Kasdi Merbah University Ouargla
Faculty of New Information and Communication Technologies
-Department of Computer Science and Technology Information-

Thesis of the End of Studied Project

In preparation for obtaining the diploma

MASTER'S DEGREE

Domain: computer science

Mobility Model-based Routing Protocols Performance Analysis In Flying Ad Hoc Networks

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Academic year
2023/2024

Acknowledgments

“

Whoever said to her"Got it."
The flight was neither short nor should it be. The dream was not close, nor was the road fraught with ease But I did it and I got it.
Praise be to God, thanks and gratitude, thanks to which I today see a long-awaited dream that may become a reality that I am proud of.
To my pure angel, and my strength after the support of the first God and my mother, “I dedicate to you this achievement that without your sacrifices would not have existed. I am grateful because.”
God has chosen you for me from among humanity, but you are the best support and compensation.
To my father, may God have mercy on him To from their airport: We will strengthen your support through your brother.)
"My brothers"
I thank my esteemed professors, Dr. Bin Bazian Muhammad, and Dr. Yassin Sahrawi, for their support and support during the research process.
And thanks to everyone who extended his hand tirelessly twice the time, my friends and all my loved ones and dear ones,

”

- Sara

Acknowledgments

“

I want to express my gratitude to the following:

First and foremost, I am thankful to Allah for helping me throughout my academic journey and providing me with the strength and courage to complete this work.

I deeply appreciate my loving parents, Mom, Dad, and my siblings' unwavering support and encouragement. Their love has played a crucial role in shaping the person I am today. I am forever grateful for their belief in me and constant presence in my life.

I thank my esteemed professors, Dr. Ben Bezziane Mohamed and Dr. Yesin Sahraoui, for their supervision, support, and guidance during the research process.

Lastly, I wish to thank everyone who has contributed directly or indirectly to the completion of this dissertation.

Thank you all so much.

”

- Lina

ملخص

في الآونة الأخيرة، شهدنا تطورًا سريعًا وملحوظًا في تقنيات الاتصال، وخاصة في مجال الشبكات العشوائية الجوية الطائرة ($FANETs$) . هذه التطورات أدت إلى ظهور فئة جديدة من الشبكات اللاسلكية تُعرف باسم $FANET$ ($FlyingAdhocNetwork$) . تمثل $FANET$ تباينًا لشبكات الشبكات العشوائية المتنقلة ($MANETs$) حيث تتكون عقد الشبكة من المركبات الجوية غير المأهولة ($UAVs$) ، والمعروفة بشكل شائع باسم الطائرات بدون طيار هذا التطور استدعى تقييمًا شاملاً وتعزيزًا كبيرًا لبروتوكولات التوجيه لتحسين الأداء الشامل للنظام. تُعتبر الشبكات العشوائية الجوية الطائرة بشكل متزايد حلاً قابلًا للتطبيق لمختلف التطبيقات التي تشمل المركبات الجوية غير المأهولة، مثل مراقبة المدن وعمليات البحث والإنقاذ. ومع ذلك، تأتي هذه الشبكات مع تحديات فريدة ومحددة في التواصل. وبناءً على ذلك، تُخصص العديد من الجهود البحثية لتقييم أدائها من خلال المحاكاة. لمواجهة التحديات المتعلقة بتوجيه البيانات بكفاءة في $FANETs$ ، حيث قد تفشل الطرق التقليدية في سيناريوهات ديناميكية، يصبح الحاجة إلى إطار فعّال أمرًا حاسمًا في معالجة هذه التحديات. يهدف هذا العمل إلى تحسين كفاءة التوجيه في سياق $FANETs$ ، من خلال تقييم أداء بعض بروتوكولات التوجيه ضمن نماذج تنقل مختلفة لكشف نقاط القوة والضعف باستخدام منصة المحاكاة $OMNeT++$.

الكلمات المفتاحية: الشبكات المخصصة للمركبات الطائرة ،الدرون

Abstract

In recent times, we have witnessed the rapid and remarkable evolution of communication technologies, particularly in the domain of Flying Ad Hoc Networks (FANETs). These developments have given rise to a fresh category of wireless networking known as FANET (Flying Ad hoc Network). FANET represents a variation of Mobile Ad hoc Networks (MANETs) wherein the network nodes consist of Unmanned Aerial Vehicles (UAVs), often referred to as drones. This evolution has necessitated a thorough evaluation and significant enhancement of routing protocols to improve the overall performance of the system. Flying ad-hoc networks are increasingly seen as a viable solution for various applications involving unmanned aerial vehicles, such as urban surveillance or search and rescue operations. However, these networks come with unique and specific communication challenges. Consequently, numerous research endeavors are dedicated to evaluating their performance through simulation. To address the challenge of efficiently routing data in FANETs, where conventional methods may fall short during dynamic scenarios, the need for an effective framework becomes paramount in addressing these challenges. In this work, our focus aims to optimize routing efficiency in the context of FANETs, evaluating the performance of some routing protocols within different mobility models to uncover their strengths and limitations using the OMNeT++ simulation platform.

Keywords: FANET (Flying Ad hoc Network), mobility models, routing protocols, Unmanned Aerial Vehicles (UAVs), Drone, OMNeT++.

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List of Acronyms

Fanet	*Flying Ad-Hoc Network*
Manet	*Mobile Ad-Hoc Network*
Vanet	*Vehicular Ad-Hoc Network*
UAV	*Unmanned Aerial Vehicle*
Omnet	*Network Simulation Framework*
Inet	*Internet Extension for Omnet*
Avens	*Aerial vehicle network simulator*
WLAN	*Wireless Local Area Network*
QoS	*qualité de service*
GPSR	*Geographic Position-Based Routing Protocols*
MN	*Mobility Node*
Wi-Fi	*wireless fidelity*
ZIGBEE	*Zonal Intercommunication Global-standard*
LTE	*Long Term Evolution*Wi-Fi stands for “wireless fidelity”
Ad hoc	*is a word Latin and means “for this” or "for this situation.*

General Introduction

Over time, humanity has aimed to expand surveillance and information gathering, even into space, while improving communication in remote and extreme conditions. This has challenged modern technology to innovate, leading to the emergence of wireless and ad-hoc networks.

Ad-hoc networks, decentralized wireless systems comprising two or more nodes capable of direct communication, are termed MANETs (mobile ad-hoc networks) when considering mobility. In MANETs, nodes move freely, resulting in frequent changes to the network's topology. Each node serves as a router, forwarding traffic to specified destinations within the network. When applied to vehicular communication, these networks are referred to as VANETs (vehicular ad-hoc networks), representing a specialized form of MANET tailored to vehicular mobility. In VANETs, vehicles adhere to predetermined movement patterns based on road layouts, buildings, and intersections.

Yet, these methods prove insufficient, given the existence of remote regions and unpredictable, rapidly changing network topologies during catastrophic events. Hence, the concept of FANET was introduced in 2013 to address such challenges. FANETs, known as aerial ad-hoc networks, represent a type of MANET where the nodes consist of unmanned aerial vehicles (UAVs). Since their inception, they have found utility across diverse domains including military and civilian applications.

Within the FANET network, UAV networks are divided into Single-UAV and UAV-to-UAV types, connecting with terrestrial base stations and among themselves. Challenges in multi-UAV networks include topology changes, information exchange, QoS, and data loss. Factors like node density, link stability, and route optimization are key concerns, requiring incremental routing protocol planning. Routing algorithms aim for high throughput, minimal delay, and reduced packet loss.

The accuracy of Protocol simulation hinges on the mobility model and simulation environment. Establishing a FANET requires networking components on each UAV, limited by safe communication ranges. Dynamic routing reconfiguration in UAV swarm applications leads to packet loss while achieving precise data transmission between UAVs poses challenges in FANET implementation.

In this context, our main research objective is to compare the performance evaluation in terms of QoS metrics and energy when applying different mobility patterns in different routing protocols.

This comparison aims to discover the suitable model for each application, gaining valuable experiences for optimizing FANET performance in diverse scenarios.

Chapter 1

General information on FANET

1.1 Introduction

Rapid advancements in electronic, sensor, and communication technologies have led to significant progress in wireless network technologies, particularly ad-hoc networks. Unmanned aerial vehicle (UAV) systems are designed to operate autonomously or be remotely controlled, covering vast surface areas on Earth and in space, eliminating the need for human personnel on board. Flying Ad-hoc Networks (FANET) are specifically created to monitor, gather information, and communicate effectively in challenging locations, including adverse weather conditions. Their versatility, flexibility, simple installation, and relatively low operating costs have contributed to their widespread adoption. However, challenges related to information exchange, communication, and service have emerged. In response, new architectures and protocols have been developed to address these challenges.

This chapter surveys the Flying Ad-Hoc Network (FANET), which is essentially an ad-hoc network between UAVs, as a new network family. The work begins with a definition, outlining potential features, applications, deployment environments, etc.

1.2 Definition of Flying Ad-Hoc Networks (FANET):

Flying Ad-Hoc Networks (FANET) represent a subset structure of ad-hoc networks and can be defined as a novel and distinct form of Mobile Ad-Hoc Network (MANET) that involves the communication and coordination of unmanned aerial vehicles (UAVs) or drones, Certainly, FANET has emerged through the integration of MANET network concepts with UAV (Unmanned Aerial Vehicle) technology [7].

FANET refers to a self-organizing and self-configuring network of drones, That communicate with each other without the need for a pre-established infrastructure, such as a fixed network of base stations. FANETs utilize wireless communication technologies like Wi-Fi, ZigBee, or LTE to establish communication links among drones [8]. A drone is characterized as an unmanned aircraft capable of autonomous navigation through an onboard system or remote control. Each UAV can connect directly through the satellite or ground station to establish an ad hoc network among all UAVs, Instead, they form a dynamic and decentralized network where each drone acts as a node that can both send and receive data.

Various factors have been discussed in the literature, including high mobility, scalability for diverse applications, and resilience to address potential communication failures. Nonetheless, several constraints persist, such as the restricted flight time of drones and the need for routing protocols capable of accommodating network dynamics. It is emphasized that ensuring the efficient and swift transmission of information between nodes in a FANET network necessitates a suite of mechanisms and protocols [9].

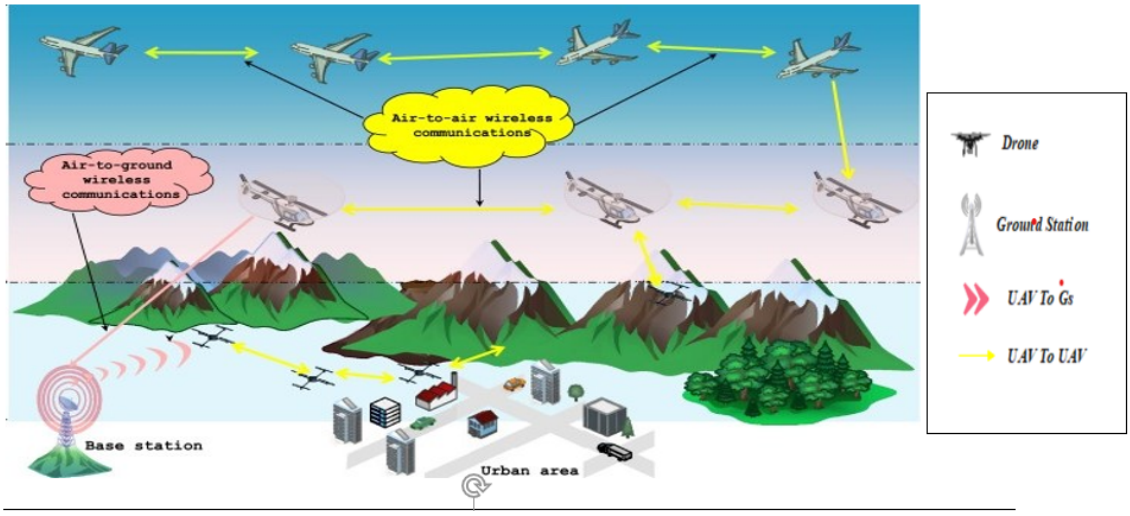

Figure 1.1: Flying Ad hoc Network (FANET).

1.3 Applications of FANETs:

There are various situations where a group of UAVs can be used to carry out a variety of tasks. Using multiple UAVs is intended to reduce the time it takes to complete a task compared to using just one UAV. UAV swarms represent a decentralized processing system, where the UAVs are treated as nodes that are controlled through internal mechanisms and ad-hoc communication [10].

Below are some potential applications of FANETs:

1.3.1 Search and rescue operations:

- UAVs were first utilized in search and rescue operations during Hurricane Katrina (2005), Fukushima (2011), and the Nepal earthquake (2015), highlighting their crucial role.
- Ho and colleagues proposed a collaborative system for disaster scenarios, which detects survivors by using victims' mobile signals.
- Scherer and others introduced a modular autonomous UAV system for search and rescue, evaluated in outdoor missions.
- Waharte and Trigoni investigated efficient UAV search strategies, considering factors such as sensors, energy, obstacles, and communication for victim detection.

1.3.2 Forest fire detection:

- UAVs have a crucial role in detecting forest fires and monitoring heat and fire risk.

- Merino et al. introduced a multi-UAV cooperative perception system designed for monitoring forest fires.

- Ghamry and Zhang proposed a fault-tolerant cooperative control strategy for UAVs to maintain a desired formation while monitoring, using a defined mobility pattern.

1.3.3 Traffic and urban monitoring:

- FANETs simplify the monitoring of roadway traffic by replacing labor-intensive methods.

- UAVs efficiently detect and report traffic crashes and provide real-time visuals for security in road and train networks.

- Military assets in urban terrain operations can monitor urban areas.

- Olsson et al. designed a multi-UAV system for extended surveillance using a link chain and multi-hop communication.

- Reshma et al. proposed a street junction formation scheme for UAVs.

- Samad et al. discuss multi-UAV systems for military reconnaissance and surveillance in urban scenarios.

1.3.4 Reconnaissance and patrolling:

- UAVs in stationary patrol oversee specific areas for defense.

- Surveillance tasks include collecting images of objects and sites over wide areas.

- UAVs aid ground units in observation, inspection, and security.

- In border policing, UAV swarms detect disturbances, weapons, drugs, and illegal crossings.

- Reconnaissance involves UAV cooperation for missions with unpredictable paths.

1.3.5 Agricultural management;

- Precision agriculture (PA) uses small autonomous UAV swarms for efficient crop monitoring.
- UAVs offer quick data retrieval on crop health, growth, and potential issues.
- Torres-Sánchez et al. describe a UAV system for image acquisition in a predetermined path.
- Chao et al. discuss cooperative remote sensing for water management using a multi-UAV system.
- Li et al. propose flight path optimization for multiple UAVs in agriculture.

1.3.6 Environmental sensing:

- Sensor networks consist of small, energy-efficient devices analyzing physical quantities.
- UAVs are increasingly used in sensor networks due to their versatility in carrying various sensors.
- Wei et al. explore UAVs for efficient wireless sensor network data collection.
- Alvear et al. suggest equipping UAVs with pollution sensors for autonomous pollution measurements.
- This concept can extend to smart city sensing by combining UAVs with diverse sensors.

1.3.7 Relaying network:

- UAVs operate autonomously as airborne relays for efficient and secure transmission of ground device-collected information.
- They deliver data from wireless sensor network (WSN) nodes on the ground to distant control centers.
- UAVs extend the communication range of ground relaying nodes, particularly in Internet of Vehicles (IoV) scenarios [11].

