Group Mobility Models Drone Swarm Networks

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Annex A

THESIS ACCEPTANCE CERTIFICATE

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To the ones who carved their way to eternal satisfaction

To the One with which we are who we are

Abstract

Group Mobility Models (GMM) Drone Swarm Networks is an emerging technology with manifold requirement in modern warfare and surveillance [1] means. Architectures of various drone swarm networks were studied with their practical efficacy to cater for future requirements in defence, agriculture, surveillance [1], security, searching, disaster management [5], logistics chain management with main focus on proposing of Hybrid GMM for search and pursuit of a target [30] in a region. The proposed Mobility Model is combination of existing two mobility models i.e. Column Mobility Model and Pursue Mobility Model. The proposed GMM has been implemented using network simulation tool NS2[2] besides BonnMotion[3] open-source software for investigating various mobility models and even generating mobility files before proposing the subject model. Column Mobility Model will help in extensive search of the area or a region using Drone Swarms as Swarm will be divided in various columns/ subgroups for better coverage while Pursue Mobility Model will be individual drone response after the target has been detected for tracking and trailing the target. The Drone Swarm Networks can use this Hybrid model to effectively search and pursue a target like Police search and pursue criminals after crime scene or like Armed Forces including Army and Airforce scout and pursue terrorists after any miscreant attack. Performance of routing protocols[4] AODV and OLSR was evaluated in proposed mobility model using various performance metrics like average end-to-end delay, average throughput, total dropped packets, packet delivery ratio and even retransmitted packets to ascertain how it will behave with regards to scalability of the swarm, performance impact of frequent agile movements in pursue behavior and searching movements in column behavior, network congestion and traffic. AODV performed better than OLSR with regards to all mentioned performance metrics in proposed GMM. Therefore, the proposed model was implemented for search and pursuit operations by Drone Swarm Networks using AODV routing protocol[4].

Keywords: *Group Mobility Model(GMM), Pursue Mobility Model, Column Mobility Model, AODV, OLSR, NS2[2], BonnMotion[3], Drone Swarm Networks*

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Abbreviations	
AODV	Ad-hoc On Demand Distance Vector
OLSR	Optimized Link State Routing
NS-2	Network Simulator
RCP	Required Communication Performance
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
FEC	Forward Error Correction
AED	Average End-to-End Delay
AES	Advanced Encryption Standard
MANETs	Mobile ad hoc networks
VANETs	Vehicular ad hoc networks
CBR	Constant Bit Rate
VBR	Variable Bit Rate
FTP	File Transfer Protocol
RED	Random early detection
	Random early discard
	Random early drop
CBQ	**C***lass-based queuing*
RP	*Routing protocol*
GMM	*Group Mobility Model*

CHAPTER 1 : INTRODUCTION

This chapter elaborates the need and efficacy of GMM Drone Swarm Networks besides its brief details. Contribution of the research work/ thesis has been presented at the end of this chapter.

1. Introduction Group Mobility Models Drone Swarm Networks

Swarm Drone is analogous to locust swarm[6], birds flock[7] or an ant colony. Various creatures move in the form of swarm, flocks and colonies. Birds migrate from one continent to another using various formations in the form of nature. We can try imitating their movements and take guidance to design and construct our movement pattern i.e. swarm drone network using various routing protocols[4] and group mobility models. How they will collaborate to achieve an assigned task without any loss in minimum possible time. [10]

1.1. Drone Swarm Networks

Drone swarm networks is collaboration[19] and coordination of multiple drones to achieve unified task/ mission[18]. They work cohesively and in a synchronized manner. Artificial intelligence and machine learning is also being used in drone swarm networks to further optimize communication and collaborative task completion. The biggest advantage of drone swarm networks is their redundancy allowing to continue functioning even if individual drones are lost or malfunction or even destroyed. Moreover, they can operate autonomously, without any need for human intervention which makes them highly adaptable according to dynamic/ fluid situations. But on the other side, there are ethical, privacy and safety concerns as well for use of autonomous swarm drone and further challenges include the advance communication, durable power arrangement and control systems to ensure their collaboration and coordination to maintain safety.[10]

Swarm drone can be used in many applications including environmental monitoring, agriculture monitoring, damage assessments in a disaster area for efficient disaster management and even military operations. Drone swarm networks are still continuously evolving and have great potential to revolutionize various industries and can provide lot of opportunities and avenues for innovation and creativity.

1.2. Need for Swarm Drones and Group Mobility Model Drone Swarm Networks

Swarm Drones are fleet of UAVs that has high efficiency with low cost of fuel and time. They can cover wide area in limited time frame with optimal results. They have improved robustness with fault tolerance capabilities. They achieve high flexibility due to their group mobility models and networking. Tasks are shared and divided among the swarm and in continuous collaboration throughout the mission [18]. That collaboration [19] is possible through Group Mobility Model Drone swarm networks. Swarm Drones work on the basis of their GMM and many tasks like disaster management[5], search and rescue operations, agriculture monitoring from insect/ locust attacks[6], irrigation monitoring, search and pursuit operations, extreme weather alerts,/ warning, drone swarm herding of birds of animals flock[7], traffic control, volcano eruption monitoring, surveying and mapping, damage assessment during any natural calamity, defence purposes, delivery of logistics like food, ration , ammunition and even weapons to troops deployed on forward lines of defence and mountains which are otherwise not easily accessible due to difficult terrain, no trafficability and even due to excessive snow can be made possible through swarm drones.

1.3. Concept of Formation of Drone Swarm Networks

The concept as already mentioned above has been inspired by animal behaviours like bird flocking[7] or fish schooling. Certain formations in a group or swarm can enhance the survival of individuals. Complex and complicated tasks can be accomplished by mimicking or replicating bird’s or fish’s formation behavior. System can be made autonomous or to some extent, level of system autonomy can be enhanced.[10]

1.4. Why is GMM Drone Swarm Network Required?

There is no denial that future warfare will be swarm drone based and complete warfare tactics have been changed after the world witnessed Nagorno-Karabakh drone war and Azerbaijan military superiority in the battlefield due to use of drones in offensive with shrinking their causalities in the battlefield. Similarly, China[14] demonstrated the use of a drone swarm to deliver food to soldiers on the frontline during the standoff in Ladakh. Research in this area was the utmost need of time to cater for future warfare needs.

1.5. Thesis Contribution

The contribution of this thesis is as follows: -

1.5.1. Presents a comprehensive background study of GMM Drone Swarm Networks, RPs and existing taxonomy of GMM Drone Swarm Networks including various approaches and algorithms as a buildup for current research.

1.5.2. Designing and Implementation of application specific Proposed GMM Drone Swarm Networks that can be used for Search and Pursue Operations using Drone Swarm.

1.5.3. Performance testing of proposed GMM using AODV and OLSR RP.

1.5.4. Proposing of three other GMM Drone Swarm Networks.

1.5.5. Presents a comprehensive body of literature regarding the related works of GMM Drone Swarm Networks.

1.6. Organization

This thesis comprises a total of six chapters. An overview of the remaining five chapters is presented as follows:

1.6.1. Chapter 2 presents the background study on Drone Swarm Networks GMM. It covers various communication routing protocols[4], normal routing protocols, common routing protocols, various algorithms[29] which are briefly discussed for path prediction and obstacle negotiation[20]. Various approaches-based utility of Drone Swarm Networks GMM have been briefly discussed in this chapter. Overall, this chapter is a build up for necessary knowledge to carry out current research effectively.

1.6.2. In Chapter 3, past and current works regarding Drone Swarm Networks has been presented.It presents the works carried out traditionally using various methodologies in the above-mentioned field. Since the field in this research is continuously evolving and being highly sensitive in nature, therefore, only limited work was available as open source.

