to deliver many kinds of goods, like Amazon delivery drones, to customers' homes. They include GPS maps, voice and video streaming, photos, plain-language instant chats, etc. For FANET applications, it is crucial to provide specific attributes to the service [23] parameters, such as delay, bandwidth, and packet loss. The extremely mobile and dynamic nature of FANET is a significant barrier that needs to be overcome when describing an exhaustive system for QoS-enabled middleware. The quality of services provided by FANET nodes may potentially be impacted by their improper actions [103].

### 1.4.4 UAV Mobility and Placement

UAVs can be used in many different situations and for many different purposes, but their placement is primarily what FANET is worried about [103]. The positioning of the UAV must be optimized. Low connection quality occurs in FANETs due to the very dynamic network architecture brought on by high mobility. Therefore, there are numerous link breaks and network splits, which intensifies the requirement for route maintenance, and discovery reduces routing performance. To study routing, many UAV mobility models have been developed [104].

### 1.4.5 Low residual energy

Consequent to the relatively great distance between UAVs, battery-powered UAVs in FANETs have limited energy supply for three tasks: (a) routing; (b) When a route fails, packets are retransmitted, and (c) support a wide range of transmissions. In the meanwhile, UAVs with heavier payloads use more energy [104].

### 1.4.6 Network security

UAV networks face a significant problem in ensuring their security because of the numerous vulnerabilities they provide to malicious assaults, unauthorized entry, and even physical attacks. Additionally, the issue of secrecy is yet another serious security flaw in such networks, especially when sensitive data needs to be gathered. If a specific UAV is misdirected or has its control taken, it can use that UAV as a doorway to probe vital information from the authenticated network. These difficulties are all still current issues that can be thoroughly investigated.

## 1.5 RESEARCH GAP AND DIRECTION

The existing routing protocols present are not mature enough to meet the requirement of routing in sparse FANETs. The existing routing algorithms are not yet developed enough to fulfill the goal of promptly delivering data to the ground station in sparse FANETs. Furthermore, there is no intelligent method of reducing the delay and overhead of routing vital data in sparse FANET.

### 1.5.1 Problem Definition

Routing in sparse FANETs can be perceived as a multi-objective optimization problem. Therefore, there is a need for an intelligent routing scheme that can efficiently forward the data in sparse FANETs. The characteristics of FANETs nodes like the node's mobility, direction, speed, distance or location, the population of nodes, and other factors impact the routing performance. Therefore, it is a multi-objective optimization problem, with the expected solution.

In our solution, we have Y as a solution set and $y_1$, $y_2 \ldots y_n$ is a set of solutions such that:

- $y_1$ is to be maximized
- $y_2$ is to be minimized
- $y_3$ is to be minimized

Where,

- $y_1$: Packet delivery Ratio.
- $y_2$: Routing Overhead.

- $y_3$: End-to-End Delay.

In this work, we aim to provide the mobility model for ferries and routing solutions in sparse FANETs by increasing the packet delivery, decreasing routing overhead, and decreasing the end-to-end delay.

### 1.5.2 Research Objectives

The research objective is to "Design and Implement an Efficient Routing Protocol for Sparse Flying Ad-Hoc Networks (FANETs)".

**Sub-Objectives:**

**i.** To design a mobility model for Unmanned Aerial Vehicles (UAVs) in sparse FANETs. **(Publication J.2, 3,4)**

**ii.** Design an approach for establishing routing in 3-D sparse FANETs. **(Publication J.1, J.4, C1, C2)**

**iii.** Implementation of the newly designed algorithm. **(Publication J.4)**

**iv.** Performance testing of the newly designed algorithm using network parameters like packet delivery ratio, end-to-end delay, and routing overhead in sparse FANETs. **(Publication J.4).**

## 1.6 RESEARCH CONTRIBUTION

The current research work is focused on the "Efficient Routing Protocol for Sparse Flying Ad-Hoc Networks" named Ferry mobility based Direction and Time-Aware Greedy Delay-Tolerant Routing (FM-DT-GDR). To summarize, the following are the primary contributions of this research:

### 1.6.1 Mobility Model for ferries

As a part of the present research program, a mobility model for ferries has been designed. The proposed efficient trajectory for the ferries helps the ferry to gather information from UAVs conducting search and rescue operations in the disaster-hit region. In the proposed mobility model, the ferries follow a fixed optimized trajectory to increase the connectivity between GS and search nodes in the sparse FANET. The proposed ferry mobility model is in-depth addressed in Chapter 4.

### 1.6.2 Routing Mechanism for selecting efficient forwarder node

The contribution of the present research program is to design and implementation of a new routing solution for sparse FANETs that combine the geographic-based routing and DTNs mechanism to get better network performance like high packet delivery ratio, low end-to-end delay, and low overhead. Particularly for sparse FANETs in search and rescue scenarios, the routing strategy is proposed. The proposed protocol makes better packet forwarding decisions by utilizing the geographic data, time, and direction provided by neighbor UAVs. As this work is a contribution to the mobility model and routing, so Chapter 2 and Chapter 3 are dedicated to literature review for mobility and routing techniques respectively. In Chapter 4, the suggested routing approach is thoroughly covered.

## 1.7 THESIS ORGANIZATION

The thesis comprises six chapters. The summary of the upcoming chapters is as follows:

Chapter 2 offers a thorough analysis of the position-based routing and delay-tolerant routing protocols currently in use. This chapter categorizes the different routing protocols that are currently in use in FANETs and gives a comparison of them. Chapter 3 provides an extensive review of the existing mobility models for UAVs. This chapter classifies existing mobility models in FANETs and presents a comparative study between various existing mobility models. Chapter 4 introduces a novel mobility model and routing protocol for sparse FANETs. This protocol supports the routing of collected data between search UAVs and ground stations for post-disaster operations in sparse FANETs. The protocol uses the concept of DTN as its backbone. Chapter 5 presents the simulation results and discusses the same in detail. Chapter 6 concludes the thesis with highlights of the summary and future scope.

# CHAPTER 2
# BACKGROUND AND LITERATURE SURVEY - ROUTING

Routing enables the flying nodes to interact and coordinate with one another so that the pathways can be created in radio access infrastructure, particularly in Flying Ad-Hoc Networks (FANETs). In time-sensitive, the data needs to deliver on time so that the rescue team can take timely actions. Otherwise, several lives will be lost. Unmanned Aerial Vehicles (UAVs) collect sensitive data in formats like images and videos. Emergency applications create a sparse network because search and rescue operations are suddenly widespread [71, 77]. UAVs frequently depart from the GS coverage region with other UAVs. The crucial information can be directly transferred to the GS or via an intermediary node, a route or connection needs to be established.

There are various routing methods used in FANETs are described in this chapter. Three basic sub-classes of routing protocols can be distinguished: topology-based, position- or geographic-based, hybrid, and delay-tolerant networking (DTN) routing protocols. Classical delay tolerant and geographic delay tolerant-based routing protocols are additional categories for the DTN routing protocols. This chapter focuses on the delay-tolerant routing protocols, as sparse FANETs are the prime focus of our work [77,80].

Section. 2.1 shows some design requirements of routing protocols for FANET, Section 2.2 contains related work on the taxonomy of routing protocols for FANET, but the DTN-based routing protocols have been focused more in detail as DTN-based protocols are the prime focus of our work. We have discussed several proposals for classic DTN and geographic DTN routing protocols to forward packets in sparse FANETs.

## 2.1 FANET ROUTING PROTOCOLS DESIGN REQUIREMENTS

FANETs have different design requirements for routing as compared to traditional ad-hoc networks. It is significant to account for the application area and related quality of service needs while designing a FANET routing protocol. The design requirement of FANET routing is as follows:

- In sparse FANETs, the data transfer in search and rescue services, and military operations, is characterized by jitter tolerance, high bandwidth, and high delay requirements.
- Power constraints, unstable links, load balancing, fast UAV mobility, frequent removal, and the addition of UAVs, must be taken into account for reliable communication from UAV-to-UAV communications and from UAVs to ground stations (GS).
- Routing protocols developed for FANETs must adapt to network separation, frequent link or topology changes, and UAV high mobility.

Moreover, FANET routing protocols also require finding reliable, and efficient, routes between UAVs, as UAVs carry critical information like videos and images[77-80].

Hence, various routing protocols have been already designed for FANET in recent years. Some routing protocols were either newly proposed or a modified version of an existing MANET or VANET routing scheme is used to meet FANET routing requirements.

## 2.2 CLASSIFICATION OF FANETs ROUTING PROTOCOLS

The following sub-classes have been created to group the existing routing protocols:

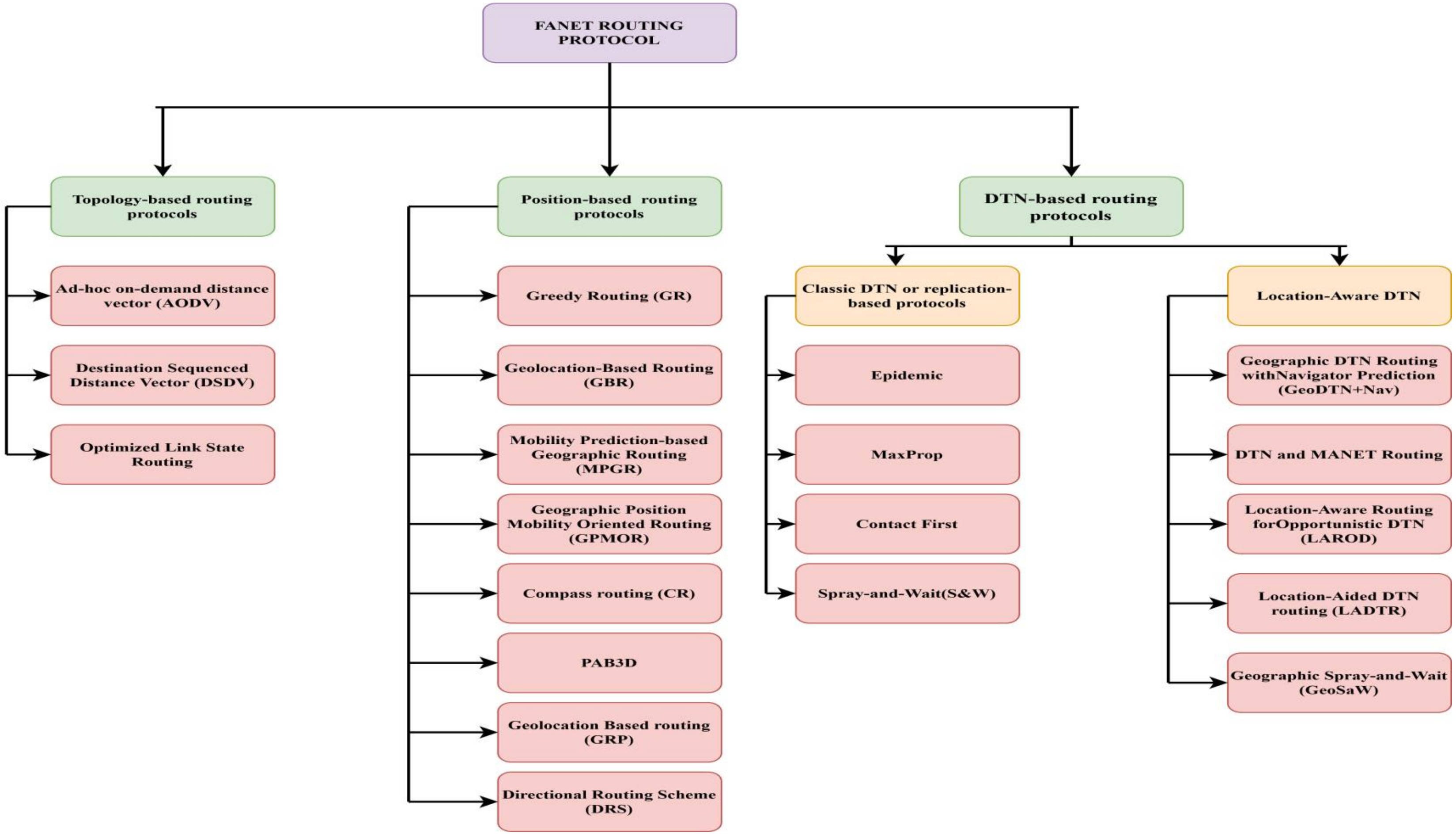


Figure 2.1: Classification of FANETs routing protocols

### 2.2.1 Topology-based routing protocols

A topology-based routing protocol considers the network topology and maintains an updated routing table that indicates the path that a packet must take to forward the data from its source to its destination. There are three routing schemes are used in topological routing protocols: reactive, proactive, and hybrid routing. Each node in the network keeps records of the network's state as part of a proactive strategy. Later, this information is used when a node requires to forward a message. DSDV [104,105] is a proactive protocol that uses an active but costly mechanism to update information about nodes that is updated to find and keep an appropriate route to the destination. Protocols are said to be reactive when routing paths are discovered when needed. AODV is a reactive routing that utilizes a route -request, reply, and error packets to search for the correct route to the destination [104, 105]. Various studies have shown that topology-based routing protocols are not fit for FANETs.

### 2.2.2 Position-based routing Protocols

The node's geographic location data is used to make decisions about forwarding data packets in position or geographic-based routing. Each UAV is set up with the assumption that its location is known using a built-in Global Positioning System (GPS) device or using other positioning systems. Geographic routing protocols use the local information of neighbor UAVs to forward data packets. It also eliminates the need for route discovery packets. Therefore, the minimum information on routing is needed for taking routing-related decisions. However, routing overhead, power consumption, and bandwidth are reduced in position-based routing [103]. It may be useful to consider a geographic routing protocol for FANETs due to UAV's high mobility, and the dynamics of their missions [106-107]. To make routing decisions, only information about neighboring UAVs and the location of the destination is required.

In geographic-based routing, the greedy forwarding method is the most popular method to forward data packets. Delay tolerant-based routing protocols are classified into classical DTN, and geographic-DTNs, each of which uses different methods to handle FANET routing issues and requirements. However, due to intermittent connectivity, pure geographic routing cannot provide a better packet-forwarding solution in UAV networks. Position-based routing schemes use local information to make routing decisions [108-111]. The characteristics of the Position-based protocols are as follows:

- Each node can find out its location using GPS.
- The location of its one-hop neighbors can be determined using hello messages.
- The position of destinations is already known.
- The nodes maintain the neighbor table and store the information of their neighbors.
- The decision of selection of the next forwarder node can be taken using the current node's position.

The position-based routing protocols for FANETs have been discussed below:

**i. Greedy Routing (GR):**

GR [112] uses a single-pass scheme that applies to a deterministic, progression-based strategy. In a greedy protocol, a node sends a packet to an adjacent node of the current node (Cn). This reduces the remaining distance from the target UAV to the current UAV [113]. The exact process continues until the data arrives at the desired destination. If the destination UAV is Dn and the current node is Cn, the next forwarding node can be determined by comparing the distance between Cn and Dn to another node that is immediately adjacent to Cn. The major problem with this protocol is that if there are no neighbors called "local minima",

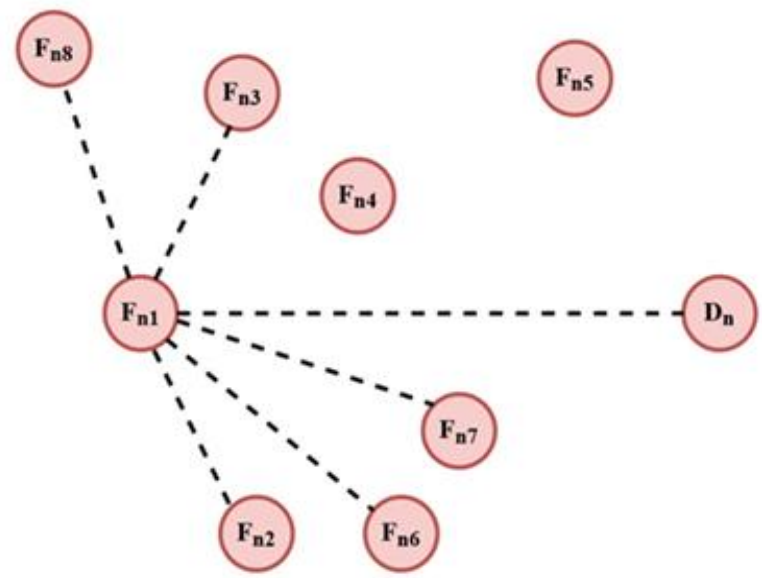


Figure 2.2: Fn1 chooses Fn7 to minimize the distance between Fn1 and Dn

the node won't transmit information to the destination. Figure 2.2 shows a figure of a greedy routing scheme in which the node Fn1 selects Fn7 to minimize the distance between Fn1 and Dn.