1.4 FANET Communication Architecture:

The Flying Ad-hoc Network (FANET) communication architecture is how Unmanned Aerial Vehicles (UAVs) communicate with one another and a ground control station (GCS) in a network. This architecture is crucial for enabling collaboration and information sharing among UAVs for various applications. Several communication architectures have been proposed for multi-UAV systems, in which we introduce four types:

1.4.1 Centralized FANET Architecture:

Centralized Architecture in Flying Ad-hoc Networks (FANETs) refers to a network structure that uses a single Ground Control Station (GCS) as the central authority to connect all Unmanned Aerial Vehicles (UAVs) within the network. This structure forms a star-like network topology, where all UAVs directly connect to the GCS.

The GCS acts as the backbone for communication and data flow, coordinating the activities of the UAVs. Data transmission between any two UAVs happens through the GCS, meaning that the UAVs send and receive data packets to and from the GCS. The GCS relays the data packets to the intended recipient UAV.

Centralized architecture is a simple and manageable solution for basic FANET applications with a limited number of UAVs. However, it has limitations in scalability and is vulnerable to single-point failure, making it less suitable for large-scale and complex deployments.

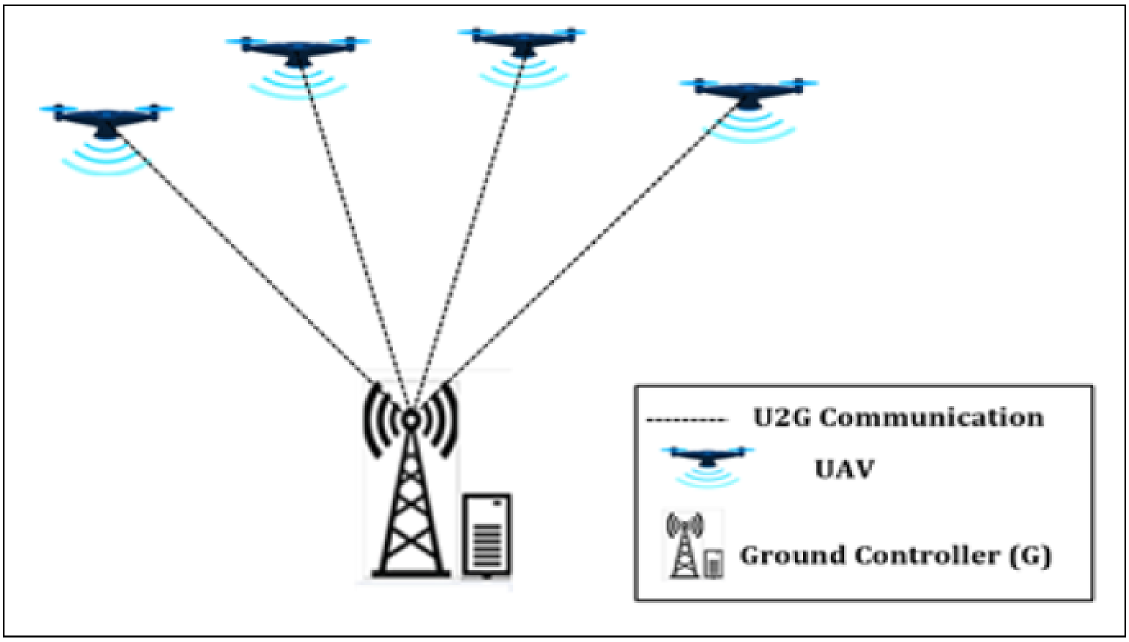

Figure 1.2: Centralized FANET Architecture

1.4.2 Decentralized FANET Architectures:

Unlike a centralized system with a single point of control, a decentralized communication architecture allows individual flying devices (drones) to communicate directly with each other forming a network without a central point of control.

Drones can use wireless protocols like Wi-Fi or Bluetooth to communicate with each other when they are within range. If the destination device is out of range, messages are forwarded through other devices in the network that act as relays. Each device uses routing protocols to determine the most efficient path to the destination. Drones in the network can discover and manage their connections with each other without the need for central control. This is done through techniques like neighbor discovery and network topology maintenance [8].

There are different sub-types of decentralized FANET architectures:

- *UAV ad-hoc network:* This is the most basic form, where all devices in the network communicate directly or through multi-hop routing [1].

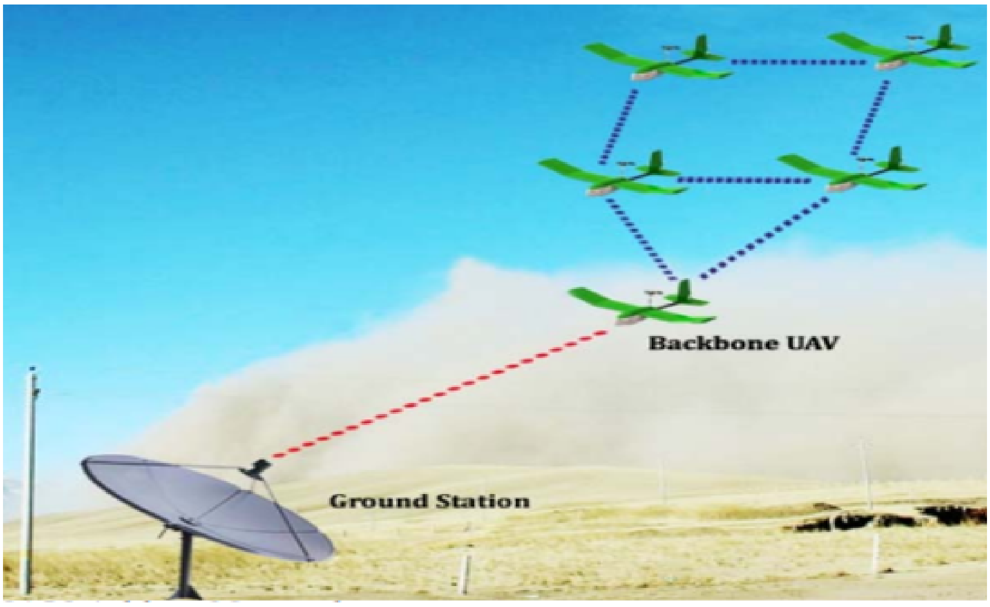

Figure 1.3: UAV ad-hoc network [1]

- *Multi-group UAV ad-hoc network:* In this type of network, devices are divided into groups, and communication primarily occurs within groups, with limited inter-group communication.

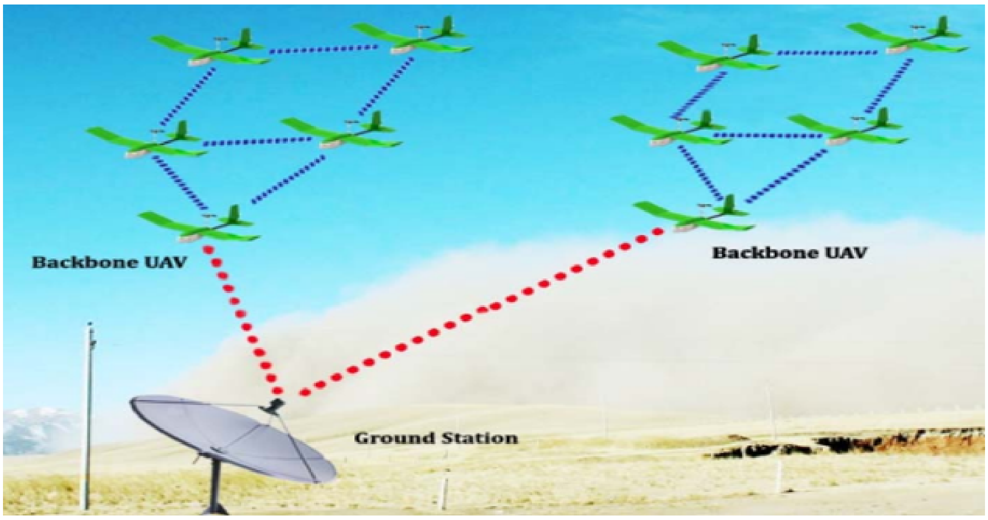

Figure 1.4: Multi-group UAV ad-hoc network [1]

- *Multi-layer UAV ad-hoc network* In this type of network, devices are organized into different layers, with communication primarily happening within layers but also allowing inter-layer communication when necessary.

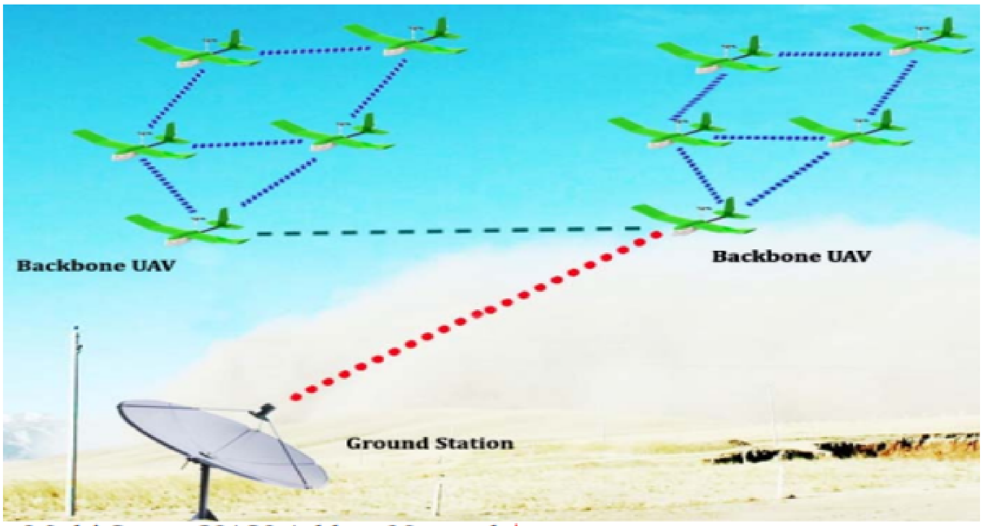

Figure 1.5: Multi-layer UAV ad-hoc network[1]

1.4.3 Hybrid FANET Architecture:

Hybrid communication is a combination of U2U and U2G communications and helps UAVs send their data to GS in a single-hop or multi-hop manner using intermediate nodes.

- **U2U (UAV to UAV):** Direct communication between individual drones, forming a decentralized network. UAVs use U2U communication for local data exchange or coordination tasks.

- **U2G (UAV to Ground):** Communication between drones and ground stations (GS), providing centralized control and data collection.

- **Data Transmission:**

⋆ **Single-hop**: When a drone is within direct range of the GCS, data can be transmitted directly in one hop. without relying on intermediate nodes.

⋆ **Multi-hop:**: When a drone is beyond direct range, intermediate nodes (other drones) act as relays, forwarding data in multiple hops until it reaches the GCS. This creates a multi-hop network

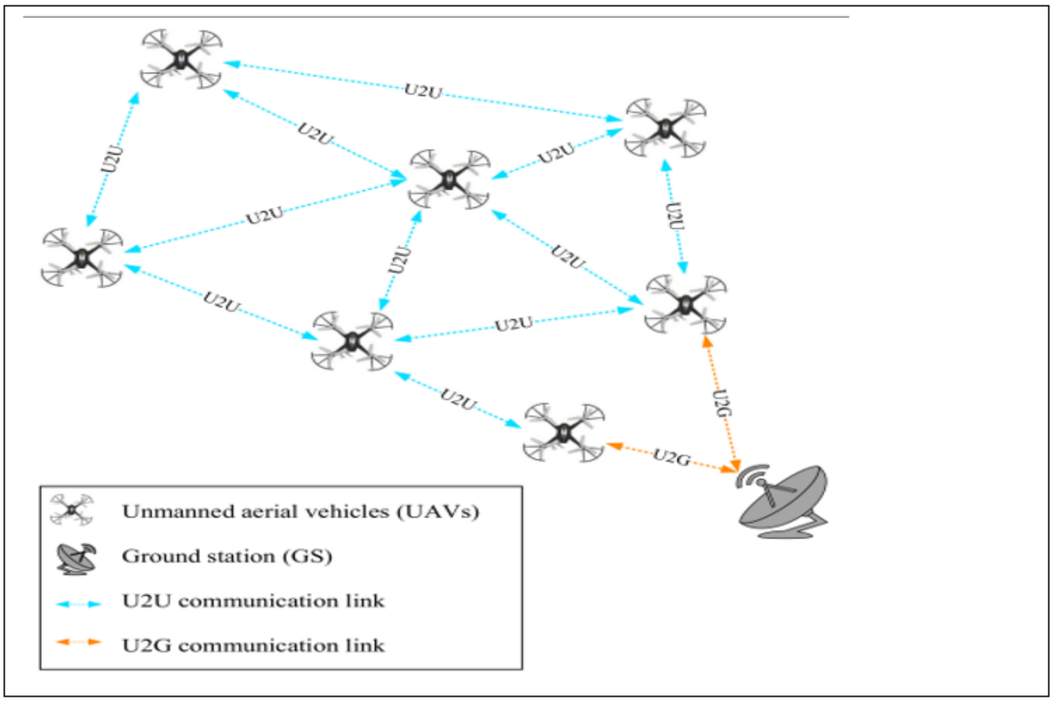

Figure 1.6: Hybrid FANET Architecture [2]

1.4.4 Hierarchical FANET Architecture

This architecture is structured into multiple layers, where each layer is responsible for a specific function and level of responsibility. The upper layer works as a coordinator, while the lower layers handle the transmission and routing of data.

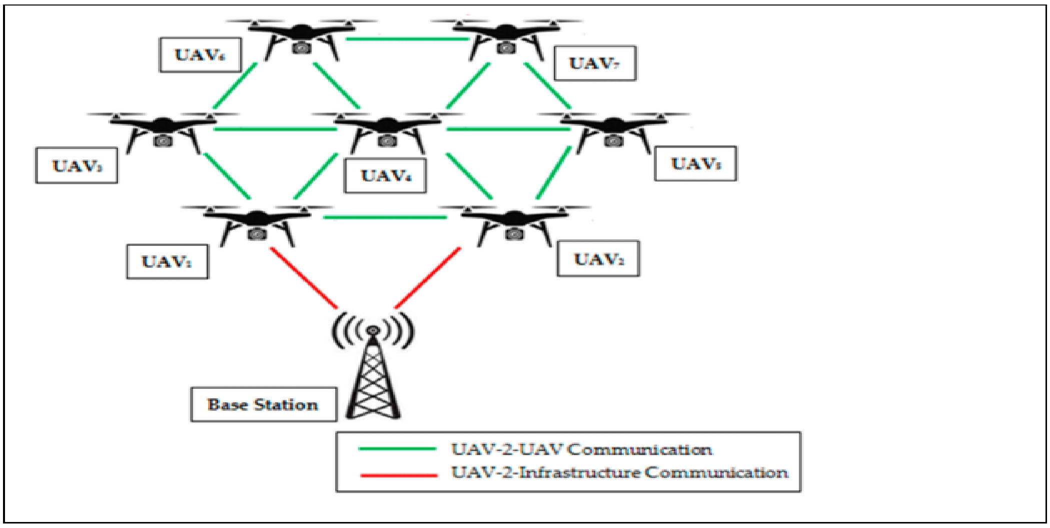

Figure 1.7: Hierarchical FANET Architecture

1.5 Components of FANET:

FANET (Flying Ad Hoc Networks) is a self-organizing network of drones designed for communication and collaboration, Various wireless technologies in FANET are chosen based on factors like mobility, range, data rate, latency, and network topology. Options include short-range communication like WiFi, Zigbee, Bluetooth, and long-range communication using Satellite, 2G, 3G, 4G, and 5G, depending on the application and mission [12].
The architecture of FANETs generally includes the following components:

- **Nodes**: UAVs or drones function as network nodes, proficient in transmitting and receiving data, and they serve as the main flying platforms with communication capabilities.

- **Communication Modules**: Equipment embedded in UAVs to establish communication links with other UAVs and ground stations.