1.6.3. In Chapter 4, an overview of the design and implementation of proposed GMM's Drone Swarm Networks has been presented. Only one proposed model has been implemented while total four GMM Drone Swarm Network have been presented. Chapter focuses on various chronological steps involved in the process with precise details. Various performance metrics have been discussed on which the success of the proposed model has been accessed/ evaluated. A section has been solely dedicated to discuss how the results were generated and compiled. For better assimilation and understanding due to complexity of the research, all the steps have been elaborated using flow chart and even mathematical modelling has been done using various equations for the proposed model for better understanding and implementation. Snippets of proposed GMM simulations have also been presented in this chapter.

1.6.4. Chapter 5 lays a foundation on the findings and results taking Chapter 4 as a jump off point. Statistical simulation data is presented along with the results basing on various performance metrics. Analysis/ inferences generated based on the results of the proposed model using two different routing protocols[4] to comment on Drone Swarm Networks scalability, network congestion, traffic quantum, discarding of packets and even retransmissions. Assistance has been taken from various graphs, scatterplots and even histograms as per need.

1.6.5. Chapter 6 summarizes the complete research work and presents possible future direction besides presenting various avenues which can further be explored basing this research as jump off point.

CHAPTER 2 : BACKGROUND STUDY

This chapter lays down the base for the complete research work. It presents comprehensive background study covering all aspects related to GMM Drone Swarm Networks to include various routing protocols[4], path planning strategies and algorithms, collision avoidance, various routing and application approaches besides motion control model, topology control model and categorization of GMM.

2. Network Routing Protocols Drone Swarm Networks Explored for Research

2.1. Common Routing Protocols Drone Swarm Networks

Routing protocols [5]are used mainly for setting up wireless communication paths among the swarm drones. These mainly include ad-hoc routing protocols[4], which basically enable the swarm drones to self-organize and establish communication paths amongst the swarm.

2.1.1. Wireless Communication Protocols

Zigbee, Bluetooth and Wi-Fi are mostly used for communication among swarm drones.[5]

2.1.2. Global Navigation Satellite System (GNSS)

Global positioning system (GPS) which is a GNSS protocol is used to provide location/ positioning information of each drone in the swarm as the same is needed for collaboration among the swarm for coordinated flight and mission/ task execution[18].

2.1.3. Time Synchronization Protocols

Time synchronization protocols ensure that complete swarm is operating on the same clock. Any time lag or delay among the swarm can prove fatal and even cause collisions amongst the drones. So time synchronization is very important for collaboration[19] and coordinated task execution besides collision avoidance amongst the swarm drones.

2.1.4. Data exchange protocols

These are mainly used for exchange of instructions/ orders and data amongst the swarm drones. Like we have MQTT as standard messaging protocol being used for data exchange. We can also generate own customized protocol for application related employment of drone swarm networks.

2.2. Routing Protocols Drone Swarm Networks

2.2.1. Ad-hoc routing protocols

They are used in swarm drone communication path establishment and are useful in dynamic network topology where nodes leave or join very frequently. These are generally decentralized i.e. each node has information has about its peer nodes and has liberty of making decisions with regards to routing data.

2.2.2. Hybrid routing protocols

Hybrid routing protocols [4] are combination of centralized and decentralized architecture to ensure optimized and reliable communication among the swarm drones[5]. In this, few drones act as coordinator and other perform the role of relaying data. Roles are generally pre-defined.

2.2.3. Geographic routing protocols

These are used where drones movement is very frequent. These protocols work like the greedy search algorithms work i.e. data is sent to nearest peer which is closest to the destination. Location information of the node is used for developing communication paths amongst swarm drones.[5]

2.2.4. Quality-of-Service (QoS) routing protocols

They are used where exists priority of data transmission and data is critical like search and rescue operations or surveillance data[1]. Most critical data is sent with highest priority. Reliability, bandwidth availability and low latency are the deciding factors for developing communication paths amongst swarm drones.

2.2.5. Energy Efficient Routing

Drones are battery operated and energy efficiency is single most important factor in designing of routing protocol[4] for drone swarm networks. Researchers have developed customized routing protocols to cater for energy consumption while preserving communication quality and reliability. [26]

2.2.6. Secure Routing

Customized secure routing algorithms have been built by researchers for industrial or military grade drone swarm networks where exchange of sensitive data is taking place. These secure routing protocols[4] protect against jamming and eavesdropping attacks.

2.3. Algorithms Explored Drone Swarm Networks

2.3.1. Ant Colony Optimization (ACO)

It is an algorithm which is inspired from nature that simulate the behavior of ants to find the shortest path[21] between two points and also the behavior of ants when they search for food. The drones move randomly and mark their paths using pheromones[8]. Peer drones use that path keeping in view intensity of pheromone and adjust their paths accordingly. Most efficient paths to destination are thus detected using this mechanism. Pheromone trails are updated continuously basing on success of failure of previous paths. Routing in drone swarm networks can be optimized by using the approach of ants for routing of data packets. ACO can be used where swarm drones need to search some target[30] in complex and rapidly changing environment.

2.3.2. Particle Swarm Optimization (PSO)

It is an algorithm which is also inspired from nature that simulates the behavior of a swarm of particles to achieve efficiency in a specific objective function. Routing protocols[4] in drone swarm networks can be optimized basing various objectives like energy preservation[26] or low latency/ delay.

2.3.3. Genetic Algorithms

These are heuristic algorithms for optimization that simulate the process of natural selection to find the most appropriate solution to a problem. They can be used for optimization of routing protocols that can respond to fluid situations/ changes in the network and traffic patterns.

2.3.4. Reinforcement Learning

Swarm drones can learn from their past experiences and accordingly adapt their response to achieve the assigned tasks using reinforcement learning algorithms.[5] They can be used for enhancement of routing performance, energy utilization [26]or any other desired objective.

2.3.5. Flocking Algorithms[7]

It is an algorithm which is inspired from nature that simulates the movement of a flock of birds which they used during movement/ migration from one place to another. It is a type of swarm intelligence[16] algorithm that can help swarm drones in a coordinated movement where they move in the form of group while keeping a particular distance and alignment/ orientation with other drones. Flocking of birds mainly surrounds around three characteristics including alignment, cohesion and separation. They can also be used for enhancement of routing performance, energy utilization[26] or any other desired objective.

2.3.6. Game Theory

Game theory is a framework that can be used for modelling of swarm drones and analyzing their interactions[28] for making of customized routing algorithms to strike the balance between the need of swarm drones versus the need of the network.[21]

2.3.7. Fish Schooling

It is an algorithm which is inspired from nature that simulates the movement of fishes in water. It is a complex model where not only movement is involved rather turning, accelerating and decelerating, collision avoidance and maintaining of a specific formation is inherent feature. Swarm drones move in using this model based on movements of peer drones.