**ii. Geolocation-Based Routing (GBR) :**

The GBR [115] uses a greedy method and a link prediction technique to choose the next forwarder based on the nodes' speeds and geographic positions. The GBR protocol helps identify the ideal closest neighbor UAV and lessens the effects of the FANET's reforming topology. For connection prediction, each node in the network sends navigation-related data such as position, current direction, and speed. This method is particularly useful for transmitting packets in greedy mode to the node that is close to the target node. Thus, local minima can lead greedy routing techniques to fail. A routing message includes the outbound region, the current destination node, and the location of the node where routing is deactivated. To address the local minimum issue, the node position is used to locate the node closest to the target location.

**iii. Mobility Prediction-based Geographic Routing (MPGR):**

The MPGR [116] algorithm employs a similar GPSR idea. To learn more about the subsequent forwarding node, the sending node sends a neighbor discovery message after forwarding the packet. Additionally, the chosen forwarding node can be too far away from the source node. As a result of the disconnection, packet loss may occur. Based on a UAV node's position and movement characteristics at a given time (t), MPGR employs a motion prediction model to determine the precise position of the node (t-1). Estimated positions allow you to evaluate the persistent connections of neighboring nodes. Therefore, selecting a forwarder node is less error-prone.

**iv. Geographic Position Mobility Oriented Routing (GPMOR):**

GPMOR [117] is a predictive-based routing technique, to forecast UAV node mobility patterns. GPS is used by each UAV to gather location-based data. To determine the mobility of nearby UAVs and determine their current position after a predetermined length of time, each node communicates position-related data. The best transport node that doesn't move around a lot is chosen by GPMOR.

**v. Compass routing (CR):**

The angle between the destination and current node is decreased by the CR protocol's constant data transmission to candidate nodes [118].

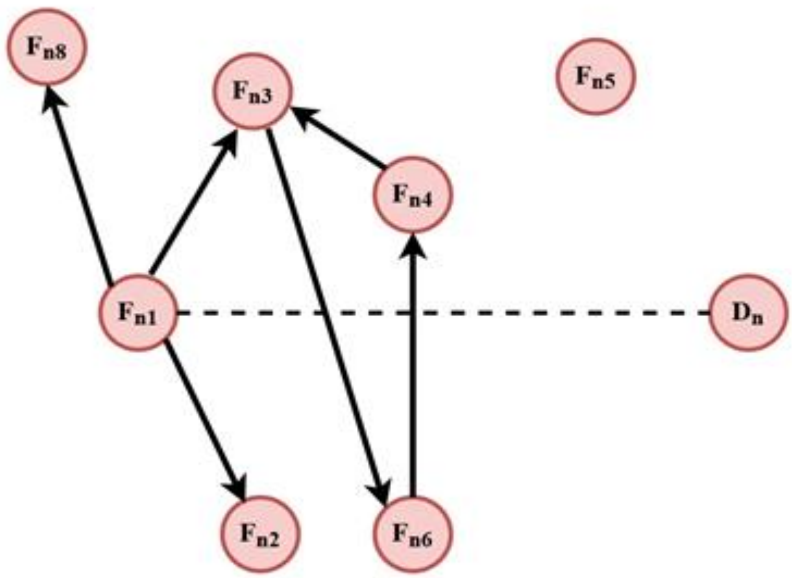


Figure 2.3: Compass routing.

Another name for compass routing is "Directional DIR." The angle or orientation of the target is determined using the target's position information. The neighboring node near the destination Dn is selected by the present node [118].

Figure 2.3 shows a compass routing diagram where the node Fn1 selects Fn3 to minimize the angle between Fn1 and Dn.

**vi. PAB3D:**

PAB3D [119] selects the closest node randomly from the current set of adjacent nodes to eliminate the "local minimum" problem [35, 36]. PAB3D sends the packet to the destination node Dn. Much research has been done on "randomization algorithms" over the years. Several researchers have focused on solutions that use a random walk approach to select random nodes to avoid loop-like conditions.

When the threshold value hits its maximum because there are too many nodes, the randomization idea fails. The additional name is Time to Live Random (TTLR). Finding the optimal adjacency candidates is simpler than improving randomization. In 3D graphs, the top and bottom don't exist. 3D top/bottom refers to the idea of a plane in three dimensions (AB3D). Instead of working with lines, the AB3D protocol uses planes. A 3D region is divided into two sections using a plane [40].

**vii. Directional Routing Scheme (DRS):**

DRS [120] is an omnidirectional and directional transmission-based directional routing scheme for the FANET. This hybrid approach uses node orbit and position information along with geo-cast and unicast routing. When compared to the AODV protocol, DRS increases the average path lifespan and packet delivery.

The delay-tolerant-based routing has been expanded in the next section i.e section 2.3.

## 2.3 ROUTING IN SPARSE FANETs USING DTN

The routing technique on this range is proposed for sparse networks which is the result of the high mobility and sparse density of UAVs in the FANETs. To deal with the problem of sparse networks and network segmentation, DTN routing methods take advantage of node mobility and message buffering techniques known as the store-carry-forward method. In case, UAVs are not able to reach suitable forwarder UAVs, this class of routing uses the store-carry and forward (SCF) method so that information packets can be forwarded to the intended destination. However, for real-time applications, overcoming delay is the main challenge of DTN-based routing protocols. In DTN, there are two types of routing strategies: classical and position-based DTN routing. The DTN-based routing protocols are discussed below.

### 2.3.1 FANET-DTN-based routing protocols

DTN's routing protocols are divided into two subclasses: Classic DTN or replication-based protocols, and geographic-based DTN protocols. The replication-based protocol allows packets to be replicated across the network which results in high traffic in the network. The geographic-based DTN protocols do not replicate data packets but find different ways to route the packet to the destination. This section describes some of the latest DTN routing techniques to consider for sparse FANETs:

### i. Classic DTN or replication-based protocols:

The classic DTN or replica-based routing techniques are used in sparse FANETs to increase the packet delivery in the network as these protocols use the mechanism of flooding or message replication. The replication-based routing protocols increase the routing overhead and delay. The classic-DTN-based routing protocols have been discussed below:

#### a. Epidemic:

A replication-based protocol is an epidemic [126]. In this method, the nodes constantly replicate and send packets to recently made contacts. One of the most well-liked and straightforward routing algorithms in the DTN sector is the epidemic protocol. In this protocol, flooding is the mechanism. Each packet in this protocol is distributed equally across the network without regard to priority or restriction. Two nodes exchange and compare a list of package IDs to locate a package that is not already in the repository of the other node. The buffer's available space must be verified in the subsequent step.

This protocol's drawback is that it uses a lot of resources because of the numerous copies that need a lot of bandwidth, storage space, and energy. As a result, in most actual application cases when these resources are not immediately available, this type of routing is not feasible.

#### b. MaxProp:

MaxProp protocol [127] is based on a flooding method. In this protocol, when contact is found, all packets are checked, duplicated, and sent to that contact. MaxProp contains an ordered queue, primarily using estimated probability of each packet's route to its destination.

**c. Contact First:**

A forwarding-based routing technique called Contact First sends all of the packets that each node currently owns to the main discovery node [128]. The host receiving the packet follows the same method, waiting for the first available contact. This process continuously runs until the packet arrives at its destination.

**d. Spray-and-Wait (S&W):**

S&W achieves resource efficiency by strictly limiting the copies of packets in the network [129]. S&W protocol has two phases: the spray, and the waiting phase. The L number is related to a package and represents the number of maximum copies of a package while the system creates a new package. During the spray interval, the L packet source is responsible for spraying or replicating individual relays. This number is reduced by the number of transmissions of this packet from each node. When the number of copies allowed reaches 1, the source node stops creating copies of the packet and retains the only copy until it meets its destination or the packet is discarded due to a buffer overflow or time to live (TTL).

Existing DTN techniques with limited, and unlimited copies incur high overhead and high delay when UAVs transmit large amounts of data.

**ii. Location-Aware DTN**

The location-aware DTN routing protocol uses location information to make routing-related decisions. The location-aware DTN-based routing has been discussed below:

**a. Geographic DTN Routing with Navigator Prediction (GeoDTN+Nav)**

Location or position-based routing [130] has proven itself in highly dynamic environments like vehicle peer-to-peer networks (VANETs) or FANETs. Greedy Stateless Perimeter Routing (GPSR) uses greedy routing to send packets by either choosing a relay with the best forwarding path to a destination or using recovery mode if these solutions do not work. These protocols can efficiently send packets in the fully connected network. Therefore, the dynamic characteristics of the network like node density, traffic patterns, and radio interference can create disconnected network partitions. GeoDTN+Nav combined with SCF technique was designed for VANETs routing protocol. This technique is inappropriate for FANETs due to the nature of UAV motion in open space.

**b. DTN and MANET Routing**

It is a hybrid approach that integrates DTN with AODV routing, wherever possible [131]. This strategy preserves the benefits of AODV while preserving end-to-end semantics, and provides DTN-based communication options when required.

**c. Location-Aware Routing for Opportunistic DTN (LAROD)**

LAROD [132] is a geographic routing approach for FANETs that combines an SCF approach with greedy routing. When the network is highly sparse then forwarding is not possible. Therefore, UAVs use the SCF scheme until a suitable neighbor node is found.

A source node simply broadcasts the data when it has data to send. The node broadcasts the data in the direction of the destination to provide a movement to the data in the direction of the destination. LAROD uses the concept of overhearing, in which neighbor nodes overhear the transmission and take the routing-related decisions. A timer for rebroadcasting the packet is used by the sender node. The timer function uses a random waiting period to prevent the simultaneous broadcast of the same data packet. The duplicate packets are discarded by the neighbor nodes when they overhear the broadcasting of the same packet. The sender node transmits the same packet repeatedly until it locates a forwarder UAV. After receiving the acknowledgment packet from the destination node, the node stops sending the packet.

**d. Location-Aided DTN routing (LADTR):**

During search and rescue operations or emergency services, the drone captures the video and photo and sends them to the ground station either in a multi-hop or directly in a one-hop node. LADTR [133] utilizes location-aided forwarding integrated with an SCF scheme. A mobility prediction technique is used to estimate the future location of nodes. Ferry UAVs are also used for routing in sparse networks that increase the connectivity between GS and UAVs, resulting in low delays and increased packet delivery rates. So, the data packets are transmitted to the ferry UAVs, if the ferry is within communication range then data gets forwarded to the GS. The UAV transfers the packet to the closest neighbor in the direction of the GS if no ferry UAV is located within range. LADTR exhibits low latency and high packet delivery as compared to flooding-based techniques like an epidemic and Spray-and-Wait. However, strong assumptions about UAV mobility in the 2D area (or a fixed height) of LADTRs that no longer fully implement UAV mobility capabilities (in 3D space) may make LADTRs impractical in real life.

**e. Geographic Spray-and-Wait (GeoSaW):**

In [134] Bujri et al. introduced the routing protocol GeoSaw for search and rescue operations. GeoSaW uses waypoints that are dependent on location. The plan makes use of the node's present position and the mission plan's route. GeoSaW routing operates by foreseeing the locations of relay nodes and the times of their arrival.

Table 2.1 outlines the existing routing protocols for sparse FANETs.

Table 2.1 Outlines the strength and weaknesses of existing routing techniques for sparse FANET's.

| S.No | Protocol | Strengths | Weaknesses |
|---|---|---|---|
| **1** | Greedy | Suitable for sparse networks. | It won't work if there are no adjacent nodes near the destination node. |

| | | | |
|---|---|---|---|
| **2** | GBR | Low overhead. | High latency. |
| **3** | GPMOR | High packet delivery, and low latency. | Not suitable for low node density networks.<br>The mobility model has a big impact on how well the routing works. |
| **4** | MPGR | High delivery ratio and low latency.<br>It outperforms other prediction-based schemes as it provides a more accurate estimation of the future positions of the node. | Don’t consider the UAV's planned route and the expiration time of the link to discover the future position of the node. |
| **5** | Compass | Highly scalable for routing. | - High packet loss in low node density networks.<br>- Suffers from the looping of packets. |

| | | | |
|---|---|---|---|
| **6** | CFace(3) | Better packet delivery ratio. | High path dilation. |
| **7** | PAB3D | - Can deal with local minima problems.<br>- Loop-free routing protocol. | High path dilation. |
| **8** | GRP | Can deal with local minima problem. | Extremely dense FANETs can result in extreme overhead. |
| **9** | AGR | Low routing overhead. | Extremely dense FANETs can result in extreme overhead |
| **10** | DRS | High path lifetime. | Frequently UAV direction changes lead to path failures. |
| **11** | GFG/GPSR | High packet delivery rate. | Moderate path dilation. |
| **12** | Greedy random greedy(GRG) | Can deal with local minima problems. Better delivery rate compared to | High path dilation. |

| | | | |
|---|---|---|---|
| | | progress-based protocols. | |
| **13** | G-OLSR[117] | Can solve the problem of local minima.<br>High rate of delivery. | Only suitable for the dense network. |

Table 2.2: Summary of characteristics of DTN-based routing protocols.

| Routing Protocol | Location Prediction | Mobility Prediction | Greedy Forwarding | Routing strategy |
|---|---|---|---|---|
| **Epidemic** | No | No | No | Flooding |
| **Spray-and-Wait** | No | No | No | Flooding |
| **First Contact** | No | No | No | Flooding |
| **GeoDTN+Nav** | No | No | No | Hybrid |
| **LAROD** | No | Yes | Yes | Hybrid |

Table 2.2 summarize the characteristics of DTN-based routing protocols.

Table 2.3: Summary of DTN-based routing protocols

| Routing Protocol | Summary |
|---|---|
| **Epidemic** | It floods the data to various other nodes to increase the probability of packet to get delivered to the destination. Therefore, epidemic routing has huge routing overhead and end-to-end delay. |
| **Spray-and-Wait** | Spray-and-Wait uses replica based routing strategy.To limit the flooding of same packet, it makes L number of copies of each packet that helps to reduce the routing overhead and end-to-end delay. |
| **First Contact** | Contact First sends all of the packets that each node currently owns to the main discovery node. The host receiving the packet follows the same method, waiting for the first available contact. This process continuously runs until the packet arrives at its destination. |
| **GeoDTN+Nav** | GeoDTN+Nav combined geographic routing with SCF technique was designed for VANETs. This technique is inappropriate for FANETs due to the nature of UAV motion in open space. |
| **LAROD** | LAROD uses geographic routing approach combined with SCF approach with greedy routing. Additionally, it uses ferry to collect the data from search nodes. |

## 2.4 CHAPTER SUMMARY

In this chapter, we have reviewed various research areas in FANETs, and a detailed review has been done of the solutions designed for the routing of the information in FANETs. There has been a considerable amount of work done in the field of information routing in sparse FANETs but such work has some limitations. Some techniques are proved better in sparse FANETs while others are in dense FANETs. The reality regarding sparse FANET is that classic DTN-based routing like Spray, and Wait, Epidemic, etc., deliver data using a data propagation strategy. It leads to network congestion. Redundant transmission raises the routing overhead and network delay. Additionally, network congestion that occurs due to replicas of the message decreases the packet delivery ratio as well. The flooding schemes are not suitable for resource-limited networks like FANETs. Therefore, data transfer in an emergency or during time-sensitive operations is an important concern to be aware of. Designing a routing system that sends data fast to its target in a time-critical emergency scenario is the answer to this problem.

# CHAPTER 3

# BACKGROUND AND LITERATURE SURVEY – MOBILITY MODELS

The Unmanned Aerial Vehicles (UAVs) path and speed variations are defined by the Mobility Model, which also depicts their position. To build a realistic simulation environment, mobility models are used. This chapter critically examines Flying Ad-hoc Networking (FANET) scenarios based on mobility models that can be used for simulation. This chapter provides an important assessment of the existing mobility models and requirements for each application using multiple UAV systems. Researchers use simulators to design, propose, and test routing protocols to analyze how routing protocols work [136,137]. In FANET, the requirement for simulators in this context is realistic motion, shape, and sound simulation of UAV communications [138]. Modeling involving mobile nodes requires mobility diagrams that reflect changes in the position and velocity of nodes during communication to analyze network performance during movement [139,140]. When considering FANETs, there needs to be a mobility model developed especially for UAVs.

Many researchers run simulations on simple mobility models, including random path mobility models specifically designed for traditional MANETs. However, due to aerodynamic limitations, the maneuverability of a UAV differs from that of a ground vehicle. As a result, MANET-based mobility techniques cannot accurately reproduce the actual behavior of UAVs, leading to erroneous simulation results [142]. Synthetic and real-world mobility models for various applications are discussed in [143].