- **Routing protocols**: Algorithms employed to ascertain the data transmission route among nodes.

- **Navigation Systems**: GPS and alternative navigation technologies utilized for accurate positioning and route strategizing.

- **Mobility models**: Models depicting the motion of nodes within the network.

- **Data link layer** : Layer accountable for dependable data transmission among nodes. which contains Onboard computing systems that process and analyze data gathered by UAVs.

- **Network management**: Mechanisms for organizing and sustaining the network, covering aspects such as security, quality of service, and energy management, including efficient power sources or batteries to support UAVs during flight.

- **Physical layer**: The communication framework facilitates data interchange among nodes.

- **Collision Avoidance Systems**: Sensors and algorithms implemented to avert collisions among UAVs and ensure secure operations.

1.6 FANET Design Characteristics:

FANET shares common characteristics with both MANET and VANET networks, while also having unique design features that set it apart from these other types of networks [7]. In this subsection, we will explain its unique design characteristics in a detailed manner.

1.6.1 Topology Change:

FANET topology is quite different from MANET and VANET topologies. This is because the FANET topology changes more frequently due to the higher mobility of its nodes. The mobility of FANET nodes and UAV platform failures greatly impact the network structure. Whenever a UAV experiences a failure, the links associated with it also fail, which requires an update to the network topology. Similarly, UAV injections that introduce new nodes into the network also trigger such updates. Additionally, link outages are another factor influencing FANET topology. These outages result from rapid changes in link quality caused by UAV movements and variations in distances between FANET nodes. As a result, link failures and alterations in network topology occur frequently in FANET environments.

1.6.2 Mobility Model:

Mobility models Represent the movement of nodes and how their location, velocity, and acceleration change over time. mobility models are used to create a realistic simulation environment. In most mobility models, the flight plan is usually set in advance and any changes require a new calculation for the map. Each model has its strengths and weaknesses. the models must be able to adapt and evolve to best fulfill their intended purposes. The dynamic and autonomous nature of UAVs in FANET emphasizes the importance of selecting an appropriate mobility model to ensure accurate simulations and performance evaluation.

1.6.3 Node mobility:

Node mobility-related issues are the most notable difference between FANET and the other ad hoc networks. Due to the high speed of UAVs, which ranges from 30 to 460 km/h, this situation poses several challenging communication design issues.

1.6.4 Node density:

Node density refers to the average number of nodes in a unit area. FANET nodes are spread in the sky, and the distance between UAVs can be several kilometers. This results in a much lower node density in FANET as compared to MANET and VANET.

1.6.5 Radio propagation model:

Radio propagation in FANET differs from MANET and VANET due to the location of nodes. In MANET and VANET, the nodes are closer to the ground level, making radio signals more influenced by obstacles such as buildings and terrain. However, in FANET, UAVs fly at higher altitudes, allowing for a clear line of sight between the sender and receiver nodes and less impact from ground-level obstacles. This leads to distinct radio propagation characteristics in FANET compared to other ad hoc networks.

1.6.6 Power consumption and network lifetime:

In FANET, the communication hardware is powered by the energy source of the UAV, which means that FANET communication hardware doesn't typically have a power resource issue like MANET. This means that FANET designs may not need to be power-sensitive, unlike most MANET applications. However, it's worth noting that power consumption can still be a design problem for mini-UAVs.

1.6.7 Computational power:

In the concept of ad hoc networks, the nodes can act as routers and must possess computational capabilities to process incoming data in real time. Typically, nodes in MANETs are battery-powered small computers such as laptops, PDAs, and smartphones, which only have limited computational power due to size and energy constraints. However, in both VANETs and FANETs, application-specific devices with high computational power can be used. UAVs have adequate energy and space to include high computational power, with the only limitation being the weight. The trend of hardware miniaturization has made it possible to incorporate powerful computation hardware in UAV platforms, but the size and weight limitation can still be critical for mini-UAVs that have limited payload capacity [5].

1.6.8 Localization:

Accurate geospatial localization is crucial for mobile and cooperative ad hoc networks. The existing methods for localization include global positioning systems (GPS), beacon (or anchor) nodes, and proximity-based localization. However, multi-UAV systems in FANET need highly accurate localization data with smaller time intervals due to their high speed and different mobility models. While GPS provides position information at one-second intervals, it may not be sufficient for certain FANET protocols. In such cases, each UAV must be equipped with a GPS and an inertial measurement unit (IMU) to offer the position to other UAVs at any time. IMU can be calibrated by the GPS signal, which helps in providing the position of the UAV at a quicker rate.

1.7 Conclusion:

In this chapter, we delved into the realm of Flying Ad-Hoc Networks (FANETs), concentrating on elucidating their definition, delineating their distinctive features, and outlining the diverse domains where they find application. Additionally, a comprehensive depiction of various FANET architectures has been furnished, spotlighting their constituent elements

Chapter 2

Literature Review

2.1 Introduction

In the realm of wireless communication, continuous technological advancements have expanded connectivity horizons, facilitating the creation of more sophisticated and adaptable network infrastructures. The inception of wireless networks marked a significant breakthrough, laying the foundation for unrestricted communication and widespread adoption of Internet of Things (IoT) applications. With the evolution of wireless technologies, the complexity and demands on networks have increased, leading to the emergence of Intelligent Automation (IA). IA leverages artificial intelligence to optimize network operations, enhance data processing, and ensure resilient communication in dynamic environments. Amidst this evolving landscape, Vehicular Ad Hoc Networks (VANETs) emerged as a crucial development tailored to the unique requirements of vehicular communications. VANETs enable direct communication between moving vehicles and roadside units, enhancing road safety, and traffic efficiency, and enabling various automotive applications. Expanding on the foundation laid by VANETs, Flying Ad Hoc Networks (FANETs) represent the next advancement in ad hoc network technology.

FANETs extend mobile ad hoc networks into the aerial domain, providing a flexible and dynamic framework for establishing connectivity among unmanned aerial vehicles (UAVs). This transition integrates advancements in wireless networks and Intelligent Automation (IA) within a highly mobile and three-dimensional space. Over the past decade, there has been significant growth in the adoption of FANET technologies across diverse applications, including traffic monitoring, search and rescue operations, healthcare, disaster management, agriculture, and delivery services. These applications leverage various communication patterns, including satellite links, mobile networks, and direct drone-to-drone communications. Several real-world applications offer a cost-effective solution to address challenges encountered by terrestrial networks and provide an alternative approach in challenging environments. Ensuring optimal performance across diverse applications necessitates guaranteeing reliability and delivering timely services while upholding high-quality standards. However, technical issues persist during FANET deployment, requiring further investigation. Additionally, various requirements specific to FANETs are often overlooked, including data dissemination with diverse mobility patterns across ground, air, and space segments, and energy constraints. Hence, focusing on these overlooked aspects is crucial for enhancing application functionality and addressing outstanding issues. The topology of FANETs experiences constant fluctuations due to the highly dynamic nature of network nodes. To maintain a reliable and well-connected network and ensure link stability, it is essential to introduce various mobility models tailored to specific applications and services. Selecting the appropriate protocol for each network type depends on its unique specifications, emphasizing the importance of employing a dependable protocol and evaluating its performance through simulation. Protocol simulation is influenced by factors such as the mobility model and communication traffic patterns.

This chapter focuses on routing protocols and mobility models used in FANET networks to address communication challenges and analyze routing protocol performance.

Tailoring these models to different applications provides valuable research insights and a better understanding of the practical implementation of Flying Aerial Network applications.

2.2 Routing Protocols in FANET:

FANETs, or Flying Ad hoc Networks, represent wireless networks formed by unmanned aerial vehicles (UAVs) collaborating to accomplish shared objectives. These networks necessitate reliable and effective routing protocols to facilitate UAV communication and facilitate diverse applications like surveillance, disaster response, and communication relays. These routing protocols can be classified in various ways, including based on topology, swarm behavior, node position, security considerations, energy efficiency, and hierarchical structure.
Over time, researchers have proposed different classification schemes to better understand and categorize FANET routing protocols. To achieve this, researchers have reviewed and selected appropriate routing protocols for specific FANET scenarios. For instance, they may choose from protocols like AODV, DSDV, and OLSR, focusing on analyzing these foundational protocols as a basis for designing a routing protocol suitable for their particular application, such as reconnaissance scenarios. Below are several routing protocols frequently employed within FANETs [13].

2.2.1 Classification Of Routing Protocols In FANET

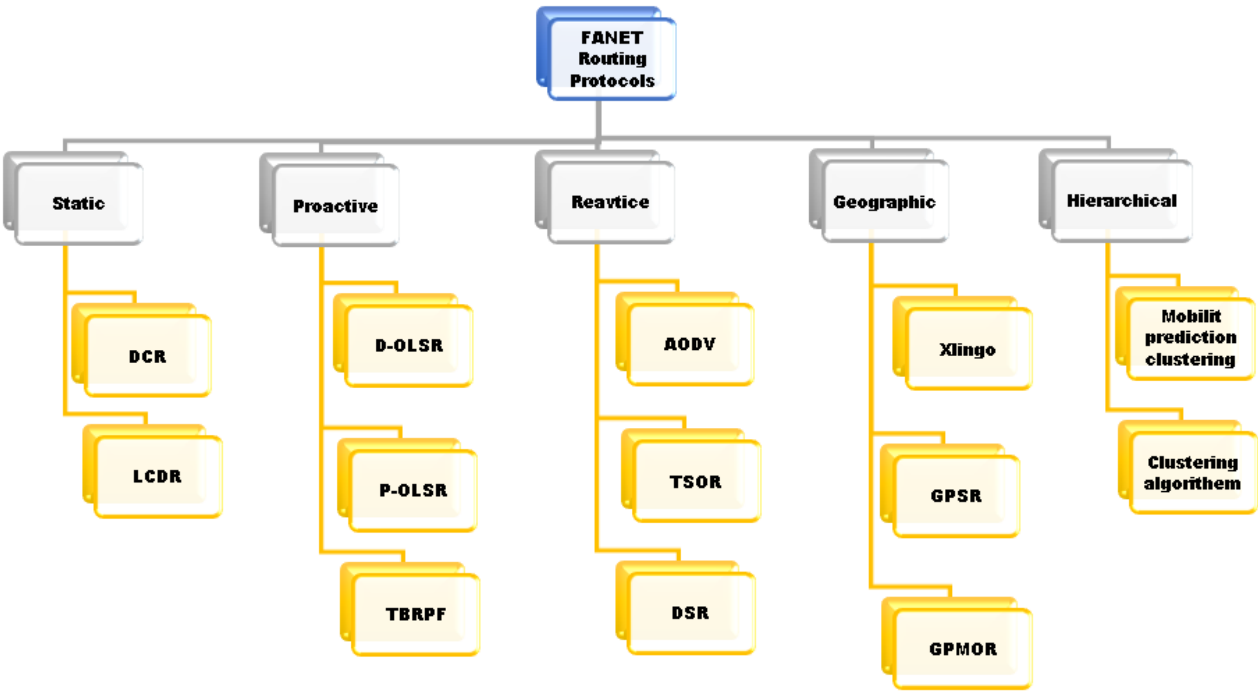

Figure 2.1: Classification Of FANET Routing Protocols

Wireless and ad-hoc networks utilize various routing protocols like flooding, dynamic source routing, and pre-computed routing. However, due to UAV characteristics such as speed and rapidly changing links between nodes, these protocols require modification or the introduction of new ones to address network challenges. FANETs demonstrate dynamic node addition and removal based on needs, categorized into five main protocol classes.

2.2.2 Static routing protocols

Static routing protocols predefine routing tables in UAVs, assuming a stable network topology throughout the mission. Communication is restricted to nodes specified in these tables, and any network changes during the mission are not accommodated. As a result, these protocols lack fault tolerance and are ill-suited for dynamic networks [14].

LCDR:

Load Carry and Delivery Routing is a foundational routing model in FANET. In this approach, a UAV retrieves data from a ground node, transports it during flight, and delivers it to a designated ground destination, such as a military team or a ground control station.

DCR:

Data-centric routing, a prospective method for FANET, involves ground nodes disseminating queries as subscription messages to gather specific data from an area. Producer nodes decide which information to publish and initiate dissemination. UAVs forward published data based on subscription messages, facilitating content-based routing and potentially employing data aggregation for energy efficiency [5].

2.2.3 Proactive routing protocols:

Proactive routing protocols maintain updated routing information in tables, ensuring no waiting time for the latest data. However, they suffer from bandwidth inefficiency due to constant message exchanges, making them unsuitable for highly mobile or large networks. Additionally, they exhibit slow responses to topology changes or failures [15].

TBRPF:

Topology Broadcast based on Reverse Path Forwarding (TBRPF) efficiently disseminates link state updates by maintaining information on each link in routing tables. It swiftly detects changes in link state, computes alternate routes, and is well-suited for FANET.

TBRPF operates in two steps: neighbor discovery and rapid broadcast of link state updates. Utilizing min-hop path spanning trees, minimizes control traffic compared to link state flooding protocols, achieving a significant reduction in update forwarding.

P-OLSR:

FANETs experience frequent topology changes, rendering traditional MANET routing protocols inadequate. To address this, Stefano Rosati proposed P-OLSR (Predictive-OLSR), an extension of OLSR. P-OLSR utilizes GPS data and adjusts transmission metrics based on factors like direction and relative UAV speed for improved routing efficiency.

D-OLSR:

DOLSR, a derivative of OLSR, prioritizes the Multi-Point Relay (MPR) concept and necessitates directional antenna-equipped UAVs. Its algorithm minimizes MPRs, reducing overhead packets and network delays [16].

2.2.4 Reactive routing protocols:

RRP also termed an on-demand routing protocol, establishes paths between nodes upon request, and alleviates the overhead issue of PRP. It utilizes RouteRequest and RouteReply messages to find and confirm paths, conserving bandwidth by employing one path per node and avoiding network-wide table updates. However, path discovery may result in slower operation compared to PRP [14].

DSR:

Dynamic Source Routing (DSR) allows packet senders to specify the complete route through packet headers, facilitating rapid adaptation to changes like host movement without periodic router advertisements. With no overhead during stability, DSR primarily conducts route discovery and maintenance operations.

AODV:

AODV enables mobile hosts to act as specialized routers, obtaining routes on-demand without frequent advertisements, making it ideal for dynamic networks. It ensures loop-free routes and efficiently repairs broken links, reducing bandwidth demands by eliminating periodic advertisements [17].

TSOR:

The Time-Slotted On-demand Routing Protocol improves quality of service and supports mobility by eliminating collisions during route determination. Based on AODV, it reduces internal node communication and collisions during route discovery, resembling slotted ALOHA protocol with allocated time slots for nodes to communicate with the cluster head.

2.2.5 Hierarchical routing protocols:

Hierarchical protocols in FANETs resolve network scalability concerns by organizing the network into clusters across different mission areas. These protocols offer a structured approach to routing solutions, enhancing network management and efficiency [18].

Clustering algorithm:

In the clustering algorithm, networks are organized into clusters, each led by a cluster head (CH). Nodes within a cluster are within direct communication range of the CH, which is connected to a satellite and can broadcast data to cluster members. This model enhances performance in large mission areas with numerous UAVs [19].

Mobility prediction clustering:

Mobility prediction clustering is designed for FANET, where clusters shift frequently due to high mobility. The protocol predicts these changes using Trie structure prediction and a mobility model. Cluster heads are selected based on weighted sums of predictive models, aiming to boost cluster stability and CH performance [20].

2.2.6 Geographical routing protocols:

Highly dynamic mobility leads to frequent changes in topology, challenging topology-based routing protocols to maintain consistent routes and performance. Geographic-based protocols prioritize selecting the best next hop for routing under such conditions [21].