2.4. Machine Learning Algorithms for Energy Preservation and Range Enhancement

2.4.1. Reinforcement Learning (RL)

As earlier elaborated, it involves decision making based on hit and trial to see error ratio. Routing algorithms can be optimized for better decision making for energy consumption[26] and range enhancement. Routing paths can be adjusted based on environmental factors and use of collaborative communication to extend range of the network thereby optimizing transmission power and frequency.[25]

2.4.2. Deep Learning (DL)

It involves training of a data set/ system for pattern recognition and consequent decision making using large amount of data. Deep learning[25] can be used for predicting network traffic patterns or other factors affecting drone swarm networks performance. These predictions can be used for adjustment of routing paths and parameter in real-time scenario to achieve optimum performance in network while minimizing energy consumption.[5]

2.4.3. Genetic Algorithms (GA)

Different routing paths and parameters can be simulated and only the one which enhances maximum range and minimize energy consumption is selected using this machine learning technique. This algorithm continuously evolves during the course of the process to cater for changing network conditions and fluid environment.[5]

2.4.4. Fuzzy Logic

Uncertain or imprecise information regarding network conditions can be manipulated to enhance the routing algorithm. Fuzzy logic[31] can for example be used to adjust routing paths based on unknown or evolving weather conditions or network traffic patterns.[5]

2.5. Path Predicting Algorithms Explored for Path Planning Drone Swarm Networks

2.5.1. Markov Decision Process (MDP)

MDP is framework[21] for decision-making problems with stochastic outcomes. It can be used to model the unpredictability of the environment and subsequent predicting the optimal path based on drones current state and probability of different outcomes. Feedback from the environment can be used for path optimization.[10]

2.5.2. Hidden Markov Model (HMM)

HMM [10] is a statistical model for modeling systems with hidden states. It can be used in similar fashion as elaborated for MDP for optimal path planning. Optimal path can be predicted based on feedback from the environment.[5]

2.5.3. Artificial Neural Networks (ANN)

It is a machine learning technique for training a network of interconnected nodes to recognize patterns in data. ANN can predict optimal path based on historical data and feedback from environment.

2.5.4. Particle Swarm Optimization (PSO)

It is an optimization algorithm inspired by behavior of bird flocks[7] and fish schools. It can be used for path prediction and moving towards optimal path using feedback from environment.

2.6. Obstacle Negotiation in Drone Swarm Networks[20]

2.6.1. Collision Avoidance

Swarm drones can use various sensors like LiDAR, cameras or ultrasonic sensors to detect obstacles and evaluate environment around them for path planning and collision avoidance. Drone path can be adjusted as per assessment of the position and velocity of the obstacle. [20]

2.6.2. Obstacle Mapping

Obstacles can be mapped and even environment can be mapped using sensors for better path planning of swarm drones and avert obstacle collision. [20]

2.6.3. Cooperative Obstacle Negotiation

Swarm drones can also share their location and surrounding information so as to inform their peers about presence of obstacles along with the general location of the obstacle which will help in coordinated movements of the swarm drones to avert collision. [20]

2.6.4. Flexible Path Planning

Optimal potential paths can be generated using various algorithms. Basing on location of obstacles in the environment, optimal path can be selected. [19]

2.7. Communication Protocols Drone Swarm Networks

2.7.1. Ad-hoc On-demand Distance Vector (AODV)

Low overhead and fast convergence time for drone swarm networks being reactive routing protocol[4]. Most suitable for highly changing environment in time domain. The current research and mobility model proposed was tested using AODV routing protocol.

2.7.2. Optimized Link State Routing (OLSR)

OLSR is most suited for drone swarm networks as being proactive in nature, it maintains consistent routing table in entire network which amply supports high density of swarm drones. It can handle large scale networks with minimum latency. Current research is mainly focused using this protocol and amply tested using proposed mobility model.

2.7.3. Zone Routing Protocol (ZRP)

Being hybrid routing protocol[4], it can also be used in drone swarm networks being combination of reactive and proactive routing protocols. Network is divided into various smaller chunk or zones thereby ensuring usage of proactive protocol inside the zone and reactive protocol amongst various zones.[25]

2.7.4. Mobile Ad Hoc Network (MANET)

MANET is most popular in drone swarm networks as it allows them to collaborate and communicate with each other without any centralized infrastructure. It gets configured at its own and is basically a network of mobile nodes.

2.7.5. Delay-Tolerant Networking (DTN)

This is used for swarm drones in hostile territory or where there is lot of network disruption and delay due to far distances or may be due to interference or jamming measures. It establishes communication between drones that are connected intermittently or are not directly connected.

2.8. Routing Approaches

2.8.1. Decentralized Routing

In this approach each drone in the swarm makes its own routing decisions keeping in the view the information it has about the network. It is more scalable than centralized routing besides being resilient. [5]

2.8.2. Centralized Routing

Decision is done by centralized controller for the entire network based on global information. Its easy to manage but can also become single point of failure and may not be scalable for larger swarm drone network.[5]

2.8.3. Hybrid Routing

This approach is combination of decisions made centrally and individually but it creates complexity being mixture of decentralized and decentralized routing.[5]

2.8.4. Multi-path routing

It involves sending of data packets along multiple paths at the same time to optimize delay and ensure reliability and redundancy however they are more power intensive.[5]

2.8.5. Load Balancing

It involves congestion avoidance and distribution of traffic along multiple paths to balance the load/ traffic and optimize network utilization.

2.8.6. Security-aware routing

It involves developing of routing protocols which can protect against intrusions such as eavesdropping, jamming and spoofing. However, more security will deteriorate performance and efficiency.

2.8.7. Energy-efficient routing

Energy efficient routing protocols can reduce power consumption of swarm drones. Adaptive transmission power, dynamic clustering[17] and sleep scheduling can be used to save power.

2.8.8. Resilient Routing

Resilient routing protocols can be developed to ensure sustenance of network in the line of interferences, disruption and network failures. They can enable swarm drones network to self-heal and recover from any delay or disruption. They should be able to detect and bypass any fault as and when it occurs.

2.9. Application-based Approaches

2.9.1. Search and Rescue

In search and rescue application-based approach, swarm drones can be used for assistance in case of a natural calamity or any disaster to help searching and finding survivors and missing persons. They can also be used for damage assessment. Routing protocols[4] and mobility models can be developed to optimize search patterns and time reduction to locate survivors.

2.9.2. Environmental Monitoring

Swarm drones can be used for meteorology data collection from the environment like pollution in the air to ascertain air quality, temperature, humidity levels and any other assessment needed to anticipate weather conditions. Accordingly routing protocols[4] and group mobility models can be built to maximize coverage area and reduce power consumption.

2.9.3. Precision Agriculture

Swarm drones can be used for irrigation monitoring, crop monitoring and even fertilization over large areas which may not be possible to traverse otherwise. Similarly, various insects attack on the crop can be timely addressed with the help of swarm drones through proper monitoring.

2.9.4. Disaster Response

Swarm drones can provide real-time situational awareness regarding an area where disaster has occurred. First responders can take guidance and assistance from the data available for better coordinated response. It can also give early warning to people travelling towards that area.

2.9.5. Surveillance and Security

Swarm drones can be used for surveillance[1] and security of an area or region. Like perimeter monitoring of any sensitive installation, traffic management and even crowd control and monitoring.

2.9.6. Delivery and Logistics

Amazon is using drones for delivery of their orders in USA. China[14] used swarm drones to deliver logistics to their army in conflict zone with India which are highly mountainous regions and were not otherwise easily accessible by road.

2.10. Military Operations-based Approaches

2.10.1. Battlefield Reconnaissance

Swarm drones can be used for real-time battlefield reconnaissance to provide early information before onset of battle or operations. They can assist in planning for the operation by giving important information on various enemy installations and manpower and even deployments. They can even assist during conduct of war with situational awareness.

2.10.2. Target Acquisition and Designation

Swarm drones can be used for target acquisition[30] and designation to identify and locate hostile targets and provide information to aviation assets, air force assets and any other weapon system held by the army which can effectively and timely engage the hostile target. They can also relay to ground forces for action. Group mobility models can be developed for swarm drones for early identification and location of targets.

2.10.3. Electronic Warfare

Swarm drones networks can be used for electronic warfare such as jamming, spoofing and even interception of enemy communication systems.

2.10.4. Logistics and Resupply

The success of any battle is dependent upon the logistics and resupply chain management. No army or force can sustain without continuous logistic support. Swarm drones can be used to transport weapons, equipment, supplies , rations and even ammunition to troops in the field. Delivery routes can be optimized besides timely and secure delivery through development of requisite group mobility models and routing protocols.