Evaluate the performance of the network using software simulations and real-world experiments (test benches). The bench allows you to evaluate and analyze protocols in a real environment. However, because test benches are very complex and expensive to build large networks, simulation-based evaluations are more feasible than test benches [144]. Evaluating simulation-based routing protocols requires the use of mobility models that determine the velocity, direction, and acceleration of a UAV over time. Therefore, there is an important requirement for a well-designed UAV mobility simulation for creating a realistic simulation environment for evaluating FANET performance [145].

The mobility model has a major influence on routing performance when it comes to packet delivery etc. It has been found that the functionality of routing protocols differs significantly for different mobility models. Therefore, it is important to select an appropriate dynamic model to understand its properties and draw useful conclusions from the simulation results. This chapter describes the existing mobility model designed specifically for FANET.

## 3.1 MOBILITY MODELS

UAV-based mobility models can be divided into the following classes: A detailed explanation of the mobility models has been discussed below:

### i. Random WayPoint (RWP) Mobility Model

In RWP [146], every node pauses for a certain period, called a pause period. The UAV chooses a random location inside the simulation field and traverses in the direction of the end position with the randomly selected speed when the pause duration elapses.

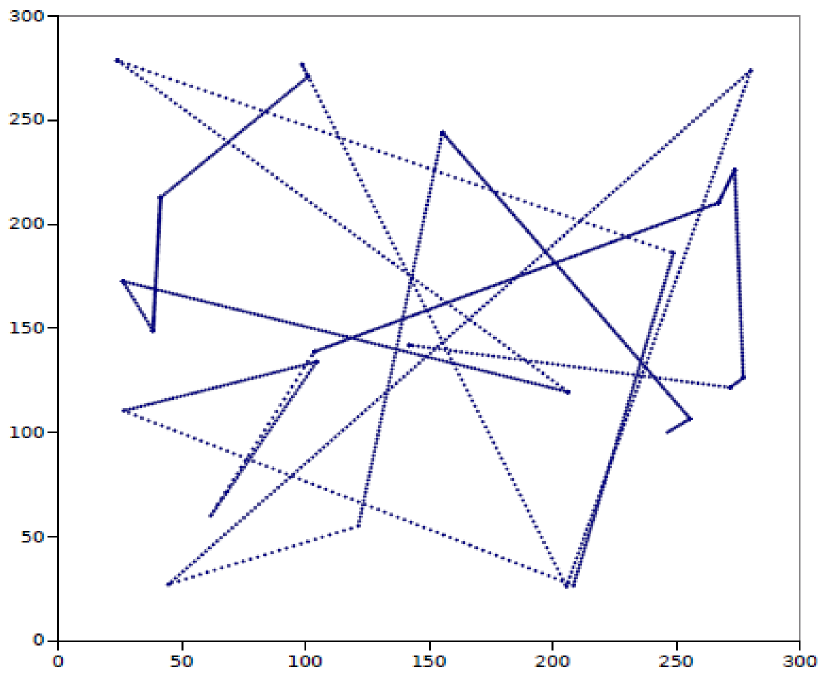


Figure 3.1: Random waypoint mobility model.

On achieving the final location, it stops again and waits for some time earlier than starting its journey to a newly selected final location [153]. In particular, the nodes focus on a significant portion of the area described for the simulation.

In addition, it has limits for the simulation of UAV networks due to the speed characteristics of the UAV, especially the sudden random modifications, and sharp turns in speed, and direction.

**ii. Random Direction (RD) Mobility Model**

Since there was a high possibility of moving towards a new location close to the center of the simulated terrain, the RD mobility model [147] seeks to solve the issue of the concentration of nodes there. The movement's direction is chosen at random by the nodes. Each node chooses a path between zero and two at the beginning of the simulation, then moves in the chosen direction at the edge of the simulation region. The node arrives at the edge, pauses, waits for a fixed time, selects a direction, and repeats the process. RD mobility model was proposed to address the problem of nodes being concentrated in the centre of the simulation region in the RWP mobility model because of the high likelihood of migrating toward a new destination near to the middle of the simulation region.

**iii. Time-Dependent mobility model**

Using numerous mathematical formulas, this mobility model executes the smooth change of motion while avoiding abrupt direction and speed changes.

**a. Gauss-Markov (GM) Mobility Model**

A single management parameter, which defines the degree of unpredictability, is used in the memory-based GM mobility model to produce various levels of randomization [149]. To begin with, each node is given an initial direction and speed. At a fixed period, speed and direction are updated according to the previous direction, and speed. In UAV network simulations, GM mobility models are proposed to extend 3-dimensional (3-D) dynamics. In this method, a pitch variable is used in the model of 3-D UAV motion and two more tuning parameters are described additionally.

**b. Smooth-turn (ST) Mobility Model**

In ST, randomly each node chooses a turn to assure a smooth trajectory before choosing a new turn for its direction, and circles around that factor for an exponentially distributed period [150]. The primary distinguishing capability of this mobility model is that it takes a smooth turn rather than a sharp turn and captures the spatial correlation of acceleration. Therefore, this mobility plan no longer includes a collision avoidance plan.

**iv. Path-planned mobility models**

In the route planning mobility model, each UAV follows a predetermined route until it reaches an end. The UAV repeats the same method or changes randomly.

**a. Semi-random Circular Movement (SRCM) Mobility Model**

In SRCM [151], the node moves along a predetermined circular path, say Ci, with a velocity vi that can range between [vmin, vmax] from a starting point Pi. The node then advances to the next step on the same circle by computing the step length, step time, and step point. When the node reaches the destination point Pi, it can choose at random which radius to move in. Once there, it stops for a predetermined amount of time before restarting its speed at the next location. After doing a full circle revolution, it randomly selects a different circle with the same center as the next moving route and repeats the prior process. The mobility pattern of SRCM is shown in the figure below:

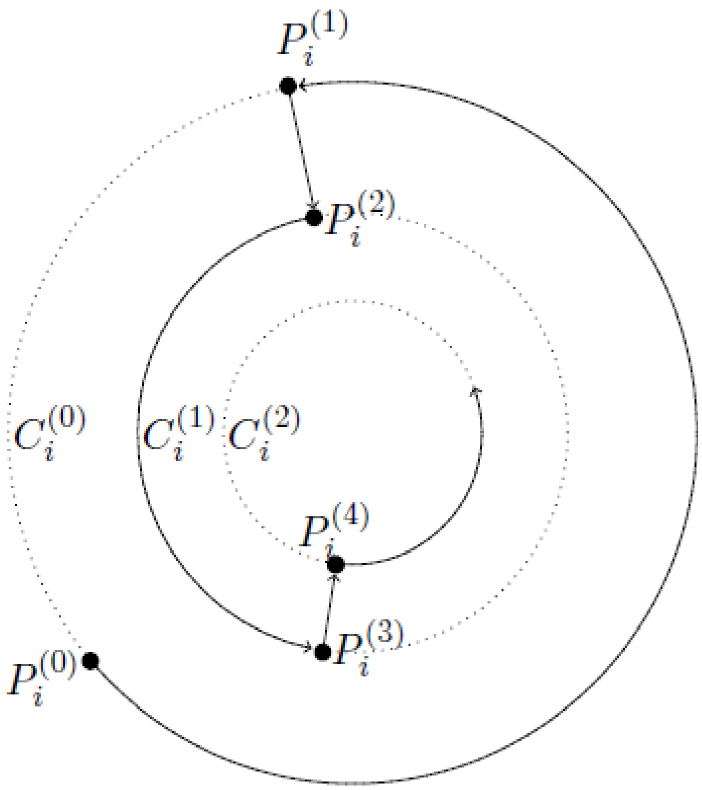


Figure 3.2.: Mobility pattern of SRCM.

**b. Paparazzi Mobility (PPRZM) Model**

Paparazzi mobility's [152] movement patterns include five possible UAV movements: waypoint, oval, stay-at, eight, and scan. Each mobility pattern can be applied to different application scenarios. Firstly, each UAV chooses the velocity, and position of movement. Their heights are first randomly fixed and fixed during the entire simulation period. The results confirmed that the PPRZM reveals nearly identical performance to the paparazzi's actual application trace compared to the random waypoint mobility model.

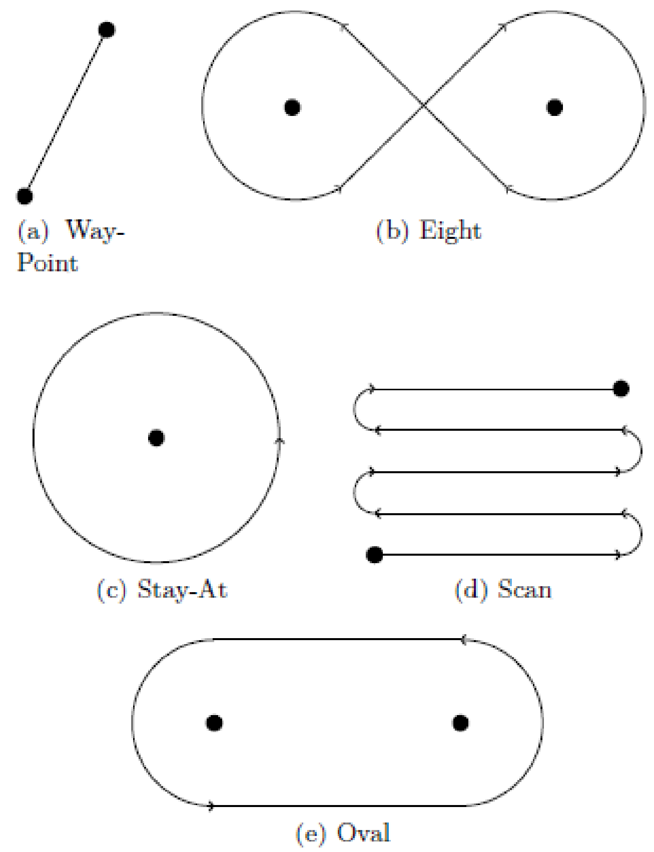


Figure 3.3.: Paparazzi mobility patterns.

Table 3.1: Outline the strength and weaknesses of existing mobility models for FANETs.

| Mobility Model | Strength | Weakness | Application Scenarios |
|---|---|---|---|
| **RWP** | Well parameterized for adjusting randomness, easy implementation | Non-uniform spatial distribution of UAVs, no collision avoidance, does not follow aerodynamic, and mechanical constraints. | Suitable for MANETs |
| **RD** | easy to implement, well parameterized for adjusting randomness | No collision avoidance does not follow the aerodynamic rule and mechanical constraints. | Suitable for MANETs |
| **GM-3D** | Has smooth acceleration | No collision avoidance mechanism. | Emergency operations. |

| | | | |
|---|---|---|---|
| **SMM** | smooth acceleration | UAVs mobility is constrained by reference points and no collision avoidance. | Cooperative monitoring and surveillance. |
| **DPR** | Better network coverage, and scanning properties, have smooth smooth turns, and acceleration. | Network connectivity is not taken into account in partial collision avoidance. restricted mobility due to the confined turn radius. | network coverage, and Search and rescue. |
| **ST** | Follows aerodynamic constraints. can mimic frequent topology changes | No collision prevention. | Patrolling and reconnaissance |
| **SRCM** | Reduces UAV collisions. | Mobility of UAVs | Searching for evading targets, |

| | | | |
|---|---|---|---|
| | | constrained with fixed turn center. | network coverage, Detection of forest fire, urban Monitoring and traffic |
| **PPRZM** | Less the sharp turn | No collision avoidance | Agricultural management, environmental sensing, search and rescue. |

## 3.2 CHAPTER SUMMARY

In this chapter, we have reviewed various mobility models used in FANETs. Furthermore, a detailed review has been done based on the weakness, strengths, and application of various mobility models. The MANET-based mobility models are not appropriate for FANETs due to UAV’s high mobility. The movement designing of UAVs in FANETs has always been a difficult task. Therefore over time, researchers have suggested a variety of mobility models for guiding node mobility within the target area. . In our study, we found that random models like RWP, RW, and RD are trivial and too unrealistic because it ignores many details of UAVs. The Group Mobility Models provide efficient network coverage, but most of the models such as the Pheromone Based

Mobility Model (PBM), and Distributed Pheromone Repel (DPR) are not capable of handling collision whereas Particle Swarm Mobility Model (PSMM) uses collision-free adjustment. In Path Planned Mobility Models, each node follows its predefined trajectories. The Paparazzi Model (PPRZM) provides more real traces than the random mobility models. As a result, it is very useful in Agricultural management, and Search and rescue operations. The Smooth Turn (ST), 3D Gauss-Markov Mobility model (3DGMM), Gauss Markov (GM), and Three-Dimensional Dynamic and Uncertain Mobility Model (3D-DUMM) fall under the time-dependent mobility models category. These models characterize the real-life moving behaviors of mobile nodes. The mobility models like entity mobility models a single aircraft used to cover a predefined simulation area without any communication with other UAVs. The Semi Random Circular Movement (SRCM) model falls under this category. The SRCM is extremely helpful in Forest fire detection, and patrolling applications. The mobility models that are designed for covering the target area while maintaining connectivity, ignore energy awareness while deciding the next move of the UAV. As per our study, at present, the mobility models being used have not considered collision avoidance against external obstacles such as buildings into consideration. Furthermore, in the future, efficient mobility models can be developed that can consider the rapid change of direction, deceleration, and acceleration of UAVs. In Chapter 4, the proposed mobility model for ferries and routing scheme for sparse FANETs has been discussed in detail.

# CHAPTER 4

# PROPOSED FERRY MOBILITY-BASED DIRECTION AND TIME-AWARE GREEDY DELAY-TOLERANT ROUTING (FM-DT-GDR) SCHEME FOR SPARSE FLYING AD-HOC NETWORK

We have discussed extensive review in previous chapters and identified the need for a mobility model and routing protocol specially designed for sparse FANETs. Hence this chapter introduces a novel mobility model and routing technique for sparse FANETs. This protocol is termed Ferry Mobility-based Direction and Time-Aware Greedy Delay-Tolerant Routing (FM-DT-GDR) Protocol. FM-DT-GDR supports the routing of collected data between search UAVs and ground stations (GS) for post-disaster operations in sparse FANETs. The protocol uses the concept of DTN as its backbone.

The proposed work is divided into two portions:

- Design the optimized trajectory for the ferries' mobility to collect the data from UAVs in sparse flying ad-hoc networks (FANETs).
- Routing strategy for quickly forwarding emergency data to the ground station (GS) in sparse FANETs.

Below Figure.4.1 presents the methodology of the proposed work.

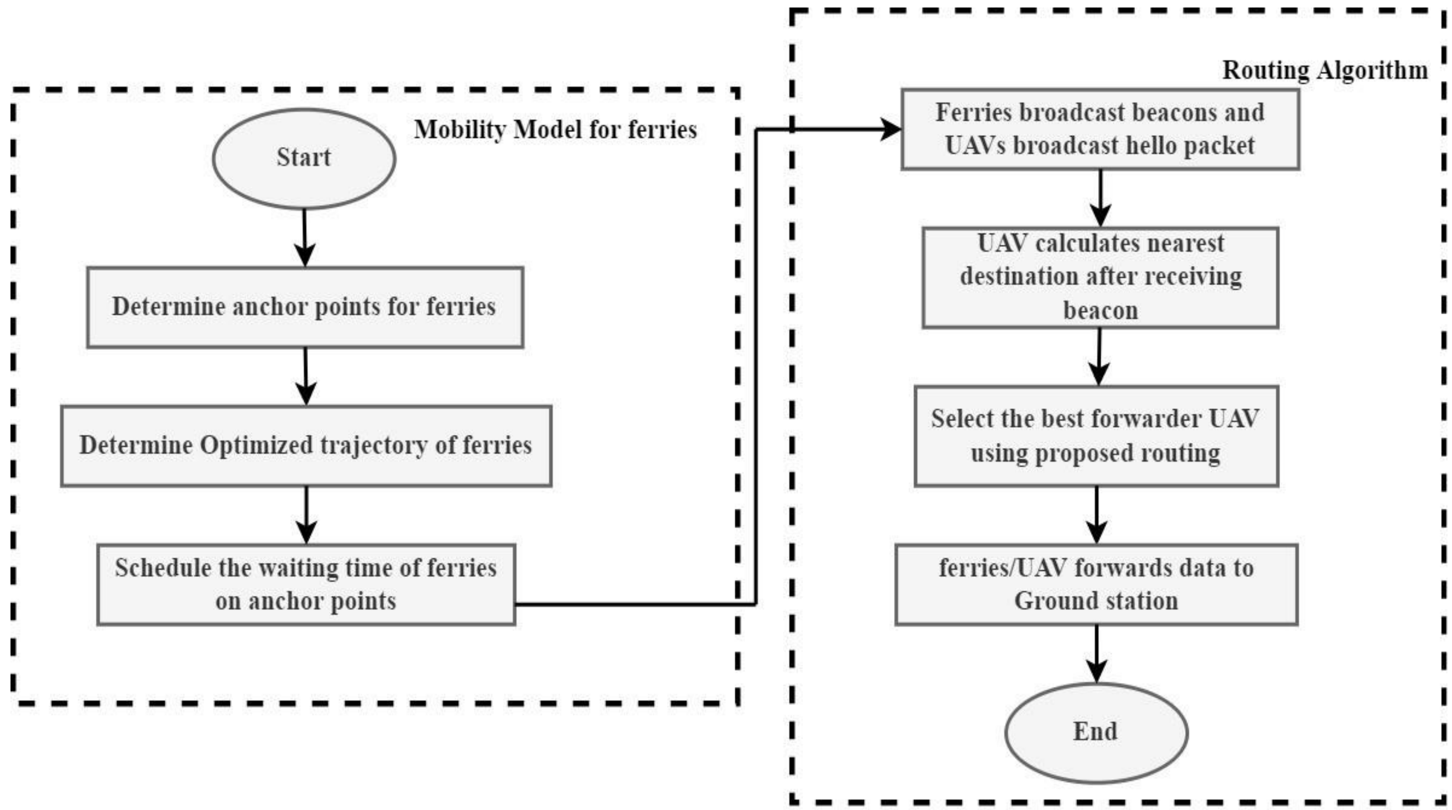


Figure. 4.1: Methodology followed in FM-DT-GDR.