GPMOR:

Geographic Position Mobility Oriented Routing (GPMOR) employs the Gauss-Markov mobility model to predict UAV movement and minimize the impact of dynamic mobility. By considering both mobility relationships and Euclidean distance, it selects the next hop for more accurate routing decisions [22].

Xlingo:

XLinGO improves video transmission in FANETs by ensuring reliable multi-hop routes. It integrates cross-layer and human-related factors, such as performance metrics and Quality of Experience (QoE), for optimal routing decisions.

2.2.7 GPSR: Greedy Perimeter Stateless Routing for Wireless Networks

The GPSR allows nodes to figure out who their closest neighbors are (using beacons) that are also close to the destination the information is supposed to travel. To calculate a path, GPSR uses a greedy forwarding algorithm that will send the information to the final destination using the most efficient path possible. If the greedy forwarding fails, perimeter forwarding will be used which routes around the perimeter of the region. GPSR uses Distance Vectors (DV), Link State (LS), and Path Vector routing algorithms. With DV, each node finds its destination from its neighbors based on a periodic beacon. LS directly floods announcements of changes in node status to every node in the network topology. According to the authors, Both DV and LS can have small inaccuracies in the state at a router [node] which can cause routing loops or disconnection. The rate of change of the topology and the number of routers in the routing domain can affect the message complexity of DV and LS routing algorithms [3].

1-1: the greedy forwarding algorithm:

Assuming the wireless routers [nodes] know their locations, the Greedy forwarding algorithm will try to find the closest router which is also the closest to the final destination as seen in 2.2.

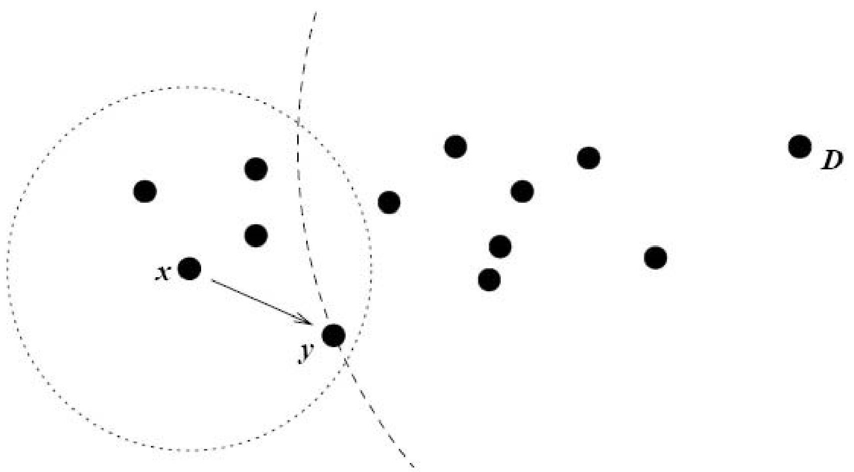

Figure 1: Greedy forwarding example. y is x's closest neighbor to D.

Figure 2.2: greedy forwarding algorithm[3]

Node x wants to send information to node D, using the greedy forwarding algorithm, x calculates that the closest neighbor that is also the closest to D and that is in x's radio range (the dotted circle surrounding x) is y. Even though there are other neighboring nodes within radio range closer to x than y, none of them are as close to D as y is, and therefore x will send its information to y, which will use the greedy forwarding algorithm to send it to the next node until the information reaches the final destination D. However, there is a drawback to the greedy forwarding algorithm which occurs when the network topology is like the one in 2.3

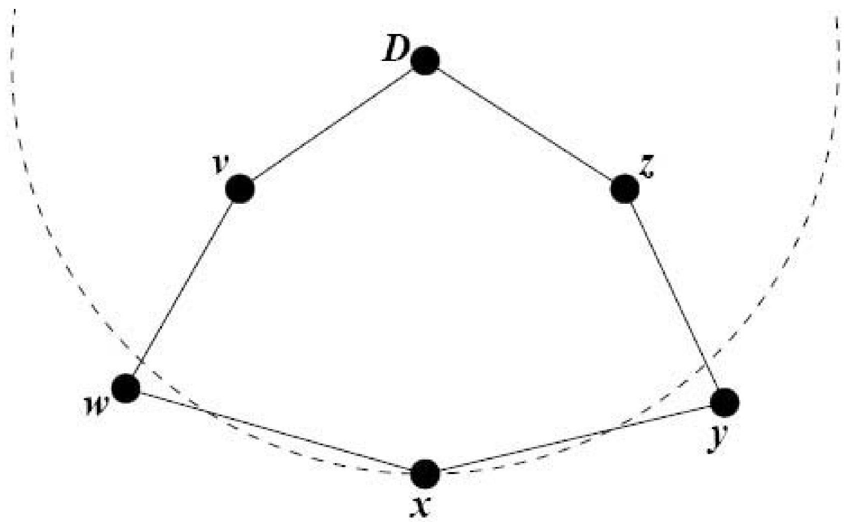

Figure 2: Greedy forwarding failure. ***x*** **is a local maximum in its geographic proximity to** ***D*****;** ***w*** **and** ***y*** **are farther from** ***D*****.**

Figure 2.3: greedy forwarding algorithm [3]

. In this type of topology, there is only one route possible, and would cause x to send information to a neighbor that is farther away from D than x is. So, in this case, x is closer to D than its neighbors w and y. Therefore, x would be forced to send its information to w or y which is farther away in geometric distance from the destination D than x is. The greedy forwarding algorithm will not allow this to happen so a different mechanism must be used to forward the information in these situations like a perimeter forwarding algorithm.

How the node finds its closest neighbor:

A beaconing algorithm tells a node the locations of its neighbors. Periodically, each node will transmit a beacon to the broadcast MAC address containing only its identifier (which is its IP address) and its location using two four-byte floating point values for the x and y coordinates. If a node doesn't receive a beacon from a neighboring node after a certain time, the GPSR router will assume the neighbor no longer exists and will remove it from its table of valid neighbors.

1-2: the perimeter forwarding algorithm:

Using the right-hand rule to find perimeters and combining that information with the no-crossing heuristic to force the right-hand rule. It is possible to find perimeters that enclose voids in regions where the edges of the graph cross. However, this algorithm doesn't always find routes when they exist. The no-crossing heuristic blindly removes whichever edge it encounters second in a pair of crossing edges and by doing so can partition the network. If it does, the algorithm will not find routes that cross the partition. While the no-crossing heuristic empirically finds over 99.5% of the n(n-1) routes among n nodes, in randomly generated networks, it is really bad for a routing algorithm to occasionally fail to find a route to a reachable node in a static, unchanging network topology. There are ways to solve this problem of crossing links from the network, one such method being Planarized Graphs. A Planar is a graph where no two edges cross2.4.

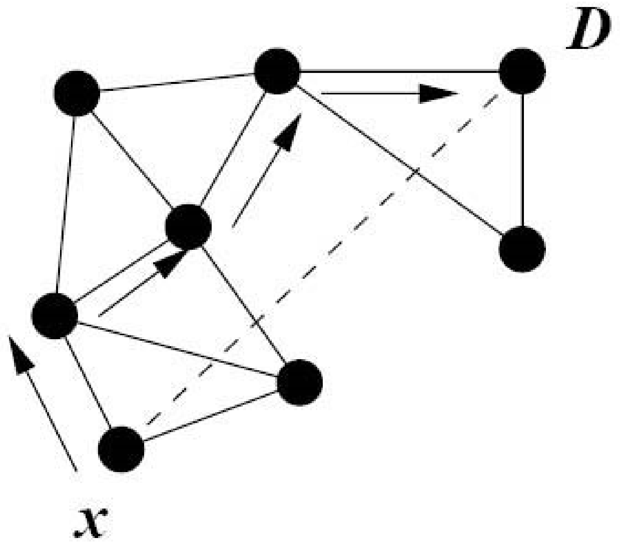

Figure 3: Perimeter Forwarding Example. ***D*** **is the destination;** ***x*** **is the node where the packet enters perimeter mode; forwarding hops are solid arrows; the line** $\overline{xD}$ **is dashed.**

Figure 2.4: greedy forwarding algorithm[3]

The GPSR is a responsive and efficient routing protocol for mobile, wireless networks. GPSR can be applied to Sensor networks, Rooftop networks, Vehicular networks, and ad-hoc networks.

3-Trusted Greedy Perimeter Stateless Routing

The T-GPSR is a variation of the GPSR protocol. The T-GPSR makes use of an integrated trust model to compute trust present in the local neighborhood. This trust is then associated with the routing process to form routes that bypass malicious nodes with a high probability of success. It is said through extensive simulations that the T-GPSR protocol outperforms the standard GPSR protocol.

2.3 Mobility Models in FANETs

The FANET mobility model depicts the maneuver of UAVs in a specific area, describing their movements over time, including changes in speed, direction, and acceleration. The models are frequently used for simulating new communication or navigation techniques. They are customized to meet the needs of each application, resulting in better performance and flexibility. Before actual deployment and evaluation, mobility models can simulate UAV behaviors practically, producing the most accurate possible findings. When evaluating FANET protocols, it is important to select the proper underlying mobility model. Several mobility models are proposed for FANETs to suit their unique characteristics [4]. These models are categorized as random-based, time-based, path-based, and topology-based mobility models [15]. Figure 2.5 illustrates the taxonomy of the mobility model in FANETs.

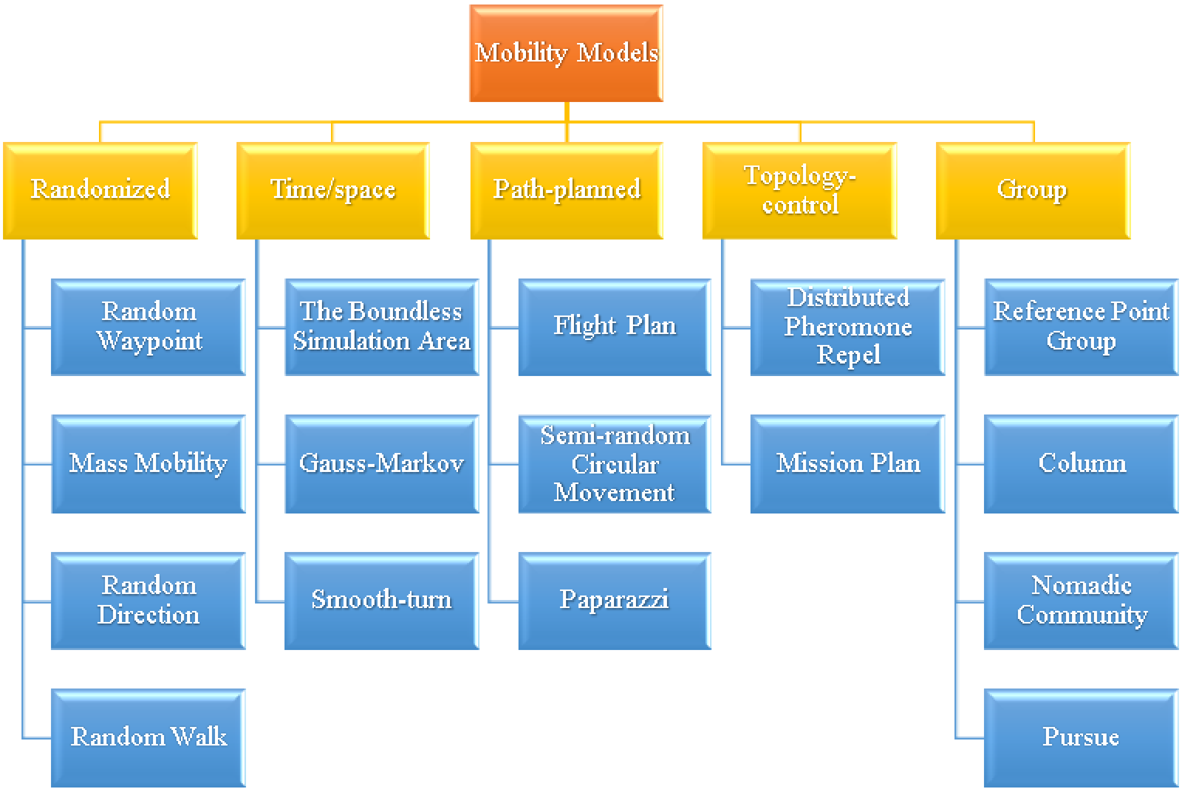

Figure 2.5: The categorization of mobility models for FANETs.

2.3.1 Randomized mobility models:

Pure randomized mobility models are simple models for network research. They represent numerous mobile nodes whose acts are fully independent of each other and their past actions at random, and the motions are also random concerning their direction, range, and duration. *Here are some examples of randomized mobility models:*

Random Waypoint (RWP) Mobility Model:

This model is commonly used in simulation scenarios to create unique movements based on straight paths where each node begins by pausing for a set number of seconds, known as the pause period. After the pause period has ended, the node picks a random end position within the simulation area and moves towards it with a randomly selected speed. Once the node reaches the end position, it stops and waits for a while before moving to a newly chosen end position. This process is repeated until the simulation period is over. This mobility model is based on three actions: going "straight", "turning left" and "turning right". UAVs decide on their action according to fixed probabilities. However, the random waypoint model is not appropriate for simulating aircraft cases as aircraft typically do not make sudden changes in direction or speed, nor can they stay in the same position for extended periods. Additionally, the model is limited in simulating UAV networks due to the sharp turns and sudden changes in direction and speed that are not characteristic of the movement patterns of UAVs. Simulation of random waypoint mobility model looks like that Fig 2.6

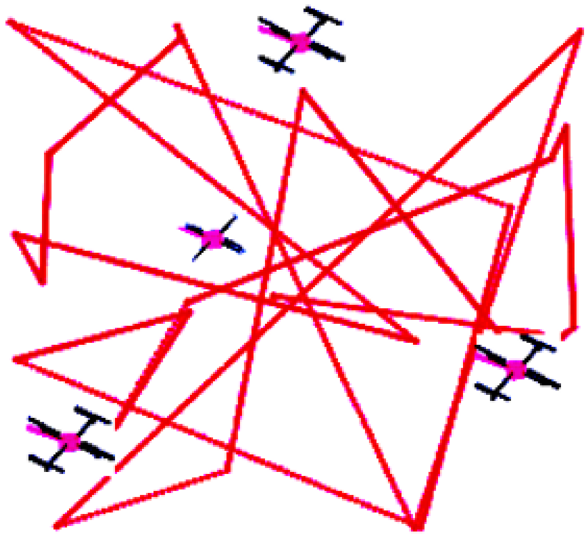

Figure 2.6: The trajectory of FANETs using RWP models [4]

Mass Mobility simple module

The Mass Mobility simple module is a random mobility model for a mobile host with mass. The host moves within the simulation area in this model following a specific pattern. It moves along a straight line for a certain period before turning. The duration of the straight-line movement is a random number, normally distributed with an average of 5 seconds and a standard deviation of 0.1 seconds.

When the host makes a turn, the new direction (angle) in which it will move is also a normally distributed random number. The average of this new direction is equal to the previous direction, and it has a standard deviation of 30 degrees. Additionally, the host's speed is a normally distributed random number with a controlled average ranging from 0.1 to 0.45 (unit/sec) and a standard deviation of 0.01 (unit/sec). A new random number

is selected as its speed when it makes a turn.
This mobility pattern is designed to model node movement in a way that reflects momentum, meaning that the nodes do not start, stop, or turn abruptly.