2.10.5. Tactical Communications

On the go communication links can be provided to the troops operating in the battlefield through swarm drones. Secure and reliable communication amongst the troops can be established using this strategy. This is highly effective for a place where establishing of permanent communication links is not possible or where force does not have to stay for longer period and are on the move or even assembling for an attack.

2.11. Stealth and Safety Drone Swarm Networks

2.11.1. Collision Avoidance

Collision avoidance is of utmost importance in drone swarm networks. Detection of obstacles, ground based assets, other drones and even other air assets is very important for swarm drones to work effectively and respond in efficient manner. [20]

2.11.2. Secure Communications

Secure communication is of utmost importance to avert any hostile interference or interception. Various advanced encryption algorithms AES or others can be used with 1024 or 2048 bit encryption besides authentication to protect against data breaches and cyberattacks. But then there is a down side for this as more security will degrade the performance. Therefore, we have to strike the balance among both to keep security as well as performance.

2.11.3. Stealth capabilities

Stealth capabilities are very important, may it be physical stealth of the swarm drones or may it be the stealth in communications amongst the drones. Frequency hopping and spread spectrum can be used to avoid communication on any particular frequency. Low observable design can be used to minimize the detectability of swarm drones.

2.11.4. Adaptive Routing

Adaptive routing can be mixed and match of various routing protocols. It can be a hybrid approach like environment based, enemy based, task based, weather based, terrain based and requirement-based switching of routing protocols and adapting accordingly. Machine learning algorithms can be used to predict and respond in changing conditions as mentioned above.

2.11.5. Redundancy and Fault Tolerance

Redundant paths for data transmission and communications amongst the swarm drones besides fault detection and healing of network. Fault tolerance is also achieved by having multiple paths of communication in the network. Any failure in communication at one place should not lead to complete network failure. Network works dynamically and recover at its own.

2.12. Motion Control

Motion control planning is the most important task in swarm drone network group mobility models. It revolves around creating an effective network topology[17], creation of topology control algorithms catering for transmission power of drones, ensuring communication reliance using task allocation algorithms, deploying and controlling of intermediatory nodes.

Motion control provides guidance information like optimal trajectories, obstacle free safety distance[20], computational time, shortest distance[21] and trajectory smoothness level.

2.13. Challenges To Topology Control

Challenges[17] include jamming, interference, prediction of network performance, variety of communication links and mobility of drones adds on to uncertainty, latency issue due to limited bandwidth, using optimal algorithms to enhance resource utilization, passage of command and control messages with minimal delay and errors, minimum exchange of messages for decision making and collaboration[19].

2.14. Challenges of Communication Networks

Communication delays will result in idle drones besides delayed response of drones to various situations. It can further lead to collisions among drones and will also hamper obstacle negotiation besides efficiency deterioration. [20]

2.15. Required Communication Performance (RCP)

Performance metrics for required communication performance are availability, continuity, integrity and latency.

2.16. Formation Control Drone Swarm Networks

Formation control or movement of whole formation of swarm drone is most challenging task. It revolves around maintaining the relative position of the swarm drones during formation motions while avoiding collisions and negotiation of obstacles[20]. The formation can be split in case of any impromptu requirement while ensuring the network communication for collaborative planning and data requirements.

2.16.1. Centralized Architecture and Drawbacks

Centralized architecture revolves around generation of control signals for complete swarm from either the leader drone or central station. Complete swarm remains within transmission range of leader drone or central station.

It needs higher bandwidth as all communication is via leader drone or central station. This increases network latency and possibility of blockage of links as downlink distance is higher than inter drone distance. This architecture will require clear line of sight or steerable antennas to manage communication with control station that will need high end controller requiring high computational power.

Failure of controller will render all network inaccessible thus will not be fault resilient. Processing and sending of desired/ useful data may also be needed if large data transfer is involved.

2.16.2. Distributed Architecture and Drawbacks

Distributed architecture revolves around generation of control signals by the swarm drone basing on their own location and peers/ neighbour's information. The communication is very fast as swarm drones are autonomous and computations are being shared amongst the swarm for collaborative task management. Complete swarm is connected with each other directly via more than one links thus makes it fault resilient as well. Drones among the swarm relay traffic for each other which increases its scalability.

Distributed architecture rely upon reliable communication links and reliable information sharing otherwise routing algorithms performance can significantly deteriorate. Large swarm will require more communication links for a single drone to work properly.

2.17. Formation Control Models/ Approaches Drone Swarm Networks

2.17.1. Leader-follower based Methods

Leader is nominated explicitly which makes it less flexible. Leader requires continuous feedback from followers which is mostly not possible.

2.17.2. Virtual Structure based Methods

VS are collision prone and not sustainable in distributed architecture implementation. They are computation and communication intensive and does not support frequent shape deformation.

2.17.3. Behaviour-based Methods

Most difficult to model and achieve stability.

2.17.4. Hybrid Model

Hybrid is combination of Leader-follower, virtual structure and behavioral based method. Leader-follower or virtual structure used for ensuring stability. Behavioral is used where we have complex environment. Scenario based switching among the methods as per requirements and dictates of situation.

2.18. Models for Drone Operations Drone Swarm Networks

These are the different levels of human intervention levels over the swarm drones.

2.18.1. Man-in-loop

In this scenario, a human operator is controlling the swarm drones. He may be passing the instructions and decision making to individuals drone or may be to complete swarm. However, it will affect scalability of the swarm. This is suitable for conditions where human decision is of utmost importance as machine learning/ AI algorithms cannot have emotions or judgement level decision making where sensitive tasks are at hand in complex environment.

2.18.2. Man-on-loop also called semi-autonomous

They are also called semi-autonomous as some but not all human intervention is involved. In this model, swarm drones can perform routine tasks autonomously at their own without any intervention. However, where some complex decision making is involved, human operator will do decision making and even override the decision of the swarm. Mostly basic level decisions like path planning[19], collision avoidance or maintaining a certain formation are done autonomously. As a whole, it can be summed up that the complete activity is under supervision of a human operator.

2.18.3. Autonomous

In this scenario, the human intervention is not there in normal operations. Machine learning and artificial intelligence algorithms are used by swarm drones to do all their tasks. Human operators can only give broad guidelines or high level mission[18] objectives but swarm drones operate independently in this model. This enhances scalability of the swarm thereby making it much suitable for large-scale applications as no human supervision is as such needed.

2.19. Categories of Group Mobility Models

2.19.1. Pure Randomized Mobility Model

2.19.1.1. Random Way Point Mobility Model

Just as the name represents, UAVs move in random positions in a particular region. Nodes can move right left and straight in this model. A random destination i.e. waypoint[23] and travelling speed is chosen in this model.

2.19.1.2. Random Walk Mobility Model

Just as the name represents, this mobility pattern caters for the unpredictable movements of various entities in the nature or surroundings. The inspiration has been taken from the Brownian Motion which was given by Robert Brown which was further mathematically explained by Einstein. Each time, UAVs take a random path. At the ending of that path, a new velocity and direction are calculated. This mobility model does not keep record of previous locations and paths and therefore called as memoryless mobility model.

2.19.1.3. Random Direction Mobility Model

The mobility model was created merely to handle the drawbacks of random waypoint mobility model. In Random waypoint mobility model, UAVs tend to concentrate in the middle of a simulated area. In random direction mobility model, every UAV instead of choosing fresh destination towards middle of the simulation area, chooses a location towards the edge of the simulation area. As the UAV reaches near the edge, it again chooses additional random position near the edge.