## 4.1 MOBILITY MODEL FOR FERRIES

The trajectory optimization of the ferry's route is an effective approach to increasing the performance of the sparse FANETs. Ferries can significantly increase the communication between the search UAVs and GS. In disaster scenarios, the control of UAV movement is not recommended as UAVs work in real-time activities like image and video recording in an unidentified disaster field. Hence, a mobility model for ferry UAVs has been proposed. To expand communication between GSs and UAVs and increase network efficiency, ferries are the primary means of data transmission method used.

Ferries move around the network gathering vital information from search UAVs, storing it, and sending it to the GS. To accomplish this, the ferry follows a planned, and optimal path while gathering data from the UAVs at the set anchor points. The following actions must be taken to determine the anchor position for a ferry:

### 4.1.1 Determine the ferry's anchor points

Ferry anchor points are calculated as follows:

i. **Calculation of center point of deployed field:**

The network is traversed by all search UAVs using the Gauss-Markov mobility model. Ferries acquire data from the UAVs by moving along a predefined optimized track and stopping at fixed anchor locations.

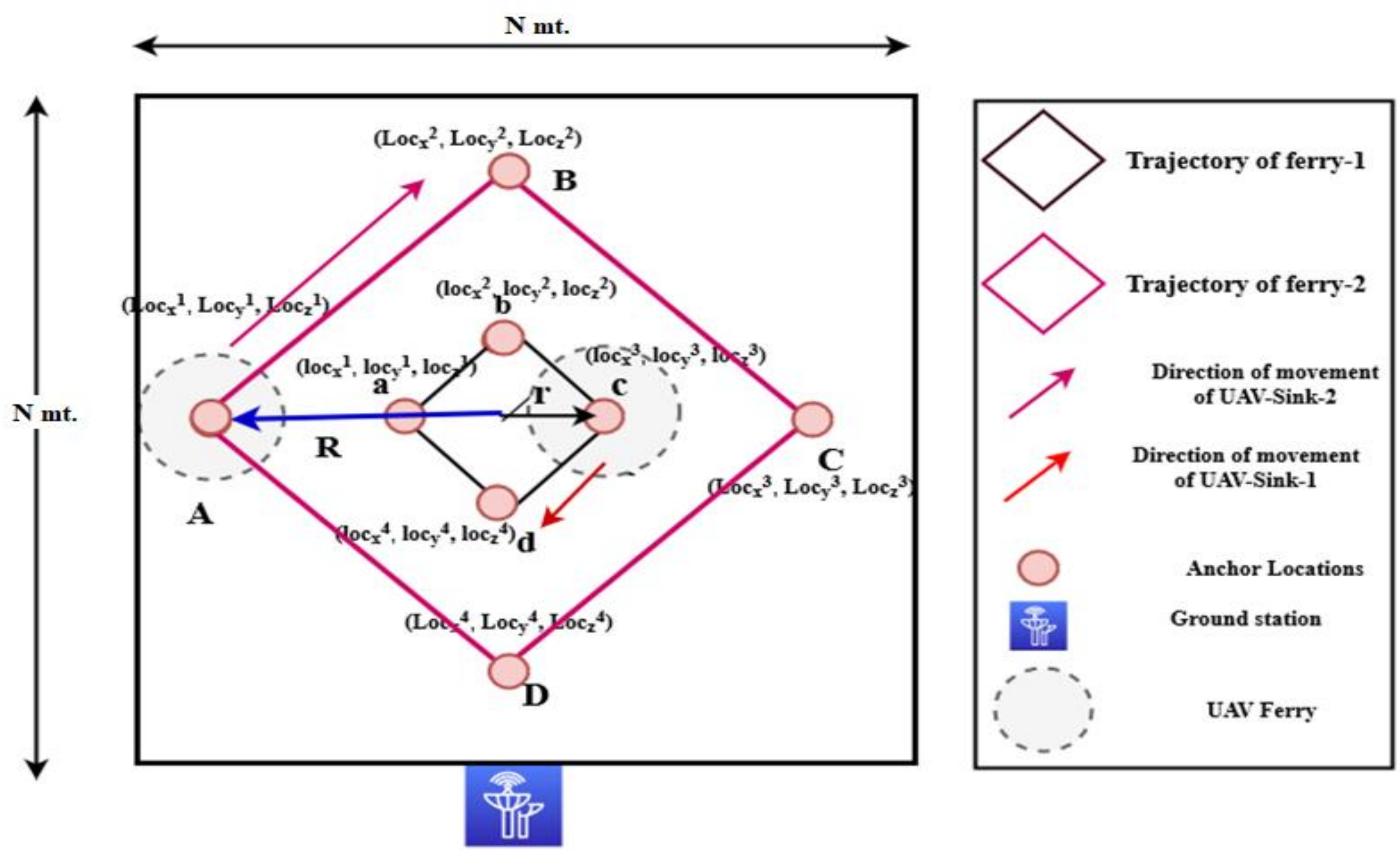


Figure. 4.2: Proposed mobility pattern.

The UAV ferry's anchor points must be distributed equally in the network, hence the ROI's center point O ($C_x$, $C_y$) is computed as follows:

$$C_x = \frac{N}{2}\ , C_y = \frac{N}{2} \qquad (1)$$

Figure 4.2 depicts the proposed ferry mobility pattern for gathering data from data-collecting UAVs. The z-axis value of the ferry is fixed.

**ii. Calculation of ferry anchor position**

Once the RoI center has been determined, the following formula is used to determine the locations of the four anchor points of both ferries:

**a. The anchor position calculation of Ferry-1:** The following formula can be used to determine the locations of the UAV ferry-1's four anchors (a, b, c, and d):

$$\mathrm{loc}_x^i = (C_r)\cos\left(\frac{2\pi}{a_p}(i+1)\right) + C_x\ ;\ \mathrm{loc}_y^i = (C_r)\sin\left(\frac{2\pi}{a_p}(i+1)\right) + C_y\ ;\ \mathrm{loc}_z^i = (C_r) \qquad (2)$$

Where, $C_r$ = communication range of ferry-1, i.e. 250 m. from the center point; $a_p$ = the number of anchor positions and i = 1, 2, … $a_p$.

**b. The anchor position calculation of Ferry-2:**

The following formula can be used to calculate the locations of the UAV ferry-2's four anchors (A, B, C, and D):

$$\mathrm{Loc}_x^i = (3 \times C_r)\cos\left(\frac{2\pi}{a_p}(i+1)\right) + C_x \; ; \; \mathrm{Loc}_y^i = (3 \times C_r)\sin\left(\frac{2\pi}{a_p}(i+1)\right) + C_y \; ; \; \mathrm{Loc}_z^i = (C_r) \qquad (3)$$

A total of two ferries were brought into use to collect data from search UAVs in this work. There are four separate anchoring points for every ferry. As the service area expands, we need to add more ferries to our network. The different trajectories have been calculated for ferry-1 and ferry-2 using formulas 2 and 3 respectively.

For both UAVs and ferries, the same transmission range is taken into account. The ferries are arranged in such a way that the geographic coverage area of both ferries does not overlap and can cover the maximum number of UAVs. The value of r corresponding to the ferry range is fixed, and the value of R (see Figure 4.2) is computed as follows:

$$R = (250+250+250) = 750 \text{ m. from O for UAV- ferry-2} \qquad (4)$$

Therefore, the ferry can collect data from the largest number of search UAVs by covering the largest disaster areas without overlapping of ferry's area coverage. Taking into account the 180-degree travel difference between the ferries, the searching UAVs can quickly forward data to at least one available ferry.

### 4.1.2 Determine the optimized trajectory of the ferry

Once the anchor positions for both ferries have been determined, the next step is to determine an optimized route from one to the other anchor point. Areas of application like rescue operations and disaster monitoring demand prompt information about disaster areas. For the ferry to reach the GS range and send the data as fast as possible, the shortest route between each anchor position is created. In comparison to the originally developed PPRZM route model [51], the suggested mobility pattern covers all anchor points at short distances.

Calculations to find the shortest path from one to another anchor points computed and compared below.

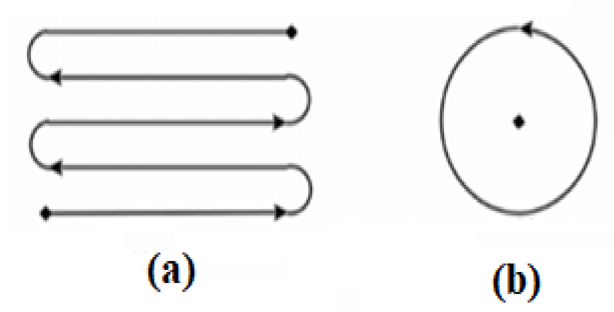


Figure. 4.3: PPRZM path schemes: (a) Scan, (b) Stay-At.

**i.** The total distance traveled by ferry in one cycle of the network is calculated as follows:

**a.** Distance traveled by ferry in the Stay-At mobility pattern = $2\pi r = 2\pi * 1000 = 6280mt.$

Where,

Radius of circle $= 1000$ mt.

**b.** Distance traveled by ferry in the Scan mobility pattern = $(4 * 2000 + \Delta)\ mt.$

Where $\Delta$ = distance of the curve.

**c.** Using the proposed diamond-shaped route, the total distance covered by a ferry to complete one cycle or a round of the network is:

- Distance from A to B=$\sqrt{750^2 + 750^2}$ = $1060.6\ mt.$
  - Ferry-2's net displacement in trajectory 1 (A-B-C-D)= $4 \times\ 1060.6\ mt. = 4242.4\ mt.$
- Distance from a to b= $\sqrt{250^2 + 250^2}$ = $353.5\ mt.$

Ferry-1's net displacement during the covering trajectory is 2. (a-b-c-d) = 4 $\times\ 353.5 = 1414\ mt.$

Total distance traveled by both the ferries, traversing on trajectory -1 and trajectory -2 = $5656.4\ mt.$

Hence, the calculations above demonstrate that the proposed movement pattern can be used to complete the network cycle by allowing the ferry to travel shorter distances. Hence, the proposed movement pattern assures faster network coverage as these ferries travel shorter distances to deliver data to the GS in lesser time. In this work, the same communication range has been considered for all the nodes in the network i.e.250 mt. The anchor location of the ferries is selected in such a manner that the four corners of the square are at the central edge of the deployed field.

Ferry-1 goes through a small orbit and Ferry-2 goes through a large orbit to collect the data from search UAVs. The ferry travels in each lane clockwise at different speeds. The designed mobility pattern covers half of the network through at least one ferry at a time. Due to the different perimeters of the two orbits, the two ferries traverse at different speeds and reach their respective anchor points simultaneously which are 180 degrees apart from each other. The change in speed helps the ferries synchronize their movements, allowing the ferries to arrive at their respective anchor places at the same moment, separated by a 180-degree angle. Ferry-1 traverses exactly at a distance of 250 mt. from the center of the operational area. Therefore, ferry-1 can cover a total area of 500 mt at a time on one side of the network and 500 mt. at a different side of the network due to mobility. Whereas, ferry-2 is located 500+250=750 mt. away from the center. So, the area which is not covered by ferry-1 is covered by ferry-2. Therefore, each ferry covers 1000 $mt^2$ of operating area which is not covered by any other ferries.

#### 4.1.3 Schedule the ferry wait times at the anchor points

Every ferry waits for a set time to get information from the search UAVs. The ferries proceed at a 180-degree difference from one another due to the predetermined wait time. The total time needed to finish the proposed orbit includes waiting time at each anchor point and traversal time:

$$T_{cycle}=t_{traverse}+ t_{waiting} \quad (5)$$

Where,

$T_{traverse}$: Total time required to travel on the proposed trajectory.

$T_{waiting}$: Total wait time at four anchor points.

The calculation of the total number of ferries required to assign in the operational field:

$$\text{Total number of ferries required for operation (n)} = \frac{A}{AF} \qquad (6)$$

Where,

A= operational area in $mt^2$ and AF= Area covered by a single ferry is fixed i.e 1000 $mt^2$.

At a time one ferry is covering a 1000 $m^2$ area. In the simulation, we have considered the total area of 2000×2000×500 $m^3$. Therefore, we are using a total of two ferries in our work.

## 4.2 ROUTING PROTOCOL

FM-DT-GDR is a geographic or position-based routing protocol that utilizes a delay-tolerant network (DTN) concept to send important data to the GS and is intended specifically for sparse FANETs. The efficient forwarder node is chosed based on the search UAVs' current range, direction, and speed. By carefully choosing the forward node from the neighbor list, FM-DT-GDR avoids the downsides of this greedy technique ("local minima"). The following steps are part of the suggested routing plan:

### 4.2.1 Ferries broadcast beacons

The ferry begins its journey by traveling along a predetermined path from one anchor point to the next. The ferry keeps on broadcasting beacon messages. The search UAVs are informed of the location of the ferries' subsequent anchor using beacon messages. Within the ferry's range, UAVs pick up beacon messages. The following fields are included in the beacon packet: waiting time, next location of the ferry, and ferry id.

### 4.2.2 Determination of neighbors

"Hello" packets are used in the network to identify nearby nodes. The UAV sends "Hello" packets by including location data. The neighbor's table is updated by the UAV that receives the "Hello" message. As a result, the "Hello" packet is used to determine the neighbor's coordinates, and the node adds a new item to the neighbor table (NT). The "Hello" packet field contains the following information: Current position, Previous position, Current speed, and Node_id.

### 4.2.3 Closest destination selection after receiving the Beacon

Once a beacon packet from the ferry is received, by comparing the distance between the GS location and the ferry's anchor point location from the current node, the closest target is determined using the formula below:

$$\sqrt{\left(x_j - x_F\right)^2 + \left(y_j - y_F\right)^2 + \left(z_j - z_F\right)^2} > \sqrt{(x_i - x_{GS})^2 + (y_i - y_{GS})^2 + (z_i - z_{GS})^2} \quad (7)$$

Where,

$(x_F,y_F,z_F)$: Coordinates of anchor position of ferry;

$(x_{GS},y_{GS},z_{GS})$: Coordinates of GS.

$(x_i,y_i,z_i)$: Coordinates of UAV.

The search node selects the closest destination to send the data packet using the formula (7).

### 4.2.4 Proposed routing strategy to find the efficient forwarder node

Every UAV continuously collects data and tries to send packets to the GS. The forwarder UAV is in charge of routing the received data, so choosing the efficient forwarder UAV to forward the packet to the ferry or GS is the most significant task.

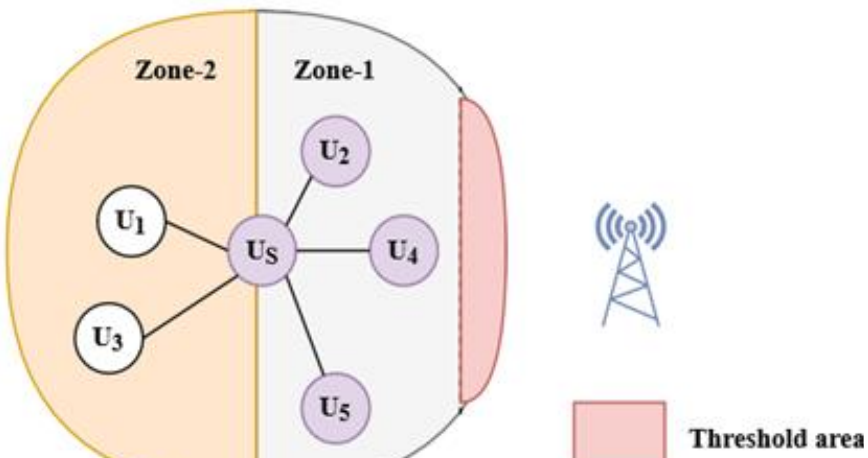


Figure. 4.4: Zone categorization and boundary node discard scheme.