Random Direction (RD) Mobility Model

In contrast to the RWP scheme, where nodes choose a random end position, in the RD scheme, nodes randomly select a direction of movement (in degrees). At the beginning of the simulation, every node selects a direction within the range of 0 to 2π (in degrees). Subsequently, each node moves to the edge of the simulation area in the chosen direction. Upon the node reaches the edge, it will stop and wait for a set period then it randomly selects a different direction between 0 and π (in degrees), and the process continues in the same way. A minor modification of the RD model is the modified RD scheme, in which nodes randomly choose a direction and determine their end position at any place along that direction of movement. In this model, nodes are not obligated to move the simulation area's edge. The RD mobility model is suggested to solve the issue of RWP, where nodes concentrate at the central location of the simulation area. Despite overcoming the crisis of the RWP mobility model, abrupt stops and starts, and sharp turns continue to be limitations of the RD mobility model for simulating a UAV network.

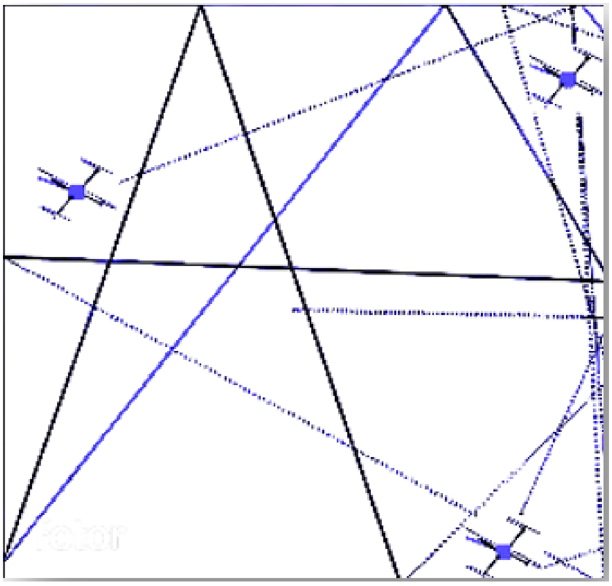

Figure 2.7: The trajectory of FANETSs using RD models [4]

Random Walk (RW) Mobility Model

The Random Walk Mobility Model is a simple model based on random directions and speeds. In this model, a mobile node (MN) transitions from its current location to a new one by randomly selecting a direction and speed to travel. The new speed and direction are chosen from predefined ranges, [speed min, speed max] and [0, 2π] respectively. Movements occur at fixed temporal intervals (t) or fixed distances traveled (d), after which a new speed and direction are calculated. If an MN reaches a simulation boundary, it 'bounces' off the border at an angle determined by the incoming direction and continues on this new path. In this model, an MN can alter its direction after traveling a set distance rather than a set time. The model is considered memoryless since it does not store any information about its previous locations or speed values. Consequently, the present speed and direction of a mobility node (MN) are independent of its past speed and direction. This can lead to unrealistic movements, such as sudden stops and sharp turns.

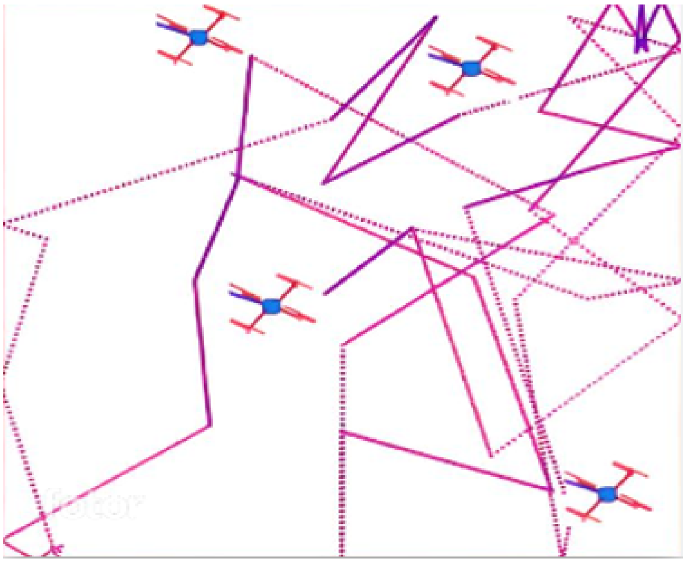

Figure 2.8: The trajectory of FANETs using RW models [4]

2.3.2 Time/space-dependent mobility models:

This category of mobility models aims to evade sudden, sharp changes in speed and direction, by employing various mathematical equations to ensure smooth changes in movement. The UAVs are managed through mathematical computations depending on the current location, previous directions, and velocities. To guarantee that movements are revised regularly and to avoid unexpected and rapid variations in speed and direction.

The Boundless Simulation Area Mobility Model:

The Boundless Simulation Area Mobility Model incorporates a unique relationship between an MN's previous and current direction of travel and velocity. Additionally, the model differs from others in handling the simulation area boundary. Rather than reflecting off or stopping at the boundary, MNs in this model continue traveling and reappear on the opposite side of the simulation area. As a result, a torus-shaped simulation area is created, enabling MNs to travel unobstructed.

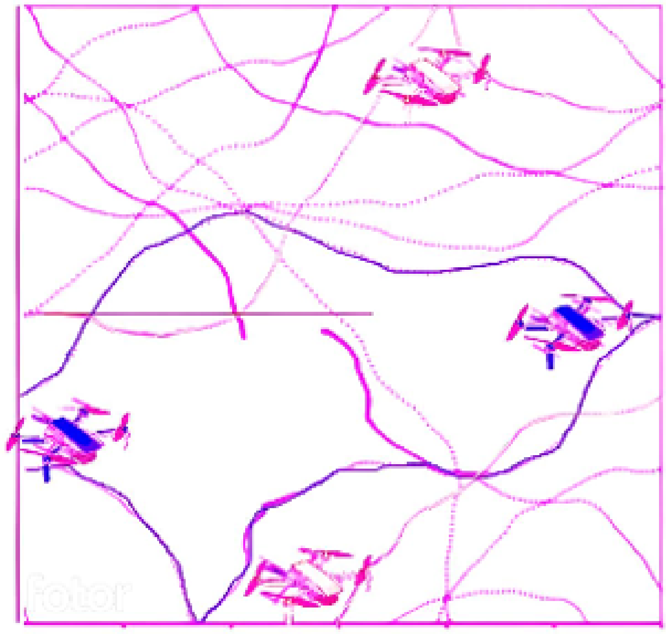

Figure 2.9: The trajectory of FANETs using BSA models [4].

Gauss-Markov (GM) Mobility Model:

The GM mobility scheme is a memory-based model introduced to be adaptable to varying levels of randomness using one tuning parameter. This parameter sets the extent of randomness. The node's position is always influenced by its previous position due to its high speed. The memory of the model determines the path of a UAV. At the outset, every node is allocated an initial speed and direction. At a specific interval of time, the direction and speed of the nodes are updated based on the previous direction and speed. Then, the next position is calculated according to the present direction of movement, speed, and position information. Specifically, the speed and direction at time n are calculated based on the value of speed and direction at time n-1 and a random variable. The GM Mobility Model is utilized to simulate the behavior of UAVs in a swarm. The size of the simulated area is variable. Figure X shows that the nodes move according to the previous node's position.

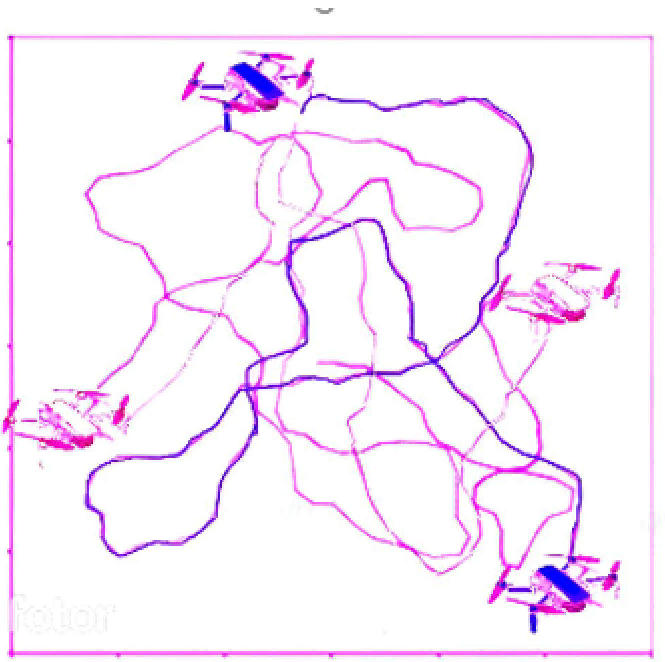

Figure 2.10: The trajectory of FANETs using GM models [4].

Smooth-turn (ST) Mobility Model:

This mobility scheme is created to be fit for patrolling applications. In the ST mobility scheme, each UAV randomly picks a turning point perpendicular to its direction to ensure a smooth trajectory. It circles that point for an exponentially distributed duration before picking a new turning point. The principal characteristic feature of this mobility scheme is that it emulates the smooth turns of UAVs rather than sharp turns and captures the spatiotemporal correlation of acceleration. Yet, it is important to note that a collision avoidance technique is not included in this mobility scheme.

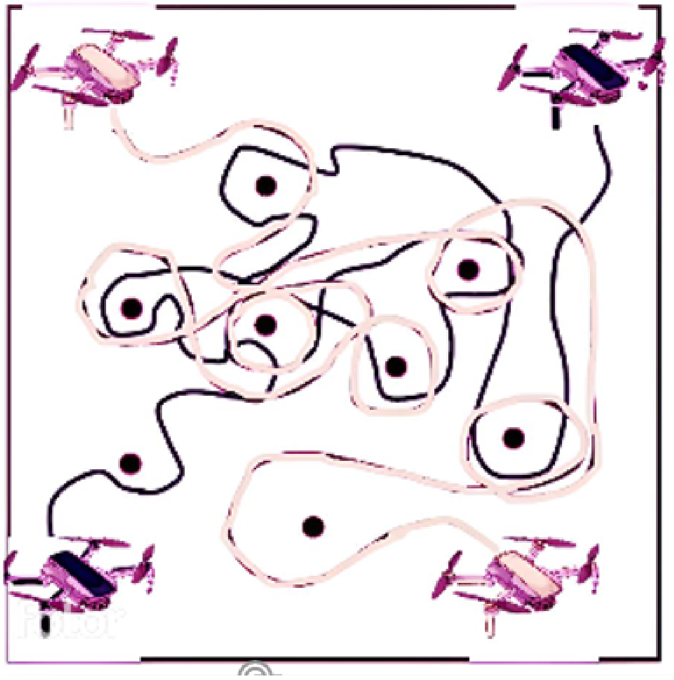

Figure 2.11: The trajectory of FANETs using ST models [4].

2.3.3 Path-planned mobility models:

In path-planned models, a pre-defined trajectory is generated and stored in each UAV, which guides it to move without making random movements. Once the UAV completes the predetermined trajectory, it can either repeat the same operation or change to a new one. Within this category, there are mobility models such as semi-random circular movement and paparazzi.

Flight Plan (FP) mobility model:

The Flight Plan (FP) mobility model is a method to define a UAV's flight plan in a special file for mobility. This model is used to create a time-dependent network topology map, as shown in Figure 2.12. The original flight plan gets modified if it doesn't match the current flight plan. The FP model is commonly used for tactical missions and aerial transportation operations, where the entire flight trajectory is planned before the mission starts. It is widely used in data collection from sensors to UAVs and can also be utilized in semantic-aware aircraft trajectory prediction. Figure 2.12 illustrates this approach.

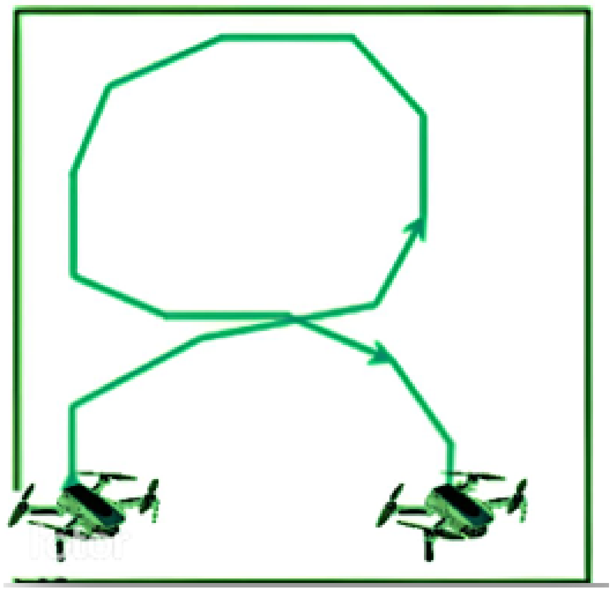

Figure 2.12: The trajectory of FANETs using FP models [4].

Semi-random Circular Movement (SRCM) Mobility Model

The SRCM mobility scheme is a model designed for circular mobility scenarios of UAVs. In this model, each UAV begins from a starting position on a predefined circle. It then moves along the circle with a randomly chosen velocity in the range of [V min, Vmax] towards the initial destination point. Once the UAV reaches the destination point, it pauses for a specified wait time before beginning its movement to the next destination point, which is also located on the same path on the circle. The UAV continues in the same manner to reach any remaining destination positions on the path.

After completing one full round of the circle, the UAV randomly selects another circle and radius around the same center as the next movement path. It then repeats the previous procedure. This model can be useful in simulating UAVs hovering over a predefined geographical area while collecting information. For instance, in search and rescue missions, where the possible position of the target entity is selected as the fixed central point, UAVs maneuver around the central point to locate the accurate target position [23].

Figure 2.13: The trajectory of FANETs using SRCM models [4].

Paparazzi Mobility (PPRZM) Model:

The Paparazzi Model (PPRZM) is a probabilistic model that simulates the behavior of Paparazzi UAVs within the Paparazzi autopilot flight motion. It is designed as a state machine that can perform five different movements: Waypoint, Scan, Stay-At, Eight, and Oval (shown in Figure 2.14).

- ***Stay-At:*** UAV hovers over a fixed position.

- ***Way-point:***UAV follows a straight path to a destination position.

- ***Eight:*** Aircraft trajectory has the 8 form around two fixed positions.

- ***Scan:*** UAV performing a scan of an area defined by two points along the round-trip trajectories.

- ***Oval:*** a shifted round-trip trajectory between two points with a turnaround once it passes each point.

Each movement pattern has a different probability of occurring, and it can be adjusted based on the application scenario.
At the beginning of the experiment, each UAV selects a starting position, movement type, and speed. Then, UAVs choose a random altitude that they maintain throughout the experiment. Figure 2.14 displays the different UAV movement patterns offered by PPRZM.

This model is useful for evaluating any communication protocol in the context of a swarm of collaborative UAVs, as it provides a realistic movement scenario. For instance, it can be used to compare several routing protocols to find the most suitable one for each UAV ad hoc network. Moreover, PPRZM can adapt to any type of mission by adjusting the probability of each movement type as needed.
PPRZM has been implemented in several FANET applications, such as software-defined networking FANETs (SDN-FANETs) and a system to predict UAV information. It is also used in UAV video dissemination services.

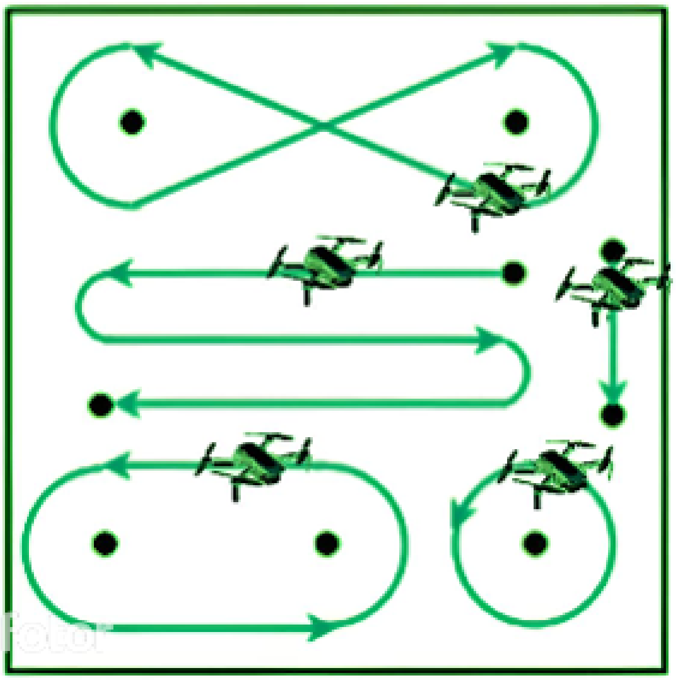

Figure 2.14: The trajectory of FANETs using PPRZ models [4].