2.19.1.4. Manhattan Grid Mobility Model

Manhattan Grid mobility model[22] is based on movement over roads or laterals. Like an automobile is moving on a road, whether it keeps on moving in the same direction or changes its direction at the crossroads. As the name represents, the movement is based on map where movement can only take place alongside a grid line like north, south, east and west. Probabilities for horizontal movement are assigned along a defined grid.

2.19.2. Time Dependent Mobility Model

These models revolve around minimizing abrupt changes in speed and direction of nodes or in other words velocity of nodes. It focuses on smooth changes in movement. Movement of UAVs depends upon past or historical data of speed and direction.

2.19.2.1. Boundless Simulation Area Mobility Model

This mobility models ensures freedom of movement of UAVs in simulation area with complete disregard to edge effects on evaluation. It keeps historical data with regards to speed and direction of UAVs and relates it to the present speed and direction. However, the freedom of movement can generate teleportation effect (moving of UAV elsewhere of an edge) which will affect the underlying condition/ prerequisite for carrying out mission[18] area of 2D applications.

2.19.2.2. Gauss-Markov Mobility Model

In this mobility model,[32] each UAV is already set to a particular direction and speed. However in due course of time, speed and direction of UAV does get randomly updated. It is mainly used for simulation of ad-hoc networks.[22]

2.19.2.3. Smooth Turn

This model revolves around turning of drones that focuses on correlation of velocity increase across time and spatial domain[23] as generally sharp turning of UAVs is not easy as compared to turning of vehicles on roads. UAVs while taking turns need a large radius as compared to a vehicle moving on ground. This model however lacks collision prevention.

2.19.3. Path Planned Mobility Model

This model provides predefined paths pattern to all nodes. UAVs follow it and then change it randomly.

2.19.3.1. Semi-Random Circular Movement Mobility Model

In this model, UAVs move in a circular or curving manner. UAVs communicate in the same curved manner. This model is mainly used for collecting of information and data in a specific area where UAVs are particularly assigned.

2.19.3.2. Paparazzi Mobility Model

This model has 5 types of different movements. [11]One is hovering over a particular fixed position. Second is waypoint[23], similar to random way point mobility model where UAVs select a random waypoint and then move towards the destination using straight path. Third is figure eight where UAVs move from one place to another and the trajectory makes figure eight. Fourth is scanning of an area by doing round trips between two fixed points. Fifth is oval trajectory round trip movement between two points.[5]

2.19.4. Group Mobility Models (GMM)

In group mobility models, movement is controlled by a reference point as UAVs move randomly around that reference point and there exists spatial constraint[23] among the UAVs.[5]

2.19.4.1. Column Mobility Model

This model was made for searching scenarios. UAVs move in the area of a reference position from start to the end point in frontward direction under a constraint. This model can avoid collision among UAVs.[11]

2.19.4.2. Nomadic Community Mobility Model

UAVs move randomly in the area of a reference position but without any constraint in contrast to column mobility model. UAVs move keeping a specified distance from the reference position.[11]

2.19.4.3. Pursue Mobility Model

UAVs follow a specific moving target in a specific direction just like criminals are followed by police. Random motion is used to trail a target.[11]

2.19.5. Topology Control Mobility Model

2.19.5.1. Distributed Pheromone Repel Mobility Model

This mobility model is used for inspection of an area to sense earth targets. Each UAV stores its pheromone map which has been inspected along with time stamp. The region which has been inspected is shared to with all other UAVs available on the network recursively. Each UAV generates its own pheromone map and also stores the map shared by other UAVs. That's how a bigger map/ picture of a region is built. Distributed pheromone repel mobility model is improved version of pheromone map. [25]

2.19.5.2. Pheromone-Based Mobility Model

Pheromone bases mobility is UAV guidance to other UAVs in an region while pheromone helps in development of UAV network in a particular area. UAVs trade data about the region they visit and share it with the rest and keep moving towards different directions. [25]

2.19.5.3. Mission Plan-Based Mobility Model

In this mobility model[25], UAV has pre calculated time of flight and knows the destination i.e. the mission area. If UAV reaches destination before completion of time need to fly to destination, it keeps on continuously flying with changed direction. This model ensures that UAV is in continuous motion till completion of mission and even after it. Mobility records that get generated after completion of mission can be used for analysis and further optimization. [18]

2.19.5.4. Self-Deployable Point Coverage Mobility Model

This model was designed for disaster management with regards to calculation of losses and damages incurred in a particular area. Point coverage ensures coverage of maximum area under consideration for evaluation of damage assessment by each UAV.

2.20. Summary

This background study was very important as a necessary buildup for the current research as there are lot many aspects which have to be gone through before moving towards proposing an application based GMM Drone Swarm Networks. Since swarm drone is evolving, so all current and past background knowledge is mandatory due to complexity of the research involved. The chapter sums up all routing protocols, various algorithms and approaches which can be used while dealing with GMM Drone Swarm Networks for better optimization, path planning[19] and collision avoidance.

CHAPTER 3 : LITERATURE REVIEW

Chapter presents comprehensive literature review of the research work being carried out in relevant domain. State of the art paper has also been discussed with all necessary details deemed feasible and relevant to current research/ thesis.

3. Related Work

“GMM for Complex Multisession Cooperation of UAV Swarm” published in 2022 was state of the art as idea for current research was taken from this research paper. This is the most recent research in the field which has been implemented as well by the researcher. It was also based on proposing of a GMM in which the researcher tested his four algorithms using three different experiments. After proposing of GMM, he tested the proposed GMM and gave way forward for testing various routing protocols to evaluate the stability of the proposed GMM. GMM proposed was for complex missions by multi-UAV cluster swarm. The proposed GMM is random node based which has been implemented through a random node selection-based algorithm. Therefore, in present thesis , a GMM Drone Swarm Network was proposed and implemented and even was tested for various routing protocols to evaluate its performance using various constraints and performance metrics.

"Toward Robust and Intelligent Drone Swarm: Challenges and Future Directions" published in IEEE Network journal on 27 March 2020 which focuses on a swarm intelligent robust solution for drone swarm by using the consensus method and grey prediction, which has advantages of small overhead and local information exchanging followed by research article "Drone Swarms as Networked Control Systems by Integration of Networking and Computing" published in open access journal "Sensors" on the science and technology on 09 Apr 21 which focuses on increasing the performance of a drone swarm and identifying a potential design choice, and a set of open research challenges for the integration of network and computing in a drone swarm as an Network Control System(NCS).

Following research work were also studied during course of research besides above-mentioned ones.

Table 3. 1 : Literature Review

Research Work	**Authors**	**Methodology**	**Results**	**Limitations**
"GMM for Complex Multisession Cooperation of UAV Swarm (2022)"	Xiaoyan, Feng, Rongwei,	OMNeT++ is used to simulate the ML-RNGM model with three experiments	a multilevel reference node mobility model based on the reference node strategy, namely, the ML-RNGM model, is proposed for multi-UAV cluster systems for complex missions	Proposed GMM was not performance tested or evaluated for various routing protocols
"A 3D Mobility Model for Autonomous Swarms of Collaborative UAVs (2019)"	Ema, Serge, Gilles	Using OMNeT++ network simulator	a three-dimensional (3D) mobility model for swarms of UAVs using both the Artificial Potential Fields	Incorporation of sensors like IR CAM Kinetics improvement with multi-rotor behavior in model

			(APF) principle and a global path planning method	
"Swarm of micro flying robots in the wild (2022)"	Xin, Xiangyong, Zhepei	A trajectory planner that can function in a timely and accurate manner based on limited information from onboard sensors	Capability of cluttered environment navigation, extensibility to diverse task requirements, and coordination as a swarm without external facilities.	Hardware dependency
"A model for rolling swarms of locusts (2008)"	Topaz, Bernoff, Logan	Using numerical simulations and tools from statistical mechanics, namely the notion of H-stability	An individual-based kinematic model of rolling migratory locust swarms incorporating social interactions, gravity, wind, and the effect of an impenetrable boundary, namely the ground	Study of larger swarms have been considered instead of smaller ones besides the parameters in model were chosen heuristically

3.1. Research Gap

Nothing circumstantial exists in the domain of GMM Drone Swarm Networks in open source. Even the GMM which exist are not as such available to be seen for their implementation. Mostly, there are survey articles which exist in current domain that too with lot of complexity. There exists a gap in existing taxonomy of GMM Drone Swarm Networks with regards to their application and efficacy which has been used as a research gap for current work.