Two zones are taken into account by the proposed routing protocol: Zone- 1 and Zone- 2.

Every UAV consists of two zones within its transmission area i.e. Zone-1 and Zone-2. Zone-1 consists of UAVs that are near the destination when compared to the source nodes. Comparatively to the source UAV and nodes in Zone- 1, the Zone- 2 node is further away from the destination. Figure 4.4 shows Zones-1 and 2 are determined by the source node's location. The search UAV zone can be determined through formula 8:

$$\begin{cases} d_{\mathrm{SD}}(\mathrm{t}) > d_{\mathrm{iD}}(\mathrm{t}) & \mathrm{Zone}-1 \\ d_{\mathrm{SD}}(\mathrm{t}) < d_{\mathrm{iD}}(\mathrm{t}) & \mathrm{Zone}-2 \end{cases} \tag{8}$$

Where,

$d_{\mathrm{SD}}(\mathrm{t})$= distance between the source and the destination at time t;

$d_{\mathrm{iD}}(\mathrm{t})$= distance between the UAV and the destination at time t;

The steps to select the efficient forwarder UAV are described below:

**i. Prediction of UAV direction**

UAV movements adhere to the laws of aerodynamics, in contrast to conventional random mobile nodes [45]. UAV’s direction from the destination is predicted using the UAV's past and present coordinates. Calculations are made to determine the distances between the destination and the candidate node's present and prior locations. It is anticipated that the following step on the neighbor node will find the candidate node that is moving toward the destination. Formula 9 determines the UAV's direction.

$$\vec{u} = \begin{cases} d_{\mathrm{ip}}(\mathrm{t}-1) > d_{\mathrm{ip}}(\mathrm{t}) & 1 \\ d_{\mathrm{ip}}(\mathrm{t}-1) < d_{\mathrm{ip}}(\mathrm{t}) & -1 \end{cases} \tag{9}$$

$$d_{ip}(t-1) > d_{ip}(t) = \sqrt{\left(x_p(t-1)-x_d\right)^2 + \left(y_p(t-1)-y_d\right)^2 + \left(z_p(t-1)-z_d\right)^2} > \sqrt{(x_i(t)-x_d)^2 + (y_i(t)-y_d)^2 + (z_i(t)-z_d)^2} = 1 \tag{10}$$

Where,

$(x_i(t), y_i(t), z_i(t))$: Search node's current position at time t.

$(x_p(t-1), y_p(t-1), z_p(t-1))$: Searching node's previous position at time (t-1).

$(x_d, y_d, z_d)$: Destination (ferry or GS) location.

$d_{ip}(t)$: distance of the UAV at time t from the destination.

$d_{ip}(t-1)$: UAV's distance from the destination at (t-1) time.

A value of 1 is assigned to u if the distance between the destination, and the UAV reduces. But if the distance increases with time, u receives the value -1. If the distance to the target stays constant over time, $\vec{u}$ receives 0 (refer to equation 9).

**ii. Calculation of minimum traveling time:**

The Zone- 1 nodes that are present and are farther away from the source node than 80% of the transmission range are disregarded.

$$d_{\mathrm{si}} = \begin{cases} d_{\mathrm{si}} > 0.8C_{\mathrm{r}} & -1 \\ \text{else} & 1 \end{cases} \quad (11)$$

Due to the nodes' quick speed, there is a larger chance of disconnection or packet loss when a node is farther than 0.8 $C_r$ from the source node.

Figure 4.4 shows the Zone categorization and boundary node discard scheme. As the source node travels toward the opposite direction of the destination, and the neighbor nodes that are present in Zone-1 but travel toward the destination, then the relative speed between the neighbor and source nodes increases. Therefore, the increased relative speed also increases the possibility of packet loss. Hence, by eliminating nodes with a distance higher than 0.8Cr from the source node, it is possible to prevent the effect of raising the relative speed between the source and neighbor nodes. Therefore, the node that is located more than 0.8 Cr away from the source node, and when the direction of the source and neighbor node is opposite is discarded.

The next step is to determine UAVs that are heading in the desired direction, and take less time to arrive at the chosen destination. To determine how long it will take each neighbor node to arrive at the destination, the source UAV must first calculate the distance and speed.

**a.** ***Distance value:*** The UAV’s distance from the destination is represented by the distance value $J_t(d)$.

$$J_t(d) = \left(\frac{|x_i - x_d|}{A}\right) \quad (12)$$

Where,

A : Maximum operational area (x/y-axis); $X_d$ : location of the destination; $X_i$ : current position of candidate UAV; $|x_i - x_d|$= the distance between the selected destination, and the candidate UAV.

***b. Speed value:*** The speed value $J_t(v)$ is the speed of the UAV.

$$J_t(v) = \left(\frac{v_c}{v_{max}}\right) \tag{13}$$

Where,

$v_c$: Current speed of UAV;

$v_{max}$ : Maximum speed of the node that is constant i.e 30 m/sec.

$T_{travel}$ of each neighbor UAV is calculated using equation 14 as below:

$$T_{travel} = \left[\left(\frac{J_t(d)}{J_t(v)}\right)\right] \tag{14}$$

Where,

$T_{travel}$ = Time that the candidate node arrives at the chosen destination.

If $T_{travel}$ is equal to 0, the neighbor and the destination are connected. Each nearby node's $T_{travel}$ is calculated by the source UAV. If the source node determines that a node in Zone-1 has a minimal $T_{travel}$ value, it will simply send the data to that node. Equation 15 calculates the node with the lowest $T_{travel}$, which is denoted by $T_{travel\_min}$. The source node should prefer Zone-1 above Zone-2 because Zone-1 nodes are near the destination.

When the source identifies the node in Zone-2 with the value $T_{travel\_min}$, the source node searches for more candidates in Zone-1 by locating the value in Zone-2 that is closest to $T_{travel\_min}$. When the source identifies more candidates, priority is given to Zone-2 nodes that are closest to the destination. A constant threshold is used to find more candidates. If the difference between the $T_{travel\_min}$ value and the $T_{travel\_i\_s}$ of additional nearby nodes is less than or equal to the threshold value, these UAVs are also considered candidate nodes.

The $T_{travel\_min}$ value is subjected to the threshold to gather all potential candidates (use equation 16). The number of candidates rises once the threshold is applied.

$$T_{travel\_min} = \min (T_{travel\_i}) \tag{15}$$

$$|T_{travel\_min} - T_{travel\_i\_s}| \leq \Delta \tag{16}$$

$$n = \text{count (U)} \tag{17}$$

Where,

$\Delta$ =threshold vale; $T_{travel\_i}$ = $T_{travel}$ value; $T_{travel\_min}$ = UAV with lowest $T_{travel}$ value.

Table 4.1: α value and its deciding factor.

| Value of $\alpha$ | Deciding factor |
|---|---|
| 0.5 | Candidates from both zones |
| 1 | Candidates from Zone- 2 |

$$P_{forward} = \left( \frac{\alpha \times J_t(d)}{\left[(1-\alpha) \times \left(\frac{v_c}{v_{max}}\right)\right] + 1} \right) \tag{18}$$

Out of the nodes received after applying the threshold value, formula 17 is used to determine the suitable forwarder UAV. The values and determining factors are displayed in Table 5.1.

To locate a suitable forwarding node, formula 18 is given a weight ($P_{forward}$). If all applicants are from Zone- 2, then is set to 1. Otherwise, the forwarder node from Zone- 1 is chosen by setting it to 0.5 if the candidates come from both zones. The zones are used to apply the value to formula 18 and get the minimal $P_{forward}$.

The value of alpha is responsible for changing the deciding factor. If the candidates belong to both Zones then node from the Zone 2 having the lowest $T_{travel}$ value should be chosen for routing of the data. Therefore the value of alpha is set to 0.5. If the candidates belong to only Zones-2 then nodes from Zone 2 having the minimum distance from the destination should be chosen for routing of the data. Therefore the value of alpha is set to 1.

The procedure of packet type checking is demonstrated by Algorithm-4.1. If a beacon packet is received, the source node determines the closest destination from the current node. "Hello" is the packet type that causes the node to update the neighbor table.

Algorithm 4.1: Check packet type.

Algorithm 4.1: Check packet type

**Input:** *hello_Packet, beacon_Packet, data_Packet.*

**Output:** *Packet type checked*

1. ***start***
2. *Packet has Received*
3. ***if** (packet_type = hello_Packet)*
4. *get neighbor_currentPosition, PreviousPosition, currentSpeed _from_hello_Packet*
5. *Update NT //update neighbor table*
6. ***else if** (packet_type = beacon_Packet)*
7. *go to algorithm 4.2*
8. ***else if** (packet_type = data_Packet)*
9. *go to algorithm 4.3 and algorithm 4.4*

*10* ***else***

*11.* *store and carry mode*

*12.* ***end if***

*13* ***end***

Algorithm 4.2: Check the nearest destination.

> Algorithm 4.2: Check the nearest destination
>
> **Input:** *US =Searching UAV; F=Ferry, GS=Ground station, $\delta$ (US, F) = distance between ferry, and UAV; $\delta$ (US, GS) = distance between ground station and UAV.*
>
> **Output:** *Nearest destination from the source node.*
>
> 1. ***start***
> 2. ***if** $\delta$ (US, F) < $\delta$ (US, GS)*
> 3. *forward the data to F*
> 4. ***else***
> 5. *send data to GS*
> 6. ***end if***
> 7. ***end***

Algorithm-4.2 is used to check the nearest destination from the current node.

Algorithm-4.3 is used to determine the future direction of the source node's one-hop neighbors. In addition, Zone- 1's boundary nodes are eliminated. The search node simply changes to store and carry mode if it cannot locate the neighbor traveling to the destination.

Algorithm 4.3. Check the future direction and discard boundary nodes.

Algorithm 4.3. Check the future direction and discard boundary nodes

Input *$(n(U_i))$= Number of neighbors; US =Searching UAV; $U_i$ =1-hop neighbor UAV; -1= node travelling in opposite direction to destination, $d_{si}$ = distance between sender node and neighbor node; $0.8C_r$ = 80% communication range of node.*

**Output:** *determine the future direction of the node and discard boundary nodes.*

1. ***start***
2. ***for*** *i → 1 to $U_i$ do*
3. ***if*** *$(n(U_i)!=0)$ // neighbor node exists*
4. *check the future direction $\forall U_i$ and US*
5. ***else***
6. *store and carry*
7. ***end if***

*Discard boundary nodes*

1. ***if*** *(Us= -1 && $d_{si} > 0.8C_r$ && Zone-1)*
2. *discard boundary nodes*
3. ***else***
4. ***end if***
5. ***end for***
6. ***end***

The border nodes are those that migrate toward the destination but are more than 80% of the source node's transmission range away while the source UAV traverses in the opposite direction. The UAV's past locations are used to forecast its future location. Formula 14 is used to determine how long it will take for each neighbor to go from their current location to their destination if the source node and its neighbors are traveling in that direction.

The efficient forwarder node calculating process is shown in Algorithm 4.4. If source and neighbor nodes are moving towards the destination, then $T_{travel,}$ and $T_{travel\_s}$ are calculated. Only $T_{travel,}$ is calculated if the source UAV travels in the opposite direction of the destination. Otherwise, Up until it locates a suitable forwarding node, the source node will keep storing data. To determine which node travels to the destination in the shortest amount of time, $T_{travel\ s}$ and $T_{travel}$ are compared.

Algorithm 4.4. Proposed FM-DT-GDR protocol executed by searching UAVs to deliver data to the ferry or ground station.

Algorithm 4.4. Proposed FM-DT-GDR protocol executed by searching UAVs to deliver data to the ferry or ground station.

Input: *US=Source node; F=Ferry; GS=Ground station;* $U_i$ *=1-hop neighbor UAV; -1=node moving in opposite direction of destination;* $(P_d)$*= data packet;* $J_t(d)$*= distance cost;* $J_t(v)$ *=speed cost;* $d_{max}$*= maximum of x/y axis;* $V_{max}$*=.maximum speed;* $V_c$*=current speed;* $T_{travel}$*=travel time a neighbor node takes to arrive destination;*

*$T_{travel\_min}$ =minimum traveling time to reach destination; $|x_i - x_d|$=distance between destination (d) and neighbor node (i); Δ = threshold value; U= candidate nodes obtained after applying threshold; n= the number of candidates found after applying a threshold; $U_{travel\_min}$ =Node with minimum travel time; $T_{travel\_min}(U_i)$ = node after applying threshold that takes minimum travel time; $d(U_i)$=node located at the shortest distance from the destination; $T_{travel\_i\_s}$= travel time of source node and neighbor nodes to arrive at destination.*

***Output:*** *Data forwarding from US to F or GS.*

1. ***start***

    ***Part-1: Traveling time computation conditions.***

2. ***if*** *((US → 1) && ($U_i$ →1))* *//if neighbor node and source node moving towards destination*
3. *compute $T_{travel\_i}$, $T_{travel\_s}$*
4. ***else if*** *((US→ -1) && ($U_i$→1))*
5. *compute $T_{travel\_i}$*
6. ***else***
7. *store and carry*
8. ***end if***

***Part-2: Forwarder node selection***

9. ***for*** *i → 1 to $n(U_i)$ do*
10. *compute $J_t(d)$=$|x_i - x_d|$*

11. $T_{travel\_min} = \left(\frac{J_t(d)}{V_c}\right)$

12. ***end for***

13. $T_{travel\_min}$ *=min (*$T_{travel\_i}$*)*

14. ***if*** *((*$T_{travel\_s} > T_{travel\_min}$*) && ({*$U_{travel\_min}$ *}∈(Zone1 || both Zones )))*

*// Select* $U_{travel\_min}$ *∈Zone1 with* $T_{travel\_min}$

15. *Forward the packet to* $U_{travel\_min}$ *in Zone-1*

16. ***else if*** *((*$T_{travel\_s} > T_{travel\_min}$*) && (*$U_{travel\_min}$ *∈Zone2)*

17. $|T_{travel\_min} - T_{travel\_i\_s}| \leq \Delta$

18. *n= count (U)*

19. ***if*** *(n≥1 && (U ∈Zone-2 || US))*

20. $P_d$ *(d(*$U_i$*)) // forward packets to a neighboring node located at the shortest distance from the destination*

21. ***else if*** *(n≥ 1 && U ∈US || Zone-1 || both Zones)*

22. $P_d$ *(* $T_{travel\_min}$ *(*$U_i$*)) // forward packets to a neighbor node located in Zone-1 that takes the minimum travel time or keep storing packets if the source node is taking the minimum travel time*

23. ***else***

24. $P_d$ *(*$U_{travel\_min}$*) // forward the packet to the node that takes the minimum travel time (calculated from step 12))*

25. ***end if***

26. ***els*e**

*27.* *store and carry*

*28.* ***end if***

**Part 3: Destination in range of UAV**

*29.* ***if*** *(US is in the range of F OR GS)*

*30.* $P_d$ *from US* → *F OR* $P_d$ *from US* → *GS*

*31*. ***else***

*32.* *go to algorithm 4.1*

*33.****end if***

*34.* ***end***

A threshold is applied to the value, if a node with $T_{travel\_min}$ is in Zone-2, and all candidates who meet the criteria are then located. The node that is closest to the destination is chosen as the forwarder node if more candidates are detected in Zone- 2 alone.

In case the candidate UAVs are located in both zones, the forwarder node is chosen as the node with the lowest $T_{travel}$ that is situated in Zone-1. If a node with $T_{travel\_min}$ is in Zone- 2, a threshold is applied to the value, and all eligible candidates are then found.

### 4.2.5 Ferries/UAV Forwards Data to the GS

When the network cycle is complete, the ferry sends the collected data to the GS. Furthermore, when it is in range, the search node sends the data immediately to the GS.

## 4.3 CHAPTER SUMMARY

This chapter provides the detail of the proposed routing protocol i.e a novel FM-DT-GDR that routes the data from search nodes to the GS. The suggested routing method is created for sparse FANETs and is intended for use in applications like disaster recovery applications. The first approach is a ferries mobility model that gives the ferries a fixed efficient path to collect information from UAVs. Routing is the second approach. It starts by figuring out a neighbor's direction and then ranks them according to how quickly they get to the chosen destination. The efficient forwarder node is the one that travels to the chosen destination in the shortest amount of time. Zones-1 and Zones-2 make up the network's two zones. Zone-1 is always preferable as the nodes are already close to the destination. In order to identify more possible nodes from Zone-1, a threshold value is used. If a neighbor cannot be discovered or travels in the opposite direction from the destination, then the source enters SCF mode until it locates an appropriate forwarder node.