2.3.4 Topology-control-based mobility models:

The real-time control of mobile node topology is necessary when network or mission constraints must be continuously satisfied. The UAVs must constantly be monitored to prevent unnecessary random motions, and they must coordinate their location with one another. Distributed Pheromone Repel (DPR) Mobility Model and Mission Plan Based Mobility Model are two mobility models in this category.

Distributed Pheromone Repel (DPR) Mobility Model:

In a reconnaissance scenario, the DPR model uses a pheromone map to guide the movement of UAVs. The pheromone map is a grid with segments of specified size, and each segment contains a timestamp that shows the last time the segment was covered. In DPR, the mobility of one UAV depends on the movement of the other UAVs, and the pheromone map that contains the areas covered by a UAV is regularly shared with other

UAVs in the network. As a result, a UAV decides whether to go straight or turn left or right based on its pheromone map. To increase the scan coverage, UAVs prefer to move to areas with a low pheromone scent. However, the pheromone repel mechanism used to achieve scan coverage may result in poor network connectivity because the UAVs are repelled away from each other.

Mission Plan-Based Mobility Model:

In the MPB model, aircraft already possess the entire trajectory information, which is typically preplanned. It means that the aircraft consistently follows a predetermined path where potential target location information is available. In the MPB mobility model, the mobility files are created and updated when the time is up. This model is designed for aircraft to move towards or away from the destination based on the mission plan. For each aircraft, starting and ending points are randomly selected, while velocity and flight time are provided. If an aircraft reaches its destination before the flight time is over, it changes direction towards the starting point and continues the flight as a round trip. as shown in Figure 2.15.

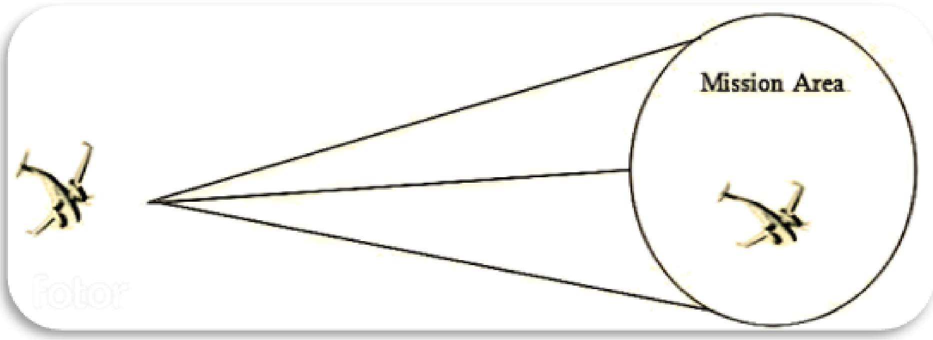

Figure 2.15: Mission Plan-Based Mobility Model [5]

2.3.5 Group Mobility Models:

In group mobility models, mobile nodes are divided into groups, each with a coverage area of a specific radius. Nodes within a group's coverage area are considered members of that group. Each group can move to any location within the network, whereas members of a group can only move within the group's coverage area.

Two main types of group mobility models can be classified based on how the mobile nodes move as a group. These two types are point-based group mobility (PBGM) models and region-based group mobility (RBGM) models. PBGM models involve nodes in a group following a lead point that determines the entire group's movement. This lead point can be a physical node or a logical center within the group [24]. On the other hand, RBGM models involve nodes following a path through a sequence of regions or areas.

PBGM and RBGM models can be further classified based on the interaction among group members. Individual group member (IGM) movements occur when group members move independently, influenced only by their lead point or targeted regions. Coordinated group member (CGM) movements, on the other hand, occur when a group member's movement may be influenced by or correlated with other group members due to existing interactions or relationships. To summarize, group mobility models can be categorized as PBGM with IGM, PBGM with CGM, RBGM with IGM, and RBGM with CGM. This group mobility classification is shown in Fig.2.16.

In this subsection, we will discuss the Reference Point Group Mobility (RPGM) Model. This model falls under the category of Point-Based Group Mobility (PBGM) with Individual Group Member (IGM) Movement. We will also explain the special cases of RPGM, which are Column (CLMN), Nomadic Community (NC), and Pursue (PRS) [6].

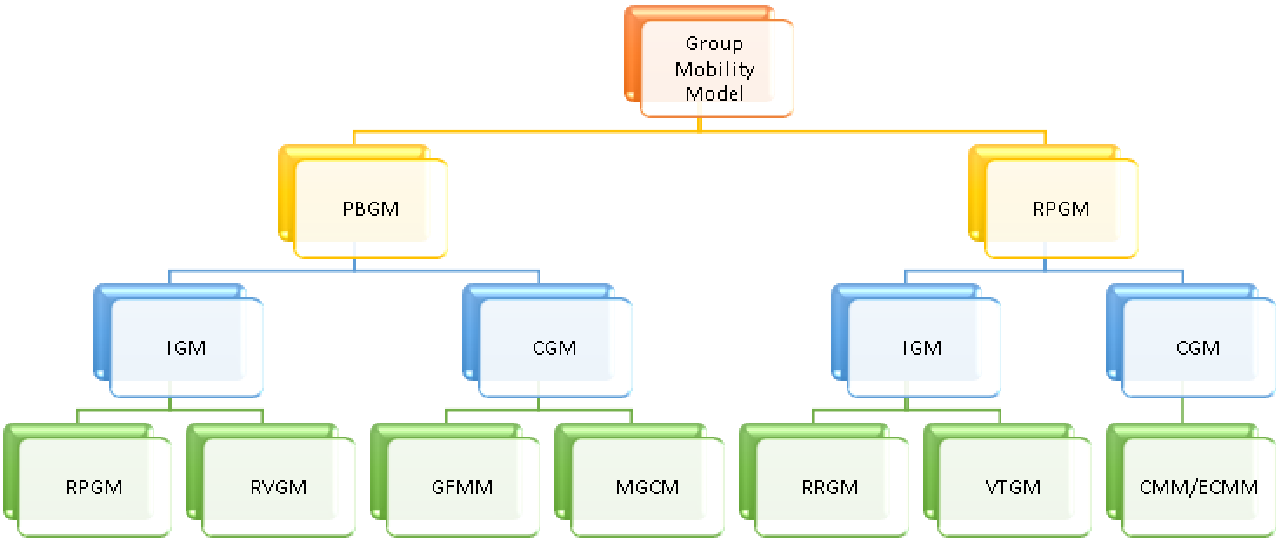

Figure 2.16: Classification of group mobility

Reference Point Group Mobility (RPGM) Model:

RPGM is a commonly used group mobility model. Each group has a lead point at the center of its coverage area, which defines the movement of the entire group, including its speed, direction, and acceleration. The lead point's trajectory can be predefined or obtained based on a certain entity mobility model. Additionally, each group member has a reference point that follows the lead point and keeps a stable distance and direction from the lead point. Whenever a group member's reference point moves to a new location, the member moves to a randomly chosen location within a circular area of radius R around the new reference point location.

RPGM defines two motion vectors: group motion vector (GM) and random motion vector (RM). GM represents the movement of the lead point that characterizes the group movement, while RM represents the movement of a group member concerning its reference point. A group member's new position is calculated as the sum of these vectors.

Figure 2.17provides an example of a group moving from time t to time t+1. When a lead point moves from time t to time t+1 based on GM, the reference point of each group member also moves to a new location based on GM. Then, based on RM, the position of each group member is updated to a new location in the area of its new reference point location [6].

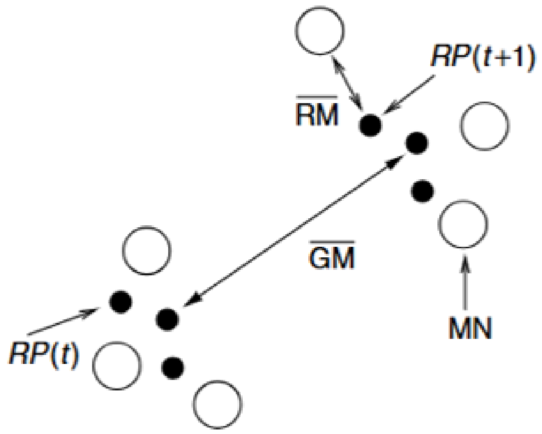

Figure 2.17: Movements of three MNs' using the RPGM model [6]

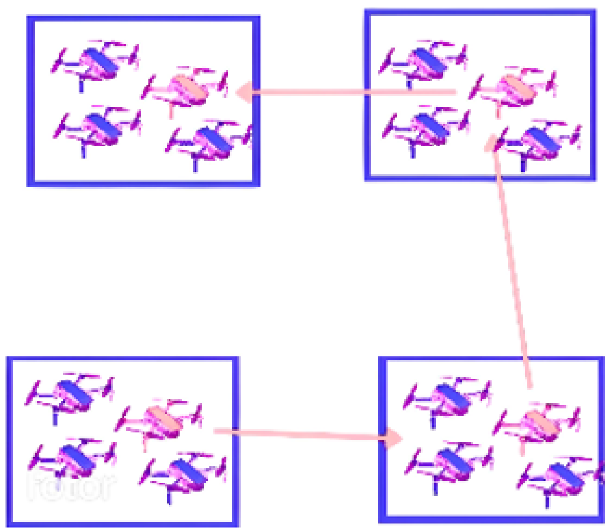

Figure 2.18: The trajectory of FANETSs using RPGM [4]

Column Mobility model:

This model defines a group of mobility nodes (MNs) that move around a provided line (or column), which is moving in a forward direction (e.g., a row of soldiers advancing toward the enemy). A slight adjustment to the Column Mobility Model enables individual MNs to trail one another (e.g., a line of young children walking to their classroom in a single file).

To implement this model, an initial reference grid (forming a column of MNs) is established. Each MN is initially positioned with its reference point on the grid and is then free to move randomly around its reference point via an entity mobility model (e.g., using the Random Walk Mobility Model, as the entity mobility model). The new reference point for a given MN is determined by the formula: new reference point = old reference point + advance vector, where the old reference point represents the MN's previous reference point and the advance vector is a predefined offset that moves the reference grid. The predefined offset is calculated. Figure 2.19 illustrates four MNs operating within the Column Mobility Model. As depicted, the MNs roam closely around their respective reference points. When the reference grid moves (based on a random distance and a random angle), the MNs follow the grid and then continue to roam around their respective reference points [6].

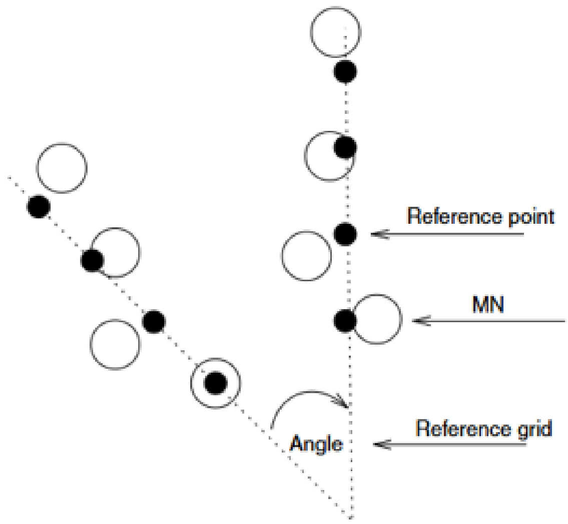

Figure 2.19: Movements of four MNs using the Column Mobility Model[6]

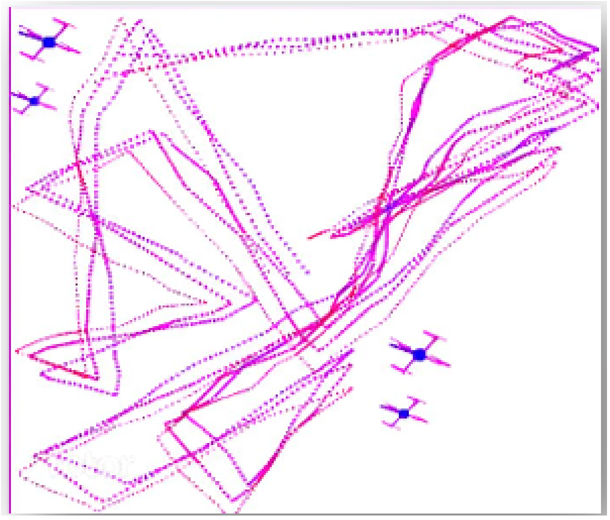

Figure 2.20: The trajectory of FANETs using CLMN [4]

2.3.6 Nomadic Community Mobility Model:

Similar to how ancient nomadic societies used to migrate from one place to another, The Nomadic Community Mobility Model represents a group of mobile nodes that move collectively from one location to another. Each individual in a community or group of MNs has their own space and moves randomly within it.
In the Nomadic Community Mobility Model, each mobile node (MN) uses an entity mobility model, such as the Random Walk Mobility Model, to roam around a given reference point. When the reference point changes, allies in the group travel to the new area defined by the reference point and then begin roaming around the new reference point. When the group's reference point changes, all MNs move to the new area defined by the reference point and start roaming around it. The mobility model's parameters determine the maximum distance an MN can move from the reference point.
In the Nomadic Community Mobility Model, MNs share a common reference point. Therefore, they are less constrained in their movement around the specified reference point.
In Figure 2.21, you can see an illustration of seven Mobile Nodes (MNs) that are moving using the Nomadic Community Mobility Model. The black dot represents the reference point that shifts from one location to another. As shown, the MNs follow the movement of the reference point. Although a simulated movement pattern for the Nomadic Community Mobility Model has not been illustrated yet, one could easily be created by using the implementation of the RPGM model. In this pattern, we can observe a group of individuals moving in a circular motion around a central point. Each individual selects a new reference point within a certain radius and moves towards it, creating a dynamic and ever-changing pattern of movement for the group as a whole [6].

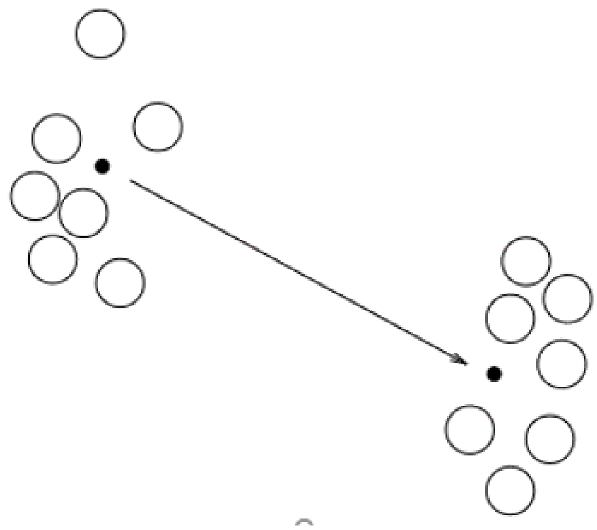

Figure 2.21: Movements of seven MNs using the Nomadic Community Mobility Model[6].