3.2. Summary

The literature review presents the level of complexity in the current domain besides elucidation of the fact that very little has been done in the current domain of GMM and is not available as open source even if some work has been performed that rendered the task of research at hand very difficult, complex and time intensive. Even to get the domain knowledge many research papers were deliberately studied for better understanding of work done already in the field.

CHAPTER 4 : METHODOLOGY

In this chapter, design of the complete methodology has been presented which has been used to propose and implement GMM Drone Swarm Networks. Mathematical equations have been made for the model for better elaboration besides diagrammatic flow of all the steps which have been executed to achieve the desired proposed model. Various performance metrics have also been discussed on which the proposed model has been evaluated for implementation purpose.

4. Proposed Group Mobility Models Drone Swarm Networks

Before discussing the proposed group mobility models and their design. First performance metrics will be discussed on the basis of which we can determine the efficacy and efficiency of a group mobility model to determine its future utilization in any field.

4.1. Performance Metrics For Group Mobility Models

I have selected the packet delivery ratio, average end-to-end delay, dropped packets and average throughput as performance metrics in order to evaluate the performance of different routing protocols and proposed group mobility model.

4.1.1. Packet Deliver Ratio

It is the ratio of packets which were successfully sent to total packets sent or in other words the ratio of total number of packets successfully delivered to the number of packets sent. It tells about the performance of the network that whether packets are reaching to the relevant place for which they were destined for or not.

(Number of Packets Successfully Delivered / Total Number of Packets Sent) * 100

4.1.2. Average end-to-end delay (AED)

This is defined as the average delay in transmission of a packet between two nodes. A higher value of end-to-end delay means that the network is congested and hence the routing protocol does not perform well. The upper bound on the values of end-to-end delay is determined by the application. This average end to end delay can be attributed to multiple factors like queuing delays, processing delays, transmission delays, propagation delays, packet reordering and congestion delays.

AED=TimePacketReceived – TimePacketSent / TotalNumberofPacketsReceived

4.1.3. Average Throughput

Average throughput is a performance metric to measure the transmission of packets or data successfully delivered in a network during some given time interval. We have considered it in Kbps. In our case of drone swarm networks, it is the average rate at which data is successfully transmitted from one drone to another or from one drone to ground station or vice versa. It is the measure of the capacity of the network to deliver data properly. Available bandwidth, network congestion, channel conditions and even signal interference besides communication protocol used can affect the average throughput.

4.1.4. Packet Loss

Packet loss is the situation where packets sent by source are not received by the destination. This can occur due to discarded packets as a result of overwhelming traffic, network congestion leading to dropping of packets, environmental factors causing signal attenuation and even noise, buffer overflow due to excessive traffic/ data packets, low prioritization of certain packets causing only delivery of high priority packets causing infinite packet starvation, firmware and even hardware bugs can be attributed to packet loss in certain circumstances. Various methods like forward error correction (FEC) and retransmission and congestion control mechanisms can be employed for mitigation.

4.2. Proposed Group Mobility Models Drone Swarm Networks

4.2.1. Hybrid Column and Pursue Mobility Model for Military Operations

This is the model which has been proposed for application specific requirement i.e. military operations for scouting, searching, finding of target followed by pursuit of the target. The subject model was implemented and simulated in Network Simulator – 2 for different number of nodes ranging from 5, 10 , 20 and so on till 100 but smaller subgroups in column mobility model were always kept five to have better results analysis and evaluation with regards to various performance metrics considered. So there were five columns in each case as a cohesive formation which are coordinated movements towards a target [30].

Pursue mobility model was also simulated in Network Simulator -2 for different number of nodes ranging from 5,10,20 and so on till 100 but in this case, there were no smaller subgroups or columns rather each drone displays a pursuit behavior with agile movements and has ability to respond and react independently for pursuit and target trailing/ tracking [30].

Switching from column to pursuit will have to be seamless transition in order for success of this mobility model.

4.2.2. Hybrid Formation and Scatter Mobility Model for Surveillance and Reconnaissance Operation

This proposed type of hybrid model can be used for surveillance[1] and reconnaissance operation. Column mobility model or nomadic community model can be used to divide swarm into smaller subgroups for surveillance[1] in an area while Scatter mobility model can be used for individual exploration and area coverage by drones

4.2.3. Hybrid Search and Rescue Mobility Model for Search and Rescue Operations

This proposed model can be used for search and rescue operations. Initially the area can be divided into sector or grids. Swarm drones can use any searching group mobility model like Column mobility model for initial searching at grid level. The grid can further be divided into smaller regions and then drones can sweep through those regions. After detecting of potential survivor, the drone can perform localized search for any other survivors in that area followed by targeted assistance by routing other drones nearby for assistance in rescue operation.

4.2.4. Hybrid Model using Ant Colony Algorithm Movement, Bird flock migration-inspired formation[7], Locust[6] Swarm-Inspired Task Assignment

Since all these algorithms were explored and studied during the course of research, therefore proposing a mobility model using amalgamation of these algorithms was very much necessary though implementation of this group mobility model is beyond the scope of this research but can pave way for any future research in the field.

In this model proposed, each drone will behave as an ant. Just like ants move in ant colony while they search for food, they communicate with other ants by leaving a trail of pheromones[8] on visited location. Intensity of which defines best path and even places where food is available. Remaining ants take decision basing on those pheromones[8]. Similarly drones will do the same for movement only in this model, they will keep a table of pheromones to use the past experiences of other drones and decide their movements accordingly. Drones will take inspiration from brid flocking which they mostly do during migration. They will mimic those the flocking behaviour through alignment of their speed and direction with peer drones, also by maintaining a proper distance from peers for collision avoidance, also by adjustment of positions to achieve desired formations. Locust swarm[27] movements will be taken as inspiration for task assignment in drone swarm networks where drones display swarm intelligence[16] by sharing information and subsequent distribution of tasks basing on capability and availability of drones and adjusting in real-time as per fast pace changing environment. So it becomes a hybrid model for movement, long distance travel or migration and task assignment for drone swarm networks.

4.3. Software Used and Results

4.3.1. Steps Involved in Generation of Proposed Mobility Model

Network Simulator - 2 software was used for evaluation of one of the proposed models. The outcome was evaluated on basis of four performance metrics including packet delivery ratio, packet loss, average end to end delay and average throughput.

Network simulator NS2 is a open source software for testing and simulating wireless as well as wired networks specifically to the research at hand like GMM Drone Swarm networks. Its tcl and C++ based software which supports network protocols like UDP and TCP.

Following steps were performed in various iterations to get the outcome and results besides various simulation parameters were used as per table 4.1.

Parameter	**Value**
Simulation tool	NS-2
Simulation time	200, 3000
MAC Protocol	802.11
Simulation Area	820 x 820
Propagation model	Free space
Routing Protocol	AODV, OLSR
Traffic	cbr
Number of nodes	5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Transmission Range	75m
CBR data rate	25 kbps
Packet size	100 bytes
Speed	10,50,100,200,300,400,500 (m/s)
Channel capacity	11 Mbps(Wireless)
Mobility models	Proposed Mobility Model Hybrid Search and Pursuit GMM for military operations

Table 4. 1 Parameters for Simulation NS2

4.3.1.1. Creation of TCL File in NS2

A tcl file was created giving all relevant details like channel type, antenna type, radio-propagation model, network interface type, MAC type, simulation area along X and Y axis, duration of simulation, routing protocol to be used, number of mobile nodes besides giving paths of trafficability file, mobility file , awk scripts[13] for evaluation of trace file which gets generated after execution of tcl file in NS-2.