# CHAPTER 5

# RESULTS AND DISCUSSION

The simulation of ferry mobility-based direction and time-aware greedy delay-tolerant routing (FM-DT-GDR) protocol is performed on Network Simulator (NS-3.25). The work of the proposed FM-DT-GDR is shown in Chapter 4. This protocol is proposed for efficient routing in sparse Flying Ad-Hoc Networks (FANETs).

This Chapter shows the outcome of the FM-DT-GDR protocol after simulation. We compared the network performance of the FM-DT-GDR protocol with LADTR, LAROD, epidemic routing, and Spray-and-Wait (S&W). Packet delivery rate (PDR), routing overhead (RO), and end-to-end delay (ETED) is calculated to find out the efficiency of FM-DT-GDR.

## 5.1 SIMULATION SETTINGS

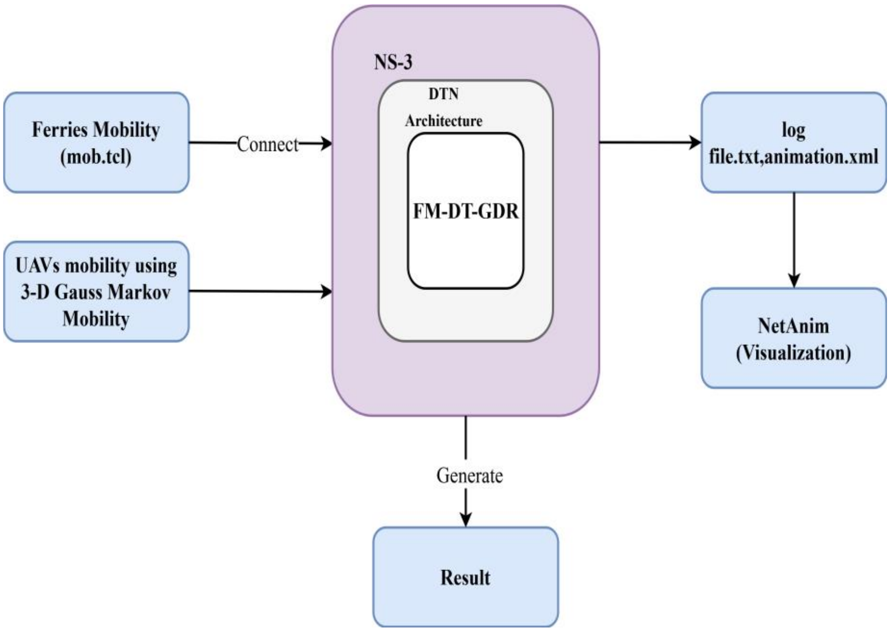


Figure 5.1: Overall Simulation Process.

Network Simulator (NS) 3.25 is used to simulate FM-DT-DDR. An Intel Core i7 processor, 32GB of RAM, and Ubuntu 16.10 Enterprise Edition (64-bit) were used to execute the simulation. Table 5.1 displays the values of the simulation parameters.

**Table 5.1:** Simulation settings.

| **Parameters** | **Value** |
|---|---|
| Network Simulator | NS-3.25 |
| Simulation Duration | 2700 s |

| | |
|---|---|
| Simulation area | 2000×2000×500 $m^3$ |
| Altitude of ferries | 250 m.(fixed) |
| Network Type | Wireless ad-hoc network |
| Communication range | 250 m. |
| Wifi-standard and frequency | IEEE 802.11n for ferry UAVs, IEEE 802.11b for searching UAVs |
| Message size | 20-100 KB(20 KB by default size) |
| Buffer size | 10-30 MB(20 MB by default size) |
| Number of ground station | 1 |
| Number of searching/ferry nodes | 8/2, 13/2,18/2,23/2 (default),28/2 |
| Routing Protocol | FM-DT-GDR, LADTR, LAROD, Epidemic, Spray, and Wait |
| Mobility of searching UAVs | Gauss-Markov mobility model. |
| Mobility of ferries | Proposed predefined mobility |
| Average speed of searching UAV | 20 m/sec |
| hello message interval | 1 message/sec |

A total area of 2000×2000×500 $mt^3$ has been considered for simulation [64]. Ten UAVs are used in the first set of simulations; two of them are ferry UAVs, while the other eight are search UAVs. The selection of the number of ferry nodes has been computed using formula 6 for the sparse network. After that, the number of UAVs in the network increased to 30 UAVs, where two UAVs are ferry UAVs and the left twenty-eight nodes are search UAVs. Ferries collect the data from searching nodes and forward the same to GS. It is assumed that the searching UAV is outside the GS radio transmission area as searching UAVs keep on moving in the large geographic area to capture the information. During the simulation, the searching UAV traverses using the Guess Markov mobility model (GMM) [22] at an average speed of 20 m/s. The GMM is considered for the mobility of searching nodes because nodes in the gauss Markov mobility model obey the law of aerodynamics [10].

For wireless communication, we employ the IEEE 802.11n and IEEE 802.11b wireless technologies. Searching UAVs utilize IEEE 802.11b. The highest bandwidth offered by IEEE 802.11 b is 11 Mbps, which is adequate for messages up to 100 KB in size [65]. The ferry UAVs use IEEE 802.11n for high-bandwidth communication suitable for large data transmission to GS [65, 68]. The performance of the network has been calculated using a varying number of UAVs, message size, speed, and buffer size. The visualization of the output of the simulation is shown in Figure 5.2. In the output, it can be seen that two ferries were utilized to gather the data from search UAVs in the deployed area.


Figure 5.2: Simulation output in NS-3.

## 5.2 RESULTS AND DISCUSSION

Various experiments with different parameters have been performed on the simulator. The experimental results are described in detail below:

### 5.2.1 Varying- UAV Number

The simulation uses different numbers of UAVs for comparing the performance of the FM-DT-GDR in terms of PDR, RO, and EED against LAROD, LADTR, Epidemic, and S&W routing. The UAV speed ranges between 10 m/s to 30 m/s, with a buffer size of 20 MB, and a message size of 20 kB. There will always be two ferries available, while the number of UAVs increases. Figure 5.3 illustrates the efficiency of FM-DT-GDR for delivering packets against protocols LAROD, LADTR, Epidemic, and Spray-and-Wait. The PDR was calculated for sending messages using different numbers of search UAVs.

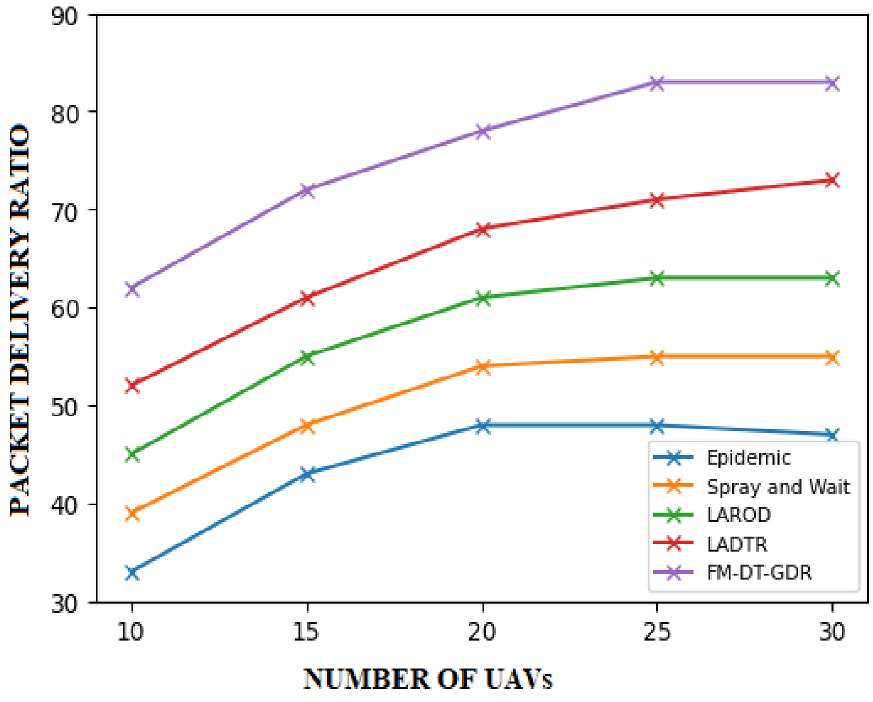


Figure 5.3: Packet delivery ratio vs. Number of UAVs.

In comparison to other routing protocols, FM-DT-GDR depicts higher PDR with increasing search UAVs because of the effective movement of ferries that collect data from anchor points. First, with 10 UAVs, FM-DT-DDR has a PDR of almost 62%. Following that, PDR rises as the network's nodes multiply. 83% PDR is achieved by FM-DT-

GDR on a total of 30 UAVs. While LADTR achieves a PDR of 73%. There are many causes for FM-DT-GDR's high PDR such as the effective utilization of the ferries to get information from the UAVs and determine the closest destination after receiving a beacon message from the ferry.

The PDR grows with the expansion of the network's nodes. The search UAV receives more UAVs for use as relay nodes, which accounts for the increase in PDR. When compared to another routing approach, epidemic routing uses flood-based forwarding, which lowers the PDR. In terms of packet delivery, LADTR performs better than LAROD, epidemic, and S&W routing.

The S&W and epidemic protocol uses flood-based forwarding, which results in a substantial buffer overflow and packet loss. The impact of increasing the number of UAVs in the EED is displayed in Figure 5.4.

LAROD, S&W, and Epidemic routing all have higher average EEDs than the average EED for FM-DT-GDR. The data gathered by the UAVs is sent to the GS with assistance from ferries in LADTR. LADTR is performing better than other previously suggested methods. The average EED decreases as UAV-UAV communication grows as the number of nodes rises.

By calculating the closest destination, making effective use of ferries, and using directional routing, FM-DT-GDR can reduce latency in comparison to other routing protocols.

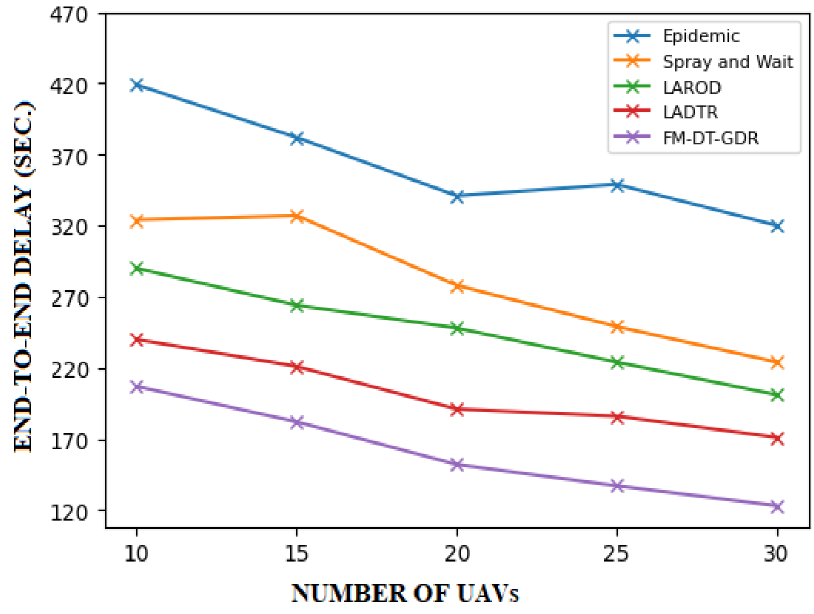


Figure 5.4: End-to-end delay vs. Number of UAVs.

Flooding is the method used by epidemic routing to send data to its destination. This adds more time to the delay. In the S&W protocol, the node must wait for the data to be correctly transmitted after spraying, which results in more delay.

The routing overhead for varying quantities of nodes is shown in Figure 5.5.

To cut down on routing overhead, FM-DT-GDR and LADTR took into account a single data copy transmission. The network's routing overhead and the number of control packets will both rise due to the number of UAVs increasing. In FM-DT-GDR, the route selection method is parameterized by both ferry mobility and fast position-based routing technique.

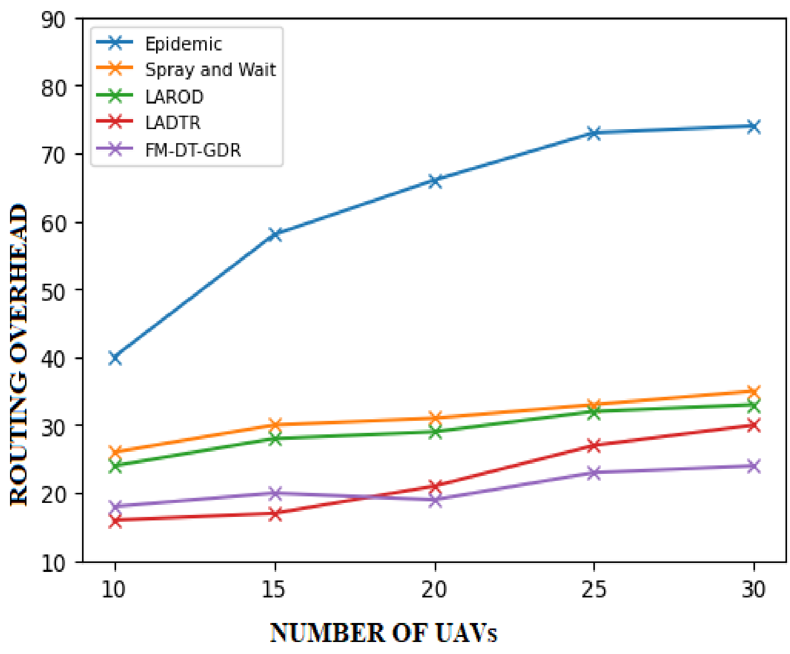


Figure 5.5: Routing overhead vs. Number of UAVs.

The network's routing overhead is increased by REEQ and REP, and as the number of UAVs rises, LADTR overhead over FM-DT-GDR also rises. Due to the ferry's excessive broadcasting of the beacon, FM-DT-GDR initially displays a higher overhead than LAROD. Comparing S&W, and LAROD to epidemic routing methods, they have lower routing overhead.

### 5.2.2 Varying -Message Size

The message size has a significant impact on how well the DTN environment performs. Delivery delays are exacerbated by heavy network traffic volumes. To evaluate how well networks with various message sizes perform, use 14 search UAVs and two ferry UAVs. The transmission range is 250 meters, the typical buffer size is 20 MB, and the UAV speed is 10 to 30 meters per second.

The message size ranges from 20 kB to 100 kB. Five messages per second are generated. Five routing algorithms for PDRs with various message sizes are compared in Figure 5.6. The findings unequivocally demonstrate that the PDR declines as the size of the message grow.

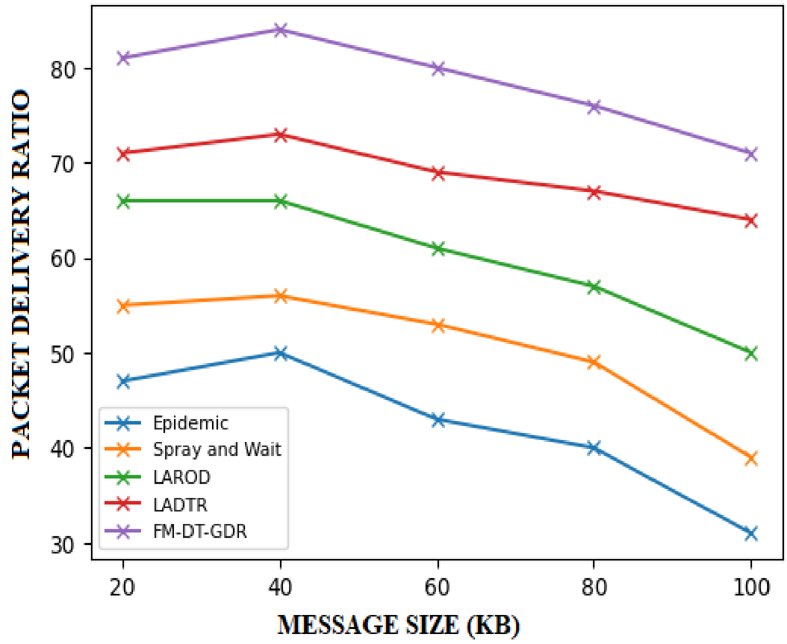


Figure 5.6. Packet delivery ratio vs. Message size (KB).