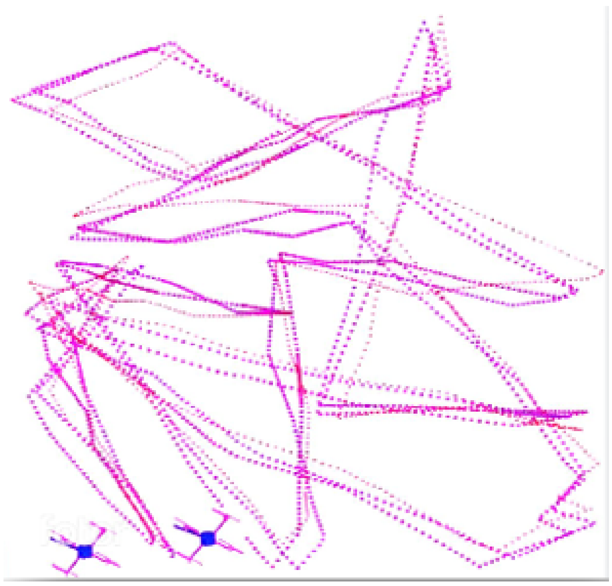

Figure 2.22: The trajectory of FANETSs using NC models [4].

Pursue Mobility Model:

The Pursue Mobility Model aims to simulate MNs tracking a specific target, such as police officers pursuing an escaped criminal.

The amount of randomness is limited for each MN to track the pursued MN effectively. The subsequent position of the MN is computed by combining its current position, a random vector, and an acceleration function. Figure 2.23 illustrates six mobile nodes (MNs) moving using the Pursue Mobility Model. The white node represents the target node, while the solid black nodes represent the pursuing nodes. Generating a simulated movement pattern for the Pursue Mobility Model is easily achievable by implementing the RPGM model [6].

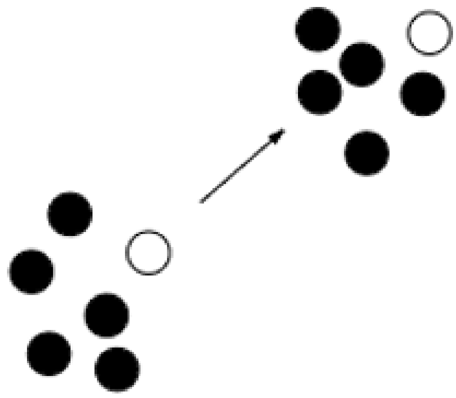

Figure 2.23: Movements of six MNs using the Pursue Mobility Model [6]

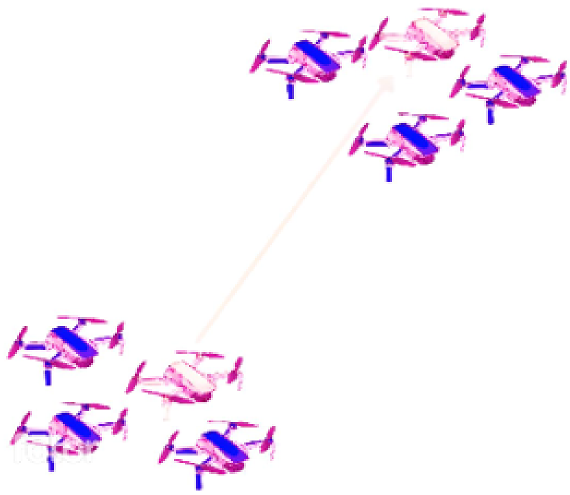

Figure 2.24: The trajectory of FANETs using PRS models [4].

2.4 CONCLUSION

In this chapter, a literature review of FANETs has been conducted, with a focus on FANETs routing protocols. Additionally, the issue of mobility, identified as the most challenging problem for FANETs, has been explored. Various mobility models that address communication issues arising from frequent topology changes in FANET networks have been discussed. Moreover, the design challenges of communication, cooperation, and collaboration in multi-UAV systems are highlighted. This paper examines ad-hoc networks among UAVs, referred to as Flying Ad-hoc Networks (FANETs), as a distinct network category. Detailed discussions on mobility models such as Random Waypoint, Gauss-Markov Mobility, Semi-Random Circular Movement, Mission Plane-Based, Pheromone-Based, and Paparazzi Mobility models are provided.

Chapter 3

Performance Analysis

3.1 Introduction:

In this chapter, we focus on the simulation of our proposal after having studied the overall architecture of FANET in the previous chapter. First of all, we investigated the effectiveness of the GPSR routing protocol by testing it within three distinct mobility models: Random Way Point, Mass Mobility, and Gauss Markov. To achieve this, we employed a variety of simulation tools. Initially, we used the OMNeT++ simulator, to replicate drone behaviors in a controlled environment, enabling us to simulate their interactions and movements based on specific parameters. Subsequently, we utilized the INET and AVENS simulation frameworks, to simulate the communication processes between drones. These tools provided advanced options for representing wireless communications and facilitated the handling of data packet exchanges between drones, allowing for a comprehensive assessment of the GPSR routing protocol across different mobility scenarios.

3.2 Different system installations:

3.2.1 Network generation:

To generate the network and install the software necessary for the communication between drones, follow these steps:

- **Step 1:** Create file collection folder - Create a new folder on your computer to collect all files necessary for network generation.

- **Step 2:** Software installation

  1. Download OMNeT++ version 4.6 from the official website at the following address:https://omnetpp.org/software/2014/12/02/omnet-4-6-released and follow the instructions to install it on your computer.
  2. Download AVENS from https://www.lsec.icmc.usp.br/en/avens and follow the specific instructions provided with the software to install it correctly.
  3. Download the INET framework version 3.2.4 corresponding to OMNeT++ from https://inet.omnetpp.org/Download.html and follow the instructions to install it.

- **Step 3:** Configuration in OMNeT++ - Launch the OMNeT++ software on your computer.

  – Import the AVENS software and the INET framework into OMNeT++ by following the instructions provided with the software.

Once you have completed these steps, you should be ready to generate the network and observe communications between drones. Be sure to check out the documentation and user guides provided with each software to get detailed information on how to use them effectively.

3.2.2 OMNeT++ :

OMNeT++ is a flexible and modular C++ simulation library and framework, designed primarily for building network simulators. The term "network" is broadly defined to include wired and wireless communication networks, on-chip networks, queueing networks, and more. Specific functionalities for different domains, such as support for sensor networks, wireless ad hoc networks, Internet protocols, etc., are provided by model frameworks developed as independent projects. OMNeT++ features an Eclipse-based IDE, a graphical runtime environment, and a variety of other tools. Extensions are available for real-time simulation, network emulation, database integration, SystemC integration, and more. OMNeT++ is distributed under an Academic Public License.

OMNeT++ provides a component-based architecture for models. Components(modules) are programmed in C++ and assembled into larger components and models using a high-level language (NED). Model reuse is free. OMNeT++ offers extensive GUI support, and its modular architecture allows for easy integration of the simulation kernel (and models) into various applications.

3.2.3 INET :

The INET Framework is an open-source model library for the OMNeT++ simulation environment. It provides protocols, agents, and other models for researchers and students working with communication networks. INET is especially valuable for designing and validating new protocols or exploring innovative or unconventional scenarios.

INET includes models for the Internet stack (TCP, UDP, IPv4, IPv6, OSPF, BGP, etc.), wired and wireless link layer protocols (Ethernet, PPP, IEEE 802.11, etc.), support for mobility, MANET, DiffServ, MPLS with LDP and RSVP-TE signaling, various application models, and numerous other protocols and components. Several other simulation frameworks use INET as a foundation and extend it in specific directions, such as vehicular networks, overlay/peer-to-peer networks, or LTE.

3.2.4 AVENS:

AVENS is part of a major research project aimed at providing a testbed for simulating the flight and control of UAVs (Unmanned Aerial Vehicles) using various controlled and scalable configurations. The primary goal of AVENS is to offer a simulation testbed for virtual experiments on network coverage and connectivity between drones flying cooperatively or sharing the same airspace.

AVENS aims to deliver a platform for analyzing mobile ad hoc networks where drones act as mobile nodes sharing the wireless medium to exchange messages. It aims to use a flight simulator to pilot aerial vehicles and a network simulator to obtain network measurements such as transmission throughput, goodput, RSSI (Received Signal Strength Indication), data rate, packet loss, retransmissions, and more.

3.3 Simulation setup:

To construct an accurate representation of our network environment, we meticulously configured simulation parameters as outlined in TABLE II. These parameters include crucial elements such as node mobility models, transmission ranges, channel conditions, and various other network characteristics, all detailed comprehensively in the provided configuration [25].

3.3.1 Simulation parameters:

Parameter	Values
Simulation Time	300s
Simulation Area	1000m×1000m×1000m
Transmission Range	500m
Transfer rate	2Mb/s
Starting energy	5J
Size of data packets	64 bytes
Mobility model type	Random Way Point, Mass Mobility and Gauss Markov mobilities.
Speed of the drone	8 m/s, 20 m/s
Density of drones	20, 50, and 100
Noise application	-90dBm

Table 3.1: PARAMETERS FOR SIMULATION

3.3.2 SC-SF global configuration:

Figure 3.1 illustrates the "Scenario" network module, representing the overall simulation scenario. It contains parameters and submodules defining the simulation environment.

- **radioMedium:** Managing the wireless communication medium, handling the transmission and reception of radio signals between different network nodes.

- **configurator:** A setup tool that helps configure network parameters, including IP addresses, routing protocols, and other network settings.

- **routingTableRecorder:** Used for logging or tracking changes in the routing table, which contains information about the paths data packets take through the network.

- **scenarioManager:** This component manages various scenarios or test cases within the network. It orchestrates events or simulations to evaluate network performance under different conditions.

Figure 3.1: "Scenario" network diagram within the OMNeT++ IDE

Configuring omnet.ini:

⋆ ***network = GPSRUAVNetwork :***The network is defined by the GPSRUAVNetwork module.

⋆ ***record-eventlog = true :***Enables event logging, which records events that occur during the simulation.

⋆ ***sim-time-limit = 300s:***This sets a time limit for the simulation, specifying that the simulation should run for a maximum of 300 seconds (5 minutes).

⋆ *****.wlan[*].typename = "IdealWirelessNic" :*** sets the type of wireless network interface card (NIC) to ***IdealWirelessNic*** for all WLAN interfaces in the network. The ***IdealWirelessNic*** typically represents a simplified wireless NIC model with idealized behavior.

⋆ *****.wlan[*].mgmt.frameCapacity= 10 :***sets the capacity for management frames in the WLAN NICs to 10. Management frames are used for network control, such as association, authentication, and coordination.

⋆ *****.host[*].mobilityType = "MassMobility":***sets the mobility type for all hosts to the Mass mobility model.

- ***host[*].mobility.changeInterval = normal(5s, 0.1s)***
- *****.host[*].mobility.changeAngleBy = normal(0deg, 30deg)***

- ***.host[*].mobility.speed = normal(8mps, 0.01mps)*

  Parameters for change intervals, angle changes, and speed for MassMobility.

⋆ ***.energyStorageType = "SimpleEnergyStorage" :***The type of energy storage is set for all nodes to SimpleEnergyStorage, which is a straightforward model for managing energy capacity.

⋆ ***.energyConsumerType = "StateBasedEnergyConsumer" :*** The type of energy consumer sets to StateBasedEnergyConsumer, which adjusts energy consumption based on the state of the node (e.g., active, idle).

⋆ ***.energyStorage.nodeShutdownCapacity = 0J :*** specifies that the node will shut down when the energy capacity reaches 0 joules.

⋆ ***description = network layer for IPv4 network protocol only (default):*** provides a description indicating that the network layer is configured for IPv4 protocol.

3.3.3 Results and discussion:

To assess the performance of the GPSR routing protocol, we conducted a comparative study that involved changing mobility models. This change acted as a standard for evaluating how mobility models affect the protocol's effectiveness. We aimed to understand how various mobility models affect the protocol's ability to transmit data reliably and its response times. To measure the effectiveness of the GPSR protocol, we used the following criteria:

- 1. **End-to-End Delay:** This metric represents the average time data packets move from the originating drone to the receiving drone, incorporating different types of delays encountered during the transmission. The delay is quantified in milliseconds (ms).

  2. **Loss Rate:** is a metric measuring the percentage of data packets that do not reach their destination in a network. Calculated by dividing lost packets by total sent packets and multiplying by 100, it reflects network reliability.

  3. **Packet Delivery Ratio:** Percentage of successfully received packets by the receiver out of the total packets sent. Calculation: (Number of successfully received packets / Total packets sent) * 100.

  4. **Energy Consumption:** Quantifies the total energy consumed by network nodes, including drones, over a specific period. It is measured in Joules (J).

As shown in Fig 3.2, Based on the values that are provided for the End-to-End Delay metric under different mobility models and varying numbers of nodes, it seems that the Gauss-Markov Mobility model has a significant impact on the End-to-End Delay. Specifically, the value for this model increases substantially as the number of nodes (drones) increases. The sharp increase in the End-to-End Delay value at 70 drones for the Gauss-Markov Mobility model suggests that this model is influencing the delay metric more prominently compared to the other mobility models. Therefore, in this context, it appears that the Gauss-Markov Mobility model has the most significant influence on the End-to-End Delay as the number of nodes increases. However, it's important to note that this interpretation may vary based on the specific simulation parameters and characteristics of our scenario.

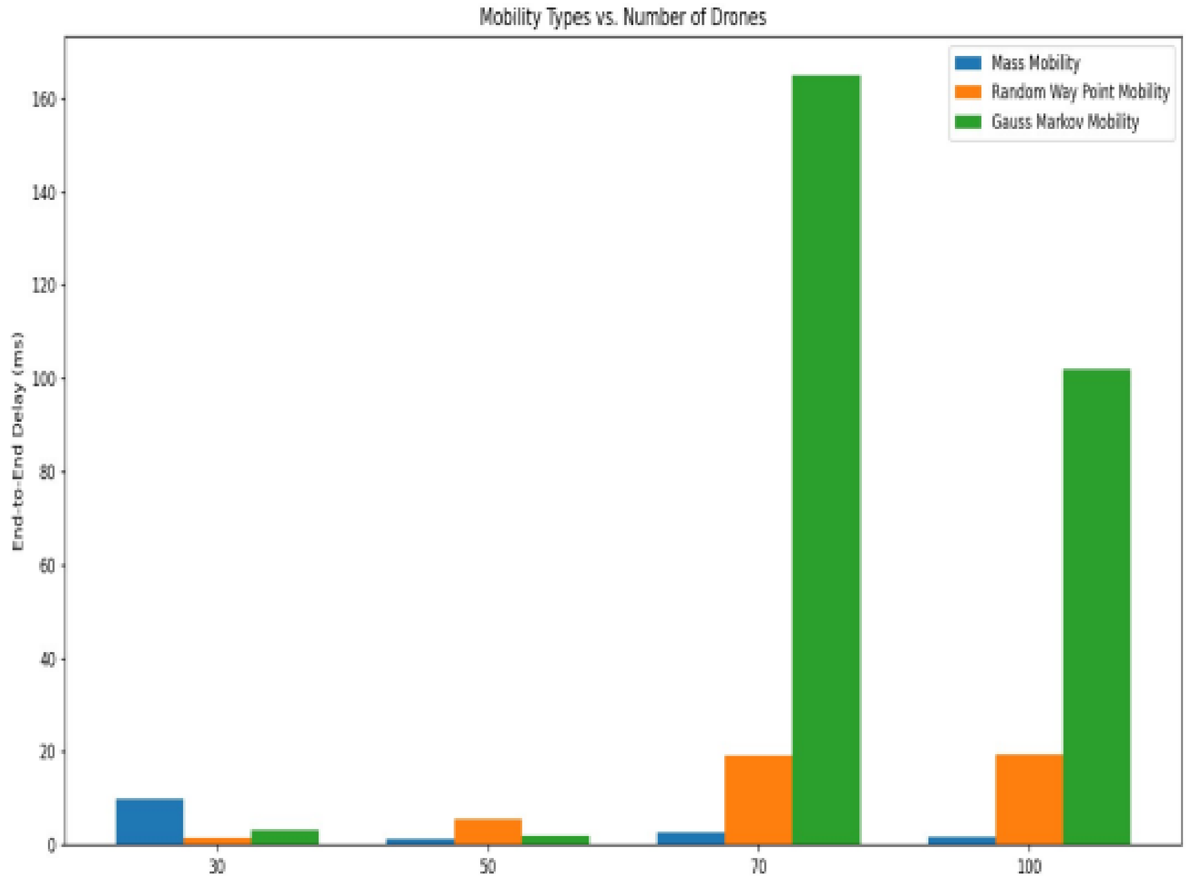

Figure 3.2: Effect of mobility models on End-to-End Delay with varying node numbers

Based on the values exhibited in Fig.3.3, the Loss Rate metric under different mobility models and varying numbers of drones, it appears that the Mass Mobility and Random Way Point Mobility models exhibit varying trends in loss rates, while the Gauss-Markov Mobility model shows consistently high loss rates across different scenarios. The significant increase in loss rates for Mass Mobility at 70 drones and Random Way Point Mobility at 50 drones suggests these models are particularly sensitive to changes in the number of drones. However, the Gauss-Markov Mobility model consistently exhibits high loss rates across all scenarios, indicating that this model has a substantial impact on the Loss Rate metric, especially as the number of drones increases.