4.3.1.2. Running of Mobility Model using BonnMotion

BonnMotion[3] is a java software which creates and analyzes mobility scenarios and used for investigation of mobile adhoc network[9] characteristics. The scenarios can further be exported to network simulators like NS-2. BonnMotion[3] is being jointly developed by the Communication Systems group at the University of Bonn, Germany, the Toilers group at the Colorado School of Mines, Golden, CO, USA, and the Distributed Systems group at the University of Osnabrück, Germany. This software was installed on Linux along with dependencies like Oracle Java 1.8 compatible Java runtime environment known as java-jre.

The native format in which BonnMotion[3] saves the movement traces is node-by-line waypoint based[23]. This means that there is one line for each node. This line contains all the waypoints. A waypoint is a position at which the movement of a node (e.g. direction, velocity) changes. A waypoint consists of the simulation time in seconds at which the waypoint is reached by the node o the x and y coordinates of the position of the waypoint.

Column Mobility Model and Pursue Mobility Model codes were run with little tweaking. Various parameters were set as per Figure 4.1 and 4.2 to generate the mobility file for nodes ranging from 5, 10 , 20 and so on till 100.

```
App:
	-D print stack trace
Scenario:
	-a <attractor parameters (if applicable for model)>
	-c [use circular shape (if applicable for model)]
	-d <scenario duration>
	-i <number of seconds to skip>
	-n <number of nodes>
	-x <width of simulation area>
	-y <height of simulation area>
	-z <depth of simulation area>
	-R <random seed>
	-J <2D, 3D> Dimension of movement output
RandomSpeedBase:
	-h <max. speed>
	-l <min. speed>
	-p <max. pause time>
Column:
	-a <number of groups>
	-r <reference point separation>
	-s <max. distance to group center>
```

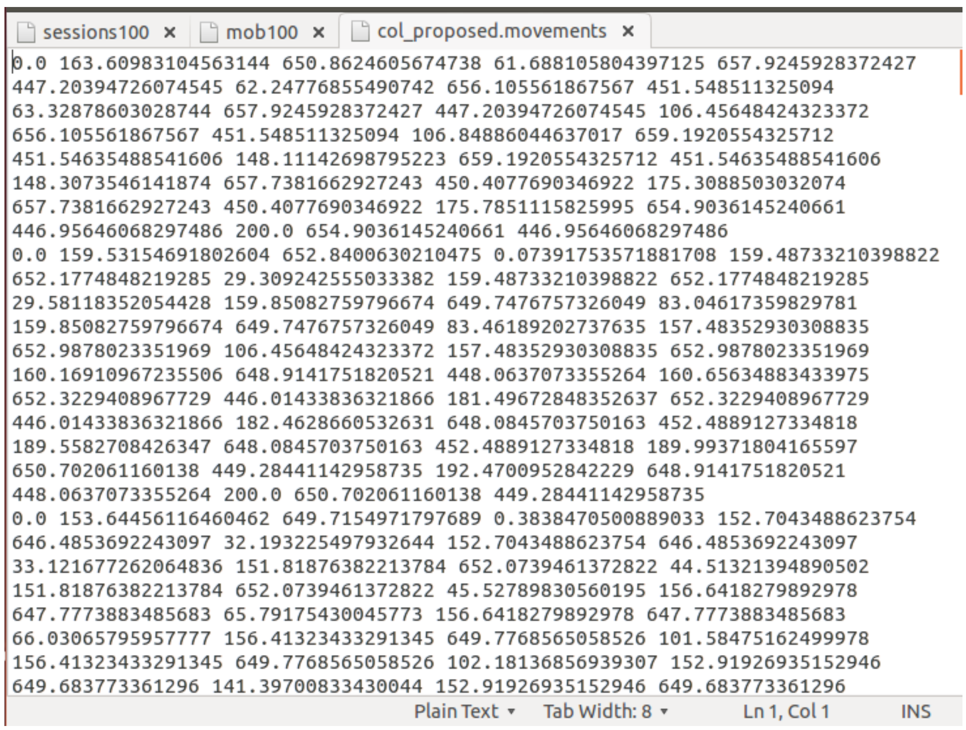
Figure 4. 1 : Parameters Setting - Column Mobility Model - BonnMotion

```
App:
	-D print stack trace
Scenario:
	-a <attractor parameters (if applicable for model)>
	-c [use circular shape (if applicable for model)]
	-d <scenario duration>
	-i <number of seconds to skip>
	-n <number of nodes>
	-x <width of simulation area>
	-y <height of simulation area>
	-z <depth of simulation area>
	-R <random seed>
	-J <2D, 3D> Dimension of movement output
Pursue:
	-o <maxspeed>
	-p <minspeed>
	-k <aggressiveness (0-1)>
	-m <pursueRandomnessMagnitude (0-1)>
```

Figure 4. 2 : Parameters Setting - Pursue Mobility Model – BonnMotion

4.3.1.3. Generation of Mobility File using Bonn Motion and Conversion to NS2 file

Mobility file .mob was generated using BonnMotion[33] software as given in Figure 4.3 and that mobility file was converted to NS-2[2] compatible file as given in Figure 4.4 so as to use it in NS-2 tcl file. After converting file to NS-2 compatible format, it was shifted to folder where tcl file was located and path of the file was given as source to be run during compiling of tcl file in NS-2.




```
0.0 163.60983104563144 650.8624605674738 61.688105804397125 657.9245928372427
447.20394726074545 62.24776855490742 656.105561867567 451.548511325094
63.32878603028744 657.9245928372427 447.20394726074545 106.45648424323372
656.105561867567 451.548511325094 106.84886044637017 659.1920554325712
451.54635488541606 148.11142698795223 659.1920554325712 451.54635488541606
148.3073546141874 657.7381662927243 450.4077690346922 175.3088503032074
657.7381662927243 450.4077690346922 175.7851115825995 654.9036145240661
446.95646068297486 200.0 654.9036145240661 446.95646068297486
0.0 159.53154691802604 652.8400630210475 0.07391753571881708 159.48733210398822
652.1774848219285 29.309242555033382 159.48733210398822 652.1774848219285
29.58118352054428 159.85082759796674 649.7476757326049 83.04617359829781
159.85082759796674 649.7476757326049 83.46189202737635 157.48352930308835
652.9878023351969 106.45648424323372 157.48352930308835 652.9878023351969
160.16910967235506 648.9141751820521 448.0637073355264 160.65634883433975
652.3229408967729 446.01433836321866 181.49672848352637 652.3229408967729
446.01433836321866 182.4628660532631 648.0845703750163 452.4889127334818
189.5582708426347 648.0845703750163 452.4889127334818 189.99371804165597
650.702061160138 449.28441142958735 192.4700952842229 648.9141751820521
448.0637073355264 200.0 650.702061160138 449.28441142958735
0.0 153.64456116460462 649.7154971797689 0.3838470500889033 152.7043488623754
646.4853692243097 32.193225497932644 152.7043488623754 646.4853692243097
33.121677262064836 151.81876382213784 652.0739461372822 44.51321394890502
151.81876382213784 652.0739461372822 45.52789830560195 156.6418279892978
647.7773883485683 65.79175430045773 156.6418279892978 647.7773883485683
66.03065795957777 156.41323433291345 649.7768565058526 101.58475162499978
156.41323433291345 649.7768565058526 102.18136856939307 152.91926935152946
649.683773361296 141.39700833430044 152.91926935152946 649.683773361296
```