As the message size rises, the PDR of FM-DT-GDR drops from 81% to 71% LADTR gets up to 71% and LAROD achieves a delivery rate of 64%. The larger the message size, the more buffer space it occupies, resulting in a rapid decrease in PDR in epidemic routing. FM-DT-GDR uses the ferry efficiently, resulting in a high PDR and low EED. The ferry travels in an optimized orbit, collecting data from the UAVs and making the UAVs buffer-free. In addition, the buffer space can be quickly free by choosing the closest target. Therefore, the packet delivery gradually decreases in the case of FM-DT-GDR. Whereas, in the case of flooding-based schemes, the packet delivery ratio decreases quickly.

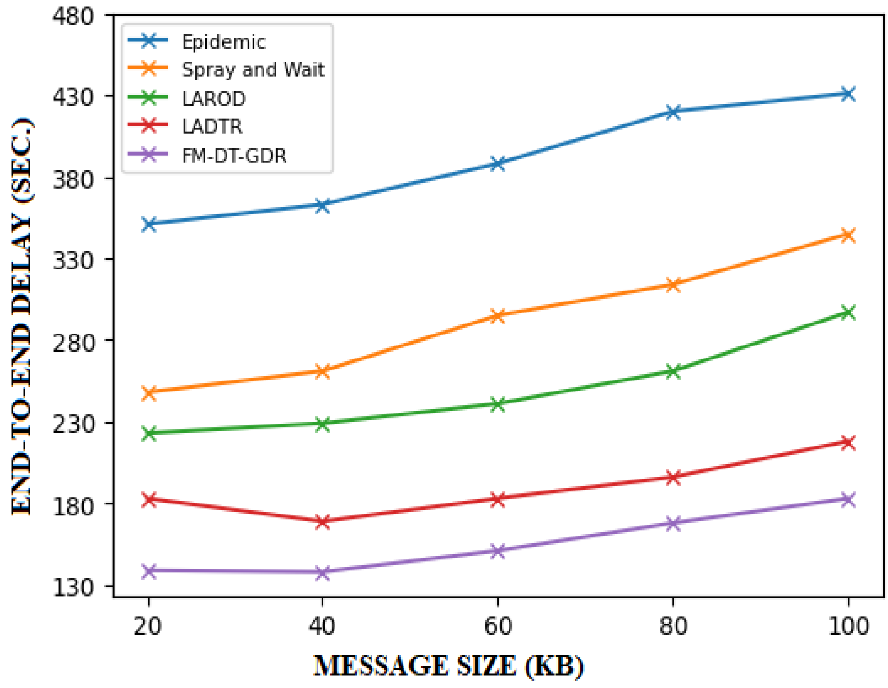


Figure 5.7. End-to-end delay vs. Message size (KB).

Figure 5.7 shows the effect of end-to-end delay in a network as the size of the message increases. Replication-based routing protocols like an epidemic and spray-and-wait routing protocols suffer from an increase in message size. FM-DT-GDR takes care of the direction and time that each node takes to arrive at the destination. Further, in FM-DT-GDR, ferries have been efficiently used to cover the maximum portion of the test bed in less time. In addition, Ferry keeps emptying the UAV's buffer, reducing the effect of increased message size.

Figure 5.8 demonstrates that the RO of FM-DT-GDR is lower than other routing protocols. Epidemic routing uses flood-based routing that highly increases the routing overhead. Whenever a packet is 20 kB in size, FM-DT-GDR's overhead is 23%; however, when the packet size is 100 kB, RO rises to 28%.

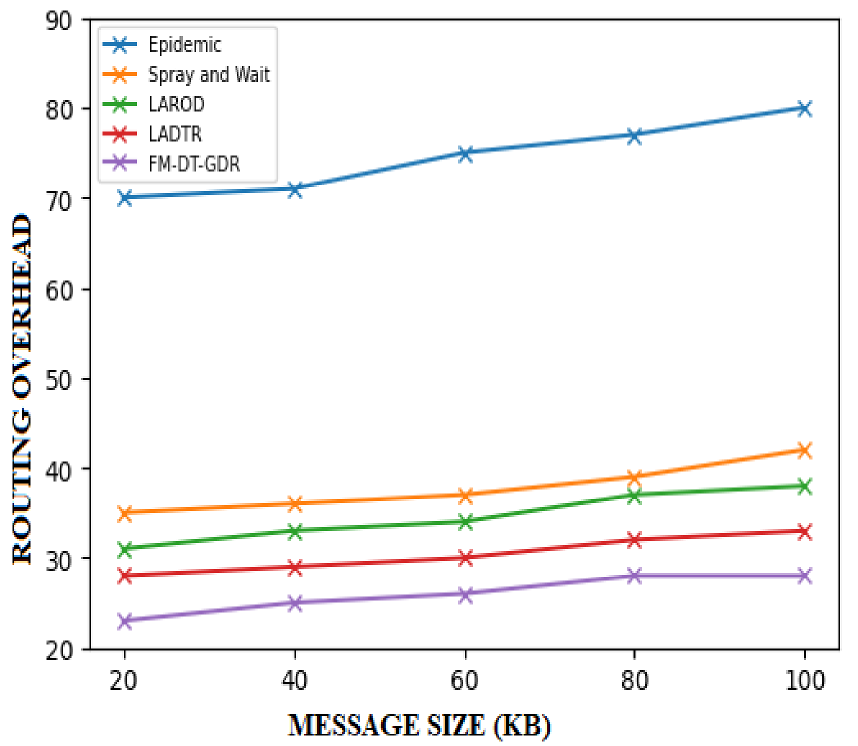


Figure 5.8. Routing overhead vs. Message size (KB).

As demonstrated in Figure 5.6, larger messages cause higher packet loss, which raises the routing overhead. Still, the single packet forwarding technique outperforms the flooding-based strategy. Flooding-based routing schemes fill their buffer with duplicate messages and then the increased size of messages makes the overhead higher.

### 5.2.3 Varying- Buffer Size

The effect of the larger buffer size on packet delivery ratio, end-to-end delay, and routing overhead performance is depicted in Figure 5.9-5.11.

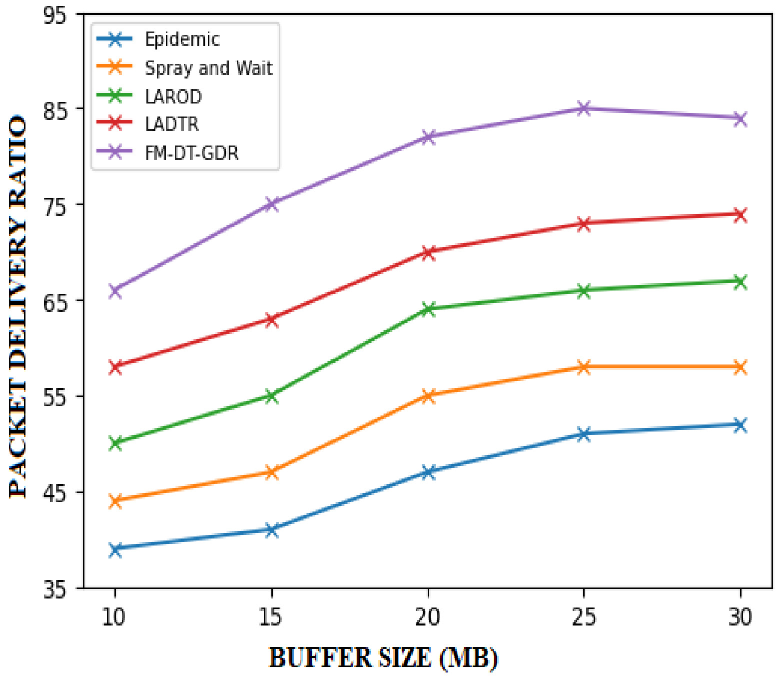


Figure 5.9. Packet delivery ratio vs. Buffer size (MB).

In comparison to LAROD, LADTR, Epidemic, and S&W routing protocols, the simulation results demonstrate that FM-DT-GDR produces greater PDR, as shown in Figure 5.9.

The single copy of the data packet that has a favorable impact on PDR is forwarded by FM-DT-GDR and LADTR. In addition, for efficient use of the ferry in FM-DT-GDR, the minimum PDR is 66% and the maximum PDR is 84% for buffer sizes of 10kB and 30kB. Epidemic routing sends data to its destination via a flood-based method, but the destination has buffer overflow issues.

Thus, epidemic routing results in the lowest PDR. Due to the usage of ferries, PDR in LADTR is improved compared to conventional routing techniques.

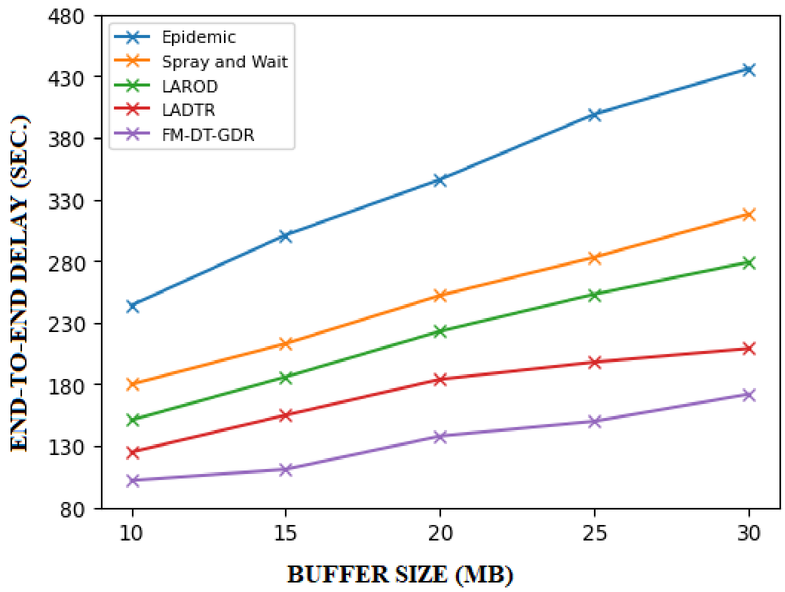


Figure 5.10. End-to-end delay vs. Buffer size (MB).

Increasing the buffer size will increase the storage capacity of the node and will increase packet delivery. As shown in Figure 5.10, when compared to other routing protocols, FM-DT-GDR offers reduced end-to-end latency. Epidemic routing has the maximum latency as it forwards multiple copies of the same message.

Therefore, the delay grows as the buffer size enlarges. EED in other routing protocols increases when the buffer size increases. Position-based routing and single copy forwarding are employed by FM-DT-GDR and LADTR. Furthermore, FM-DT-GDR gathers information from the search UAV and transmits it to the GS via effective use of the

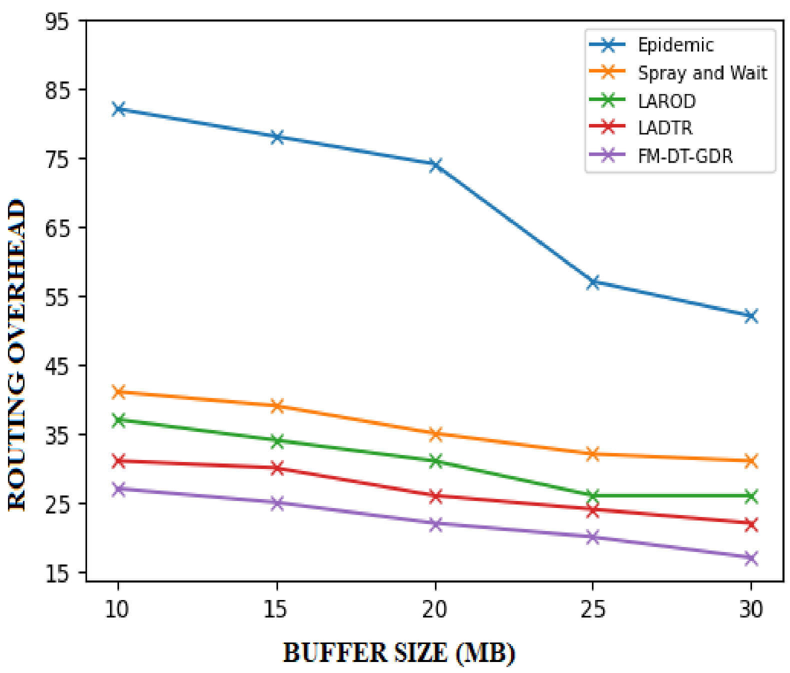


Figure 5.11. Routing overhead vs. Buffer size (MB).

ferry's trajectory.

Figure 5.11 depicts a performance graph of routing overhead versus buffer size for LAROD, LADTR, Epidemic, and Spray-and-Wait routing protocols. Network congestion reduces when the buffer size increase as packet delivery increases with the increase in buffer size. Epidemic routing depicts the maximum overhead as the data flooding-based routing strategy results in high overhead.

### 5.2.4 Varying UAVs Speed

FM-DT-GDR performance is assessed at various UAV speeds for LAROD, LADTR, Epidemic, and Spray-and-Wait routing algorithms.

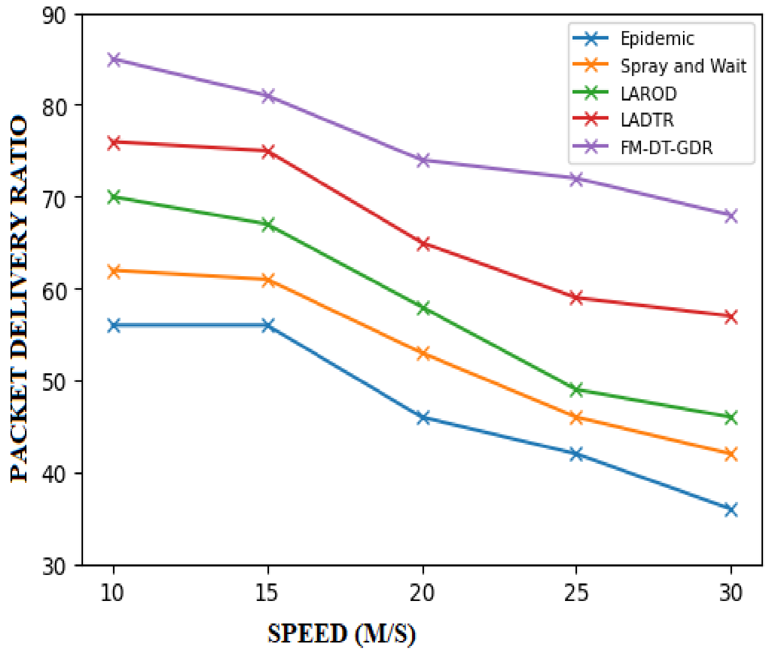


Figure 5.12: Packet delivery ratio vs. Speed (M/S).

Figure 5.12 depicts that the FM-DT-GDR maintains a packet delivery of at least nearly 68% and up to 85% at speeds of 10-30 m/s because of the high contact rate between search UAVs and ferries. As shown in a sparse FANET network, the duration of connectivity is quite short. The proposed scheme designed ferry's trajectories in such a way that one ferry can cover half of the deployed area at a time. The difference in movement between ferries is 180 degrees, allowing the UAV to access the ferry as much as possible. Routing based on epidemic flooding increases network congestion and increases network delay. The delay in epidemic routing diminishes as the node's speed rises. The end-to-end delay rate for FM-DT-GDR and all other routing protocols is displayed in Figure 5.13. The EED of FM-DT-GDR varies from 221 seconds to 179 seconds as the UAV speeds up. The EED initially decreases with an increase in UAV speed. However, after a certain point, when UAV speed reaches its maximum value, EED starts to increase since nodes lose contact with their neighbors as a result of high mobility.

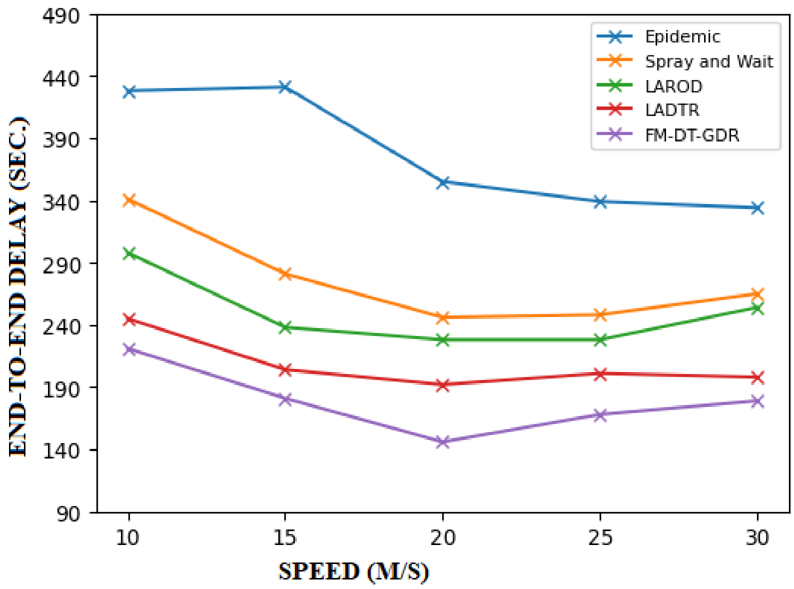


Figure 5.13. End-to-end delay vs. Speed (M/S).