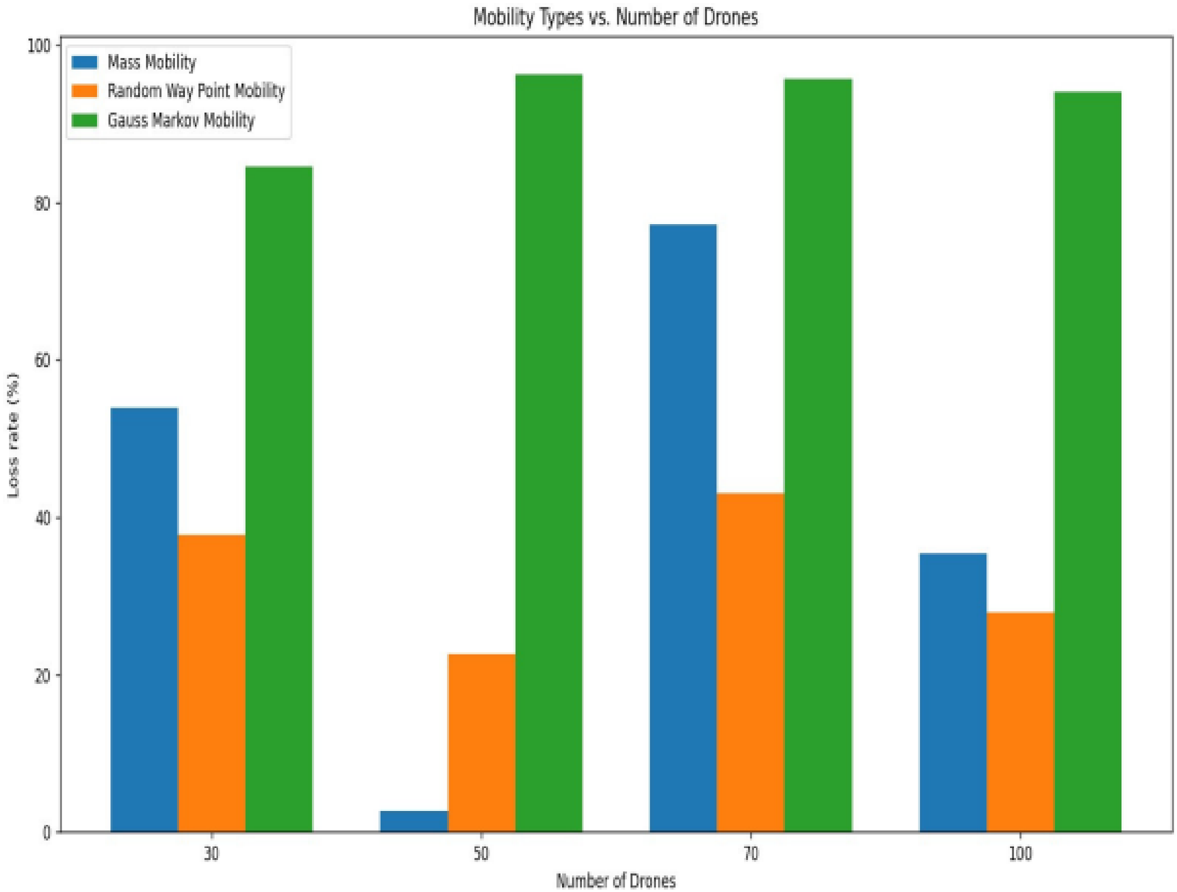

Figure 3.3: Effect of mobility models on Loss Rate with varying node numbers

The obtained results, shown in Fig.3.4 investigate PDR across varying numbers of drones, specifically 30, 50, 70, and 100. Mass Mobility exhibits significant variability in PDR across different drone densities. The PDR is particularly high at 50 drones but drops considerably at both lower and higher drone densities. Random Way Point Mobility shows a more consistent performance in terms of PDR, with a peak at 50 drones and relatively stable values at other drone densities. Gauss Markov Mobility consistently demonstrates low PDR values across all scenarios. While the PDR is the lowest at 50 drones, the values remain relatively low at other drone densities.

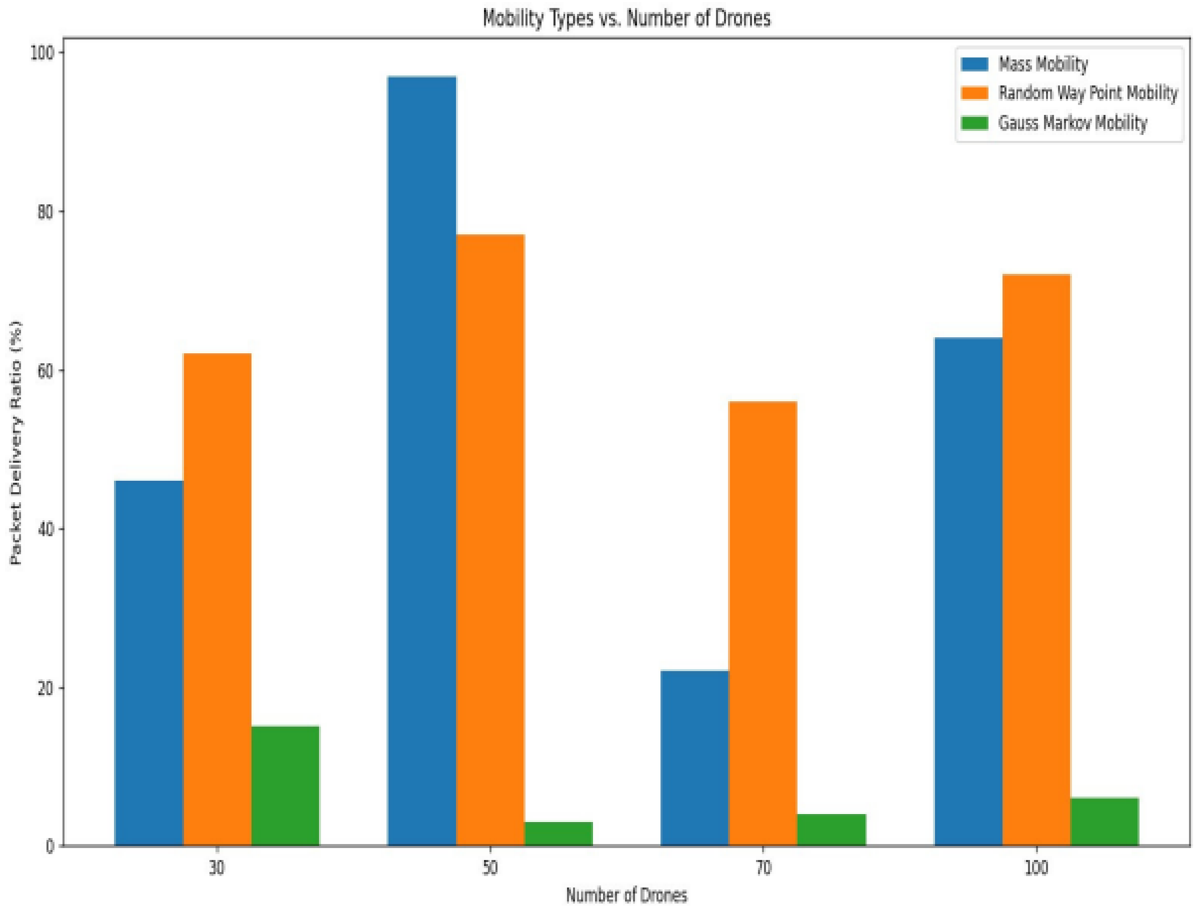

Figure 3.4: Effect of mobility models on Packet Delivery Ratio with varying node numbers

The results in Fig.3.5 show that Mass Mobility exhibits an increasing trend in energy consumption as the number of drones rises. This suggests that energy consumption per drone is proportional to the number of drones in the network. Random Way Point Mobility shows a moderate increase in energy consumption with the growing number of drones. The values indicate that the energy consumption per drone is relatively stable across the examined scenarios. Gauss Markov Mobility displays a gradual increase in energy consumption as the number of drones increases. Similar to Mass Mobility, suggests a proportional relationship between energy consumption and the number of drones. the progressive energy consumption in the case of Gauss Markov Mobility can be justified by The randomness in movement might lead to more distributed energy usage across the network.

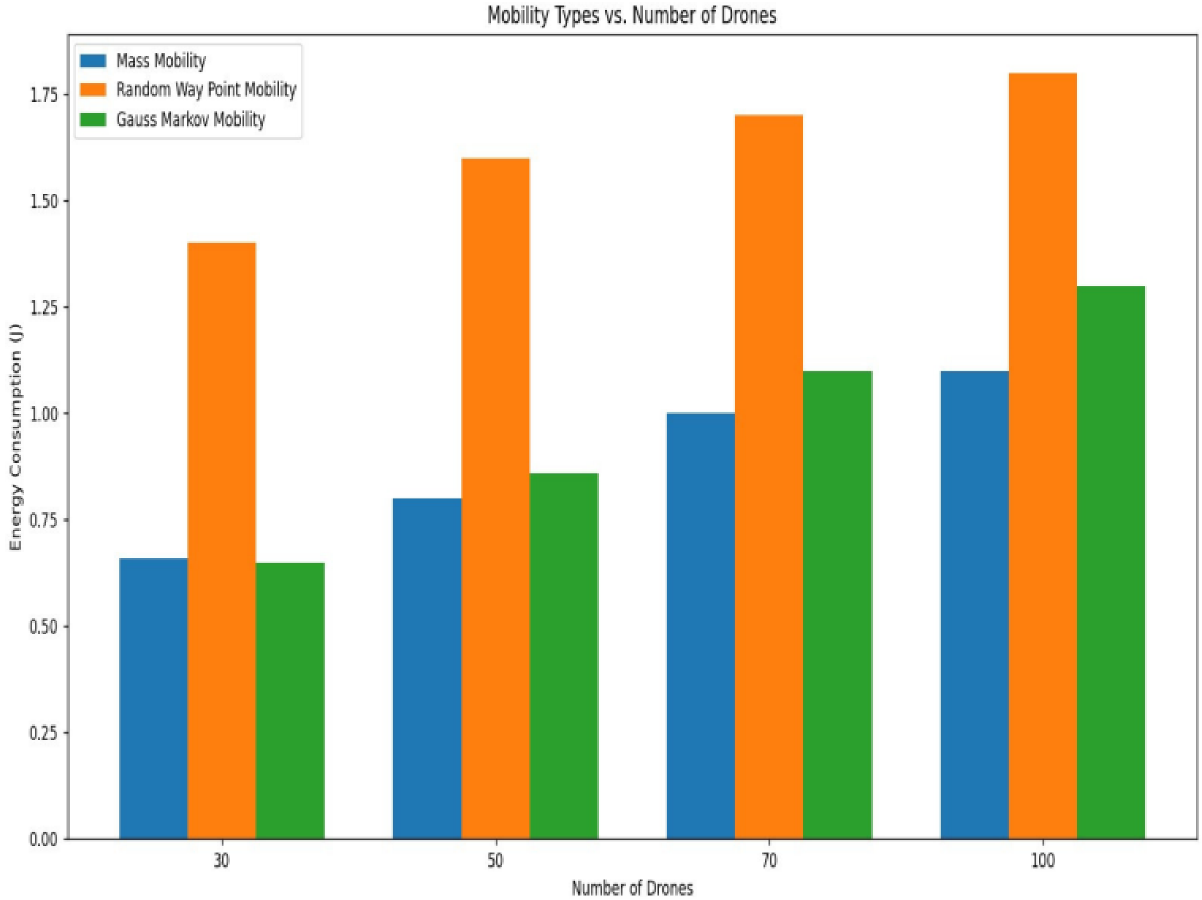

Figure 3.5: Effect of mobility models on Energy Consumption with varying node numbers

3.4 Conclusion:

In this chapter, we have discussed the different stages of installing the system, including configuration in working frameworks OMNeT++, INET, and AVENS.

Our study examined the GPSR routing protocol, focusing on how different mobility models affect its performance. We found that the Gauss-Markov Mobility model significantly increases End-to-End Delay as the number of drones rises. The Mass Mobility and Random Way Point models showed sensitivity to drone density changes, impacting network reliability metrics. Energy consumption trends revealed that both the Mass Mobility and Gauss-Markov models increase energy use proportionally with more drones, while the Random Way Point model had higher per-drone energy consumption. Future research should optimize GPSR parameters and explore the interaction between mobility models, communication range, and transmission power to enhance protocol efficiency.

General Conclusion

Our research focused on the performance analysis of mobility model-based routing protocols in flying ad hoc networks. We explored various aspects of these areas, including concepts, architectures, routing protocols, and mobility models.

In the first chapter, we laid the groundwork by defining FANETs, highlighting their characteristics, and potential applications, and examining different architectures and components, energy consumption, and lifespan.

In the second chapter, we discussed various categories of routing protocols. These include Reactive (On-Demand) Routing Protocols, Proactive (Table-Driven) Routing Protocols, Hybrid Routing Protocols, Position-Based (Geographic) Routing Protocols, and Hierarchical Routing Protocols. Additionally, we explained mobility models in the FANET that can simulate UAV behaviors. These mobility models are categorized as random-based, time-based, group-based, path-based, and topology-based.

In the third chapter, we looked at how well the Greedy Perimeter Stateless Routing (GPSR) routing protocol performed under different mobility models, including Random Waypoint Mobility (RWP), Mass Mobility, and Gauss Markov mobility models. We used the OMNET++ simulator to thoroughly test and evaluate the results, discussing their significance and limitations.

In summary, our research has led to a deeper understanding of FANETs, researching preliminary UAV routing protocol with various mobility models to examine factors such as latency, average end-to-end (E2E) delay, packet delivery ratio (PDR), etc. in a dynamic environment with numerous nodes counts and node speed variations, for estimating network performance and behavior.

Our experimental results have shown the effectiveness of our approach. For prospects, there are still several challenges due to the high mobility of UAVs, including unstable connections, limited connection options, and frequent topology changes. The rapid movement of UAVs leads to frequent link breakages, making it difficult for routing protocols to maintain accurate routing tables and find new routes quickly. These areas provide exciting opportunities for future research and development.

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