In Figure 5.14, the epidemic routing shows maximum routing overhead at all different UAV speeds. The copy of the same data packet causes the routing overhead to be at its peak in flood-based routing strategy. The network link begins to break as the speed of the UAVs rises. Therefore, the PDR declines as a result. The low packet delivery

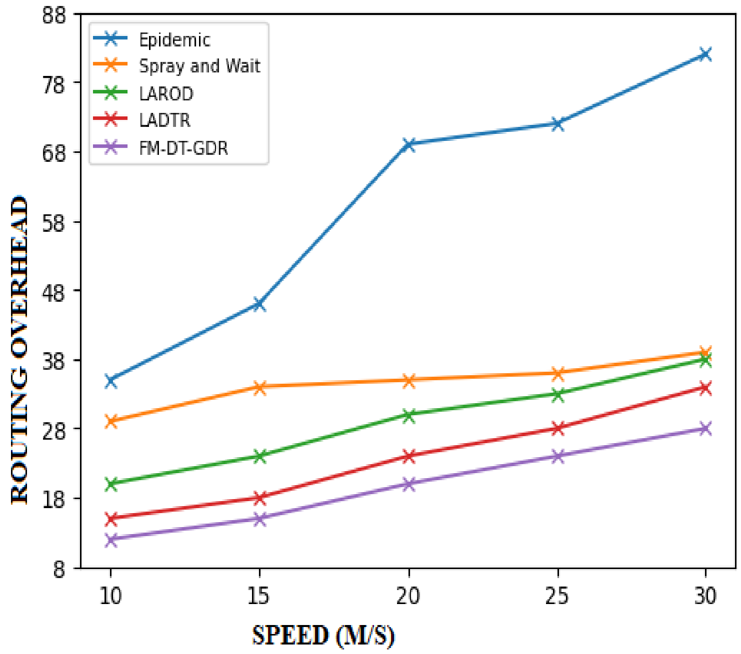


Figure 5.14. Routing overhead vs. Speed (M/S).

also affects the routing overhead. Routing overhead decreases as packet delivery decreases.

## 5.3 STATISTICAL ANALYSIS

This section presents a detailed statistical analysis of two independent samples. An upper-tailed t-test with a significant level of 5% is performed for the packet delivery ratio. Whereas, a lower-tailed t-test has been performed for static analysis of delay, and routing overhead.

### 5.3.1 Statistical Analysis for Packet delivery ratio Vs. Number of UAVs

The results and analysis for two separate samples are shown in detail in Figure 5.15, along with an upper tail t-test with a significance level of 5% to the FM-DT-GDR's packet delivery ratio and the contrasted protocols.

| Packet Delivery Ratio (PDR) w.r.t Number of UAVs | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.045 | H0 | **Significantly YES** |
| LAROD | 0.004 | H0 | **Significantly YES** |
| Spray and Wait | 0.000 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.15: Packet Delivery Ratio Vs. Number of UAVs.

Maximum packet delivery is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

### 5.3.2 Statistical Analysis for End-to-end Vs. Number of UAVs

The results and analysis for two separate samples are shown in detail in Figure 5.16, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's EED and the contrasted protocols. Minimum EED is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| End-to-end delay vs. Number of UAVs. | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.034 | H0 | **Significantly YES** |
| LAROD | 0.002 | H0 | **Significantly YES** |
| Spray and Wait | 0.001 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.16: End–To–End Delay Vs. Number Of UAVs

### 5.3.3 Statistical Analysis for Routing overhead Vs. Number of UAVs

The results and analysis for two separate samples are shown in detail in Figure 5.17, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's routing overhead and the contrasted protocols.

| Routing Overhead(RO) w.r.t Number of UAVs | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.326 | Ha | **Significantly NO** |
| LAROD | 0.001 | H0 | **Significantly YES** |
| Spray and Wait | 0.000 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.17: Routing Overhead Vs. Number Of UAVs.

Minimum routing overhead is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

### 5.3.4 Statistical Analysis for Packet delivery ratio Vs. Message Size

The results and analysis for two separate samples are shown in detail in Figure 5.18, along with an upper tail t-test with a significance level of 5% to the FM-DT-GDR's packet delivery ratio and the contrasted protocols.

| Packet Delivery Ratio (PDR) w.r.t w.r.t Message Size | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.004 | H0 | **Significantly YES** |
| LAROD | 0.001 | H0 | **Significantly YES** |
| Spray and Wait | <0.0001 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.18: Packet Delivery Ratio Vs. Message Size (KB).

Maximum packet delivery ratio is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

### 5.3.5 Statistical Analysis for End-to-end Vs. Message Size

The results and analysis for two separate samples are shown in detail in Figure 5.19, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's end-to-end delay and the contrasted protocols. Minimum end-to-end delay is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| End-to-end delay(EED) w.r.t Message Size | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.011 | H0 | **Significantly YES** |
| LAROD | 0.000 | H0 | **Significantly YES** |
| Spray and Wait | <0.0001 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.19: End–To–End Delivery Vs. Message Size (KB).

### 5.3.6 Statistical Analysis for Routing overhead Vs. Message Size

The results and analysis for two separate samples are shown in detail in Figure 5.20, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's routing overhead and the contrasted protocols.

Minimum routing overhead is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| Routing Overhead(RO) w.r.t Message Size | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.053 | Ha | **Significantly NO** |
| LAROD | 0.000 | H0 | **Significantly YES** |
| Spray and Wait | <0.0001 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.20: Routing Overhead Vs. Message Size (KB).

### 5.3.7 Statistical Analysis for Packet delivery ratio Vs. Buffer Size

| Packet Delivery Ratio (PDR) w.r.t Buffer Size(MB) | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.032 | H0 | **Significantly YES** |
| LAROD | 0.003 | H0 | **Significantly YES** |
| Spray and Wait | 0.000 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.21: Packet Delivery Ratio Vs. Buffer Size (MB).

The results and analysis for two separate samples are shown in detail in Figure 5.21, along with an upper tail t-test with a significance level of 5% to the FM-DT-GDR's packet delivery ratio and the contrasted protocols.

Maximum packet delivery ratio is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

### 5.3.8 Statistical Analysis for End-to-end Vs. Buffer Size

The results and analysis for two separate samples are shown in detail in Figure 5.22, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's end-to-end delay and the contrasted protocols.

Minimum end-to-end delay is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| End-to-end delay(EED) w.r.t Buffer Size(MB) | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.040 | H0 | **Significantly YES** |
| LAROD | 0.007 | H0 | **Significantly YES** |
| Spray and Wait | 0.002 | H0 | **Significantly YES** |
| Epidemic | 0.000 | H0 | **Significantly YES** |

Figure 5.22: End–To–End Delivery Vs. Buffer Size (MB).

### 5.3.9 Statistical Analysis for Routing overhead Vs. Buffer Size

The results and analysis for two separate samples are shown in detail in Figure 5.23, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's routing overhead and the contrasted protocols. Minimum routing overhead is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| Routing Overhead(RO) w.r.t Buffer size(MB) | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.056 | Ha | **Significantly NO** |
| LAROD | 0.008 | H0 | **Significantly YES** |
| Spray and Wait | 0.000 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.23: Routing Overhead Vs. Message Size (MB).

### 5.3.10 Statistical Analysis for Packet delivery ratio Vs. Speed

The results and analysis for two separate samples are shown in detail in Figure 5.24, along with a upper tail t-test with a significance level of 5% to the FM-DT-GDR's packet delivery ratio and the contrasted protocols. Maximum packet delivery ratio is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

### 5.3.11 Statistical Analysis for End-to-end Vs. Speed

The results and analysis for two separate samples are shown in detail in Figure 5.25, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's end-to-end delay and the contrasted protocols. Minimum end-to-end delay is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

| Packet Delivery Ratio (PDR) w.r.t speed of UAVs | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.046 | H0 | **Significantly YES** |
| LAROD | 0.006 | H0 | **Significantly YES** |
| Spray and Wait | 0.001 | H0 | **Significantly YES** |
| Epidemic | 0.000 | H0 | **Significantly YES** |

Figure 5.24: Packet Delivery Ratio Vs Speed (M/S).

| End to end delivery vs. speed (m/s) | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.049 | H0 | **Significantly YES** |
| LAROD | 0.002 | H0 | **Significantly YES** |
| Spray and Wait | 0.001 | H0 | **Significantly YES** |
| Epidemic | <0.0001 | H0 | **Significantly YES** |

Figure 5.25: End–To–End Delivery Vs. Speed (M/S).

### 5.3.12 Statistical Analysis for Routing overhead Vs. Speed

The results and analysis for two separate samples are shown in detail in Figure 5.26, along with a lower tail t-test with a significance level of 5% to the FM-DT-GDR's routing overhead and the contrasted protocols. Minimum routing

| Routing Overhead vs. speed (m/s) | | | |
|---|---|---|---|
| FM-DT-GDR vs. | p-value (one-tailed) | Rejected Hypothesis | Research Answer |
| LADTR | 0.199 | Ha | **Significantly NO** |
| LAROD | 0.033 | H0 | **Significantly YES** |
| Spray and Wait | 0.001 | H0 | **Significantly YES** |
| Epidemic | 0.001 | H0 | **Significantly YES** |

Figure 5.26: Routing Overhead Vs. Message Size (M/S).

overhead is a requirement for an efficient protocol, and after testing the findings, we determined that FM-DT-GDR was the most significant of all the studied protocols.

## 5.4 CHAPTER SUMMARY

This chapter started with a detailed explanation of the simulation environment and performance comparison of the various routing schemes against the proposed FM-DT-GDR. The proposed FM-DT-GDR protocol is designed for sparse FANETs. The proposed protocol was compared against the various routing protocols on evaluation parameters like PDR, EED, and RO. The graphical representation of the result has been carried out with a detailed explanation. We also conducted statistical analysis to make sure the results are significantly correct. We observed that the proposed FM-DT-GDR protocol is performing better against the other routing protocols. The next chapter concludes the work done in this thesis work by listing some of the future work and directions.

# CHAPTER 6

# CONCLUSION AND FUTURE SCOPE

Efficient routing in a sparse flying ad-hoc network (FANETs) is an important concern. After a natural disaster, wireless communication is crucial for search and rescue activities. Due to their quick mobility, unmanned aerial vehicles (UAVs) can be employed in post-disaster scenarios to collect video, and image data from the catastrophe area and transmit it to a ground station. However, in highly dynamic UAV networks, forwarding data is difficult because of unreliable links and sparse connectivity.

The prime focus of the research work was to study routing solutions in sparse FANETs and to provide an efficient routing strategy that fulfills the requirement of disaster and recovery operations in sparse FANETs. The purpose of the present research is to “Design and Implement an Efficient Routing Protocol for Sparse FANETs”.

At the start of the thesis, we presented a detailed introduction to FANETs and their importance in routing in sparse FANETs. Additionally, the chapter also presented the research objective of the present research program. Chapter 2 gives detailed literature on routing protocols. Special emphasis is given to delay tolerant network (DTN) based routing protocols. In the survey, we noticed that most of the proposed routing protocol is based on the replica-based approach which is not suitable for emergency applications such as disaster or search operations. Chapter 3 discusses the literature on the mobility model present so far. Chapter 4 presents the proposed routing approach. Finally, the present research program is concluded in Chapter 6 and future direction is also discussed.

## 6.1 CONTRIBUTION

***(Contribution 1): Proposed Mobility Model for Ferries to Collect the Data from Searching UAVs.***

We proposed a novel mobility model for ferries to collect data from searching UAVs. The proposed mobility model for ferries provides an optimized trajectory so that data from search UAVs can be collected efficiently. This work has been discussed in detail in Chapter 4.

***(Contribution 2): Proposed routing scheme in sparse FANETs***

We proposed a novel routing solution for applications like disaster recovery, and search and rescue missions where a sparse FANET exists. Unmanned aerial vehicles (UAVs) quickly transmit the information it has collected to the GS in search and rescue operations. A small number of UAVs are deployed for rescue operations when a rapid natural disaster affects a vast geographic area, resulting in intermittent or sparse networks. The routing in sparse FANETs is a challenging task.

A new ferry mobility-based directional and time-aware greedy delay-tolerant routing (FM-DT-GDR) protocol is the second solution. The FM-DT-GDR first ascertains the neighbors' directions and arranges them according to the time needed to travel to the desired location. The UAV that arrives at the chosen location in the shortest time is considered to be the efficient forwarding UAV. Zones-1 and Zones-2 make up the network's two zones. Since nodes in Zone- 1 are already near the destination, Zone- 1 always gets precedence. The candidate node is subjected to the threshold to obtain further nodes from Zone-1 if there is no node in Zone-1. If the neighbor is traversing in the opposite direction from the destination or if there is no neighbor, the source node switches to store-carry-forward mode. The store and carry mode is employed up until a suitable carrier is found. According to simulation data, the FM-DT-GDR routing protocol delivers packets at a higher rate than LAROD, LADTR, Epidemic, and S&W. In addition, you can get better results in your simulations by designing an optimized ferry trajectory, routing your data to the closest destination, and using distance, and time-aware greedy routing. Routing protocols like epidemics and S&W rely on flood-based forwarding, which introduces overhead and delay.

## 6.2 FUTURE RESEARCH DIRECTIONS

In this work, some parameters like the energy efficiency routing were not considered. As the UAV collects information across large areas, the UAV's power is quickly exhausted. In addition to UAV positioning autonomy, and the limited computational capabilities of UAVs make energy conservation a significant issue. Memory buffer bloat is another limitation of our work. Buffer overflow requires a large buffer size in-network. Considering buffer space availability when making routing decisions can significantly improve network performance. Buffer bloat can cause high packet loss as packet drops when the buffer didn't have sufficient space. Therefore, taking care of space availability before forwarding the data to the node can highly reduce packet loss in the network. Hence, buffer bloat is the main limitation of this work.

These two limitations of research work are part of future work.

The future scope of this research work is as follows:

- To design energy-efficient and memory buffer space-aware routing which is the limitation of research work.
- To design a dynamic mobility model for ferries that would collect data from UAVs from fixed waypoints but with real-time traffic situations.

## 6.3 CHAPTER SUMMARY

In this study, some parameters like the energy efficiency routing were not considered in the work. As the UAV collects information across large areas, the UAV's power is quickly exhausted. In addition to UAV positioning autonomy, the limited computational capabilities of UAVs make energy conservation a significant issue. Memory buffer bloat is another limitation of our work. Buffer overflow requires a large buffer size in-network. Considering buffer space availability when making routing decisions can significantly improve network performance. These two limitations of research work are part of future work.

The future scope of this research work includes designing energy-efficient and memory buffer space-aware routing which is the limitation of research work. In addition, a dynamic mobility model can be designed for ferries that would collect data from UAVs from fixed waypoints but with real-time traffic situations.

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# LIST OF PUBLICATIONS

### Journals

**C1.** Agrawal, J., & Kapoor, M. (2021). A comparative study on geographic-based routing algorithms for flying ad-hoc networks. *Concurrency and Computation: Practice and Experience*, *33*(16), e6253, **(SCI), (Published)**

**C2.** Agrawal, J., & Kapoor, M. (2022). A comparative study of mobility models for flying ad hoc networks. *International Journal of Sensor Networks*, *38*(3), 204-214. **(SCI), (Published)**

**C3.** Agrawal, J., Kapoor, M., & Tomar, R. (2022). A novel unmanned aerial vehicle-sink enabled mobility model for military operations in sparse flying ad-hoc network. *Transactions on Emerging Telecommunications Technologies*, *33*(5), e4466. **(SCI), (Published)**

**C4.** Agrawal, J., Kapoor, M., & Tomar, R. (2022). A ferry mobility based direction and time-aware greedy delay-tolerant routing (FM-DT-GDR) protocol for sparse flying ad-hoc network. *Transactions on Emerging Telecommunications Technologies*, *33*(9), e4533. **(SCI), (Published)**

### Conferences

**C5.** Juhi Agrawal, "Ferry based geographical delay-tolerant routing protocol for sparse FANETs" in 2022 6th International conference on advances in computing and data sciences (ICACDS-2022), Pullaiah college of engineering and technology, Kurnool, Andhra Pradesh, India, April-2022 **(Presented).**

**C6.** Juhi Agrawal, “Ferry mobility -aware routing for sparse flying ad-hoc network”, 10th international conference on recent trends in computing (ICRTC-2022), SRM Gaziabaad 3-4 June 2022**. (Scopus), (Presented).**

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