Figure 4. 3 : BonnMotion Mobility File Proposed Model

```
sessions100 ×   mob100 ×
$node_(0) set X_ 256.46468174991367
$node_(0) set Y_ 408.6317224888677
$ns_ at 0.0 "$node_(0) setdest 611.6129599599329 273.9539946320984
8.99854906550712"
# $ns_ at 42.20978144026584 "$node_(0) setdest 611.6129599599329
273.9539946320984 0.0"
$ns_ at 58.148969098502995 "$node_(0) setdest 610.0362370145061
273.2064499848082 7.901932839030689"
# $ns_ at 58.36979582346723 "$node_(0) setdest 610.0362370145061
273.2064499848082 0.0"
$ns_ at 63.73730369197941 "$node_(0) setdest 610.3060149249563
275.2770666866887 6.112732663653227"
# $ns_ at 64.07890496333482 "$node_(0) setdest 610.3060149249563
275.2770666866887 0.0"
$ns_ at 71.99530196955514 "$node_(0) setdest 609.814311185382
274.71946728472943 9.85341970313683"
# $ns_ at 72.07075100433973 "$node_(0) setdest 609.814311185382
274.71946728472943 0.0"
$ns_ at 94.24581086081697 "$node_(0) setdest 610.3198200202951
271.5740553236944 9.874162873390723"
# $ns_ at 94.56844823061547 "$node_(0) setdest 610.3198200202951
271.5740553236944 0.0"
$ns_ at 97.66051851117533 "$node_(0) setdest 610.4825325862524
273.6963585368528 9.845042912233211"
# $ns_ at 97.87672188477804 "$node_(0) setdest 610.4825325862524
273.6963585368528 0.0"
$ns_ at 129.27820722081043 "$node_(0) setdest 609.8396500746463
                    Plain Text ▾   Tab Width: 8 ▾        Ln 1, Col 1
```

Figure 4. 4 : NS2 Compatible Mobility File Proposed Model

4.3.1.4. Generation of Trafficability File in NS2 using cbrgen Tool

Trafficability fie was generated in NS-2 using a tool names as cbrgen as per Figure 4.5. It generates traffic for defined number of nodes at constant bit rate (CBR). Same file is used according to number of nodes for which constant bit rate traffic is generated in tcl file in NS-2.

```
sessions100 ×   mob100 ×   col_proposed.movements ×
#
# nodes: 99, max conn: 25, send rate: 0.25, seed: 1.0
#
#
# 1 connecting to 2 at time 2.5568388786897245
#
set udp_(0) [new Agent/UDP]
$ns_ attach-agent $node_(1) $udp_(0)
set null_(0) [new Agent/Null]
$ns_ attach-agent $node_(2) $null_(0)
set cbr_(0) [new Application/Traffic/CBR]
$cbr_(0) set packetSize_ 512
$cbr_(0) set interval_ 0.25
$cbr_(0) set random_ 1
$cbr_(0) set maxpkts_ 10000
$cbr_(0) attach-agent $udp_(0)
$ns_ connect $udp_(0) $null_(0)
$ns_ at 2.5568388786897245 "$cbr_(0) start"
#
# 4 connecting to 5 at time 56.333118917575632
#
set udp_(1) [new Agent/UDP]
$ns_ attach-agent $node_(4) $udp_(1)
set null_(1) [new Agent/Null]
$ns_ attach-agent $node_(5) $null_(1)
set cbr_(1) [new Application/Traffic/CBR]
$cbr_(1) set packetSize_ 512
Plain Text ▾   Tab Width: 8 ▾   Ln 10, Col 27   INS
```

Figure 4. 5 : Trafficability File Using cbrgen tool NS2 Proposed Model

4.3.1.5. Creating of AWK scripts for Evaluation of Trace File

When we execute tcl file in NS-2, it generates a trace file. Each line of trace file represents data regarding type of event, time of event, from and to, packet size, source and destination address followed by sequence number and packet ID. Awk scripts[13] were used to get results from the trace file basing on various performance metrics. Awk[13] is a programming language used for manipulating data and text processing. The awk scripts[13] can be used for data extraction, data transformation, data filtering, data summarization, report generation, data cleaning, searching and pattern matching and even joining trace files with relevant data.

Awk[13] in our case was used to parse the data and relevant information from generated trace file (in Figure 4.7) was extracted to calculate statistics for visualization and further analysis. Awk[13] is a very powerful language that eased the process of our reading of relevant data from within the trace files which would have been very cumbersome otherwise if done manually. Since for every combination of node, a trace file was generated and eleven different combinations of nodes were simulated for column and pursue behavior each.

Following is the specimen of the header of a trace file as per Figure 4.6 [15] which has been evaluated using various Awk[13] scripts for performance metrics. After that we have a figure of proposed model trace file as per Figure 4.7 which was generated during simulation of column mobility model using AODV routing protocol.

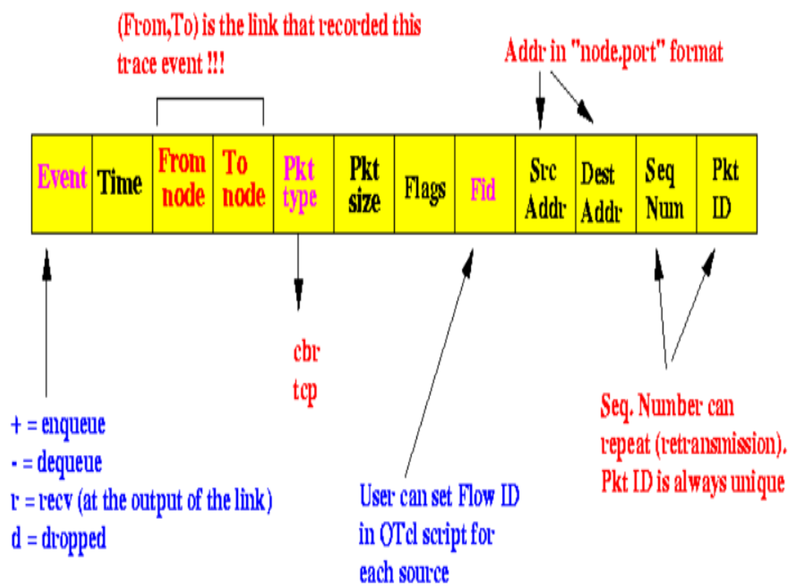


Figure 4. 6 : Trace File Header Format[15]

```
aodv70.tcl ×   aodv40.tcl ×   out.tr ×   aodv.tcl ×
M 0.00000 7 (394.99, 234.01, 0.00), (393.81, 232.64), 7.53
M 0.00000 8 (685.83, 272.74, 0.00), (687.52, 272.35), 8.50
M 0.00000 9 (683.68, 270.39, 0.00), (685.99, 270.64), 9.85
M 1.47563 1 (646.95, 746.77, 0.00), (644.91, 745.91), 8.17
s 2.556838879 _1_ AGT  --- 0 cbr 512 [0 0 0 0] ------- [1:0 2:0 32 0] [0] 0 0
r 2.556838879 _1_ RTR  --- 0 cbr 512 [0 0 0 0] ------- [1:0 2:0 32 0] [0] 0 0
s 2.556838879 _1_ RTR  --- 0 AODV 48 [0 0 0 0] ------- [1:255 -1:255 30 0] [0x2
1 1 [2 0] [1 4]] (REQUEST)
s 2.556953879 _1_ MAC  --- 0 AODV 106 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557801960 _0_ MAC  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557802448 _3_ MAC  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557802452 _2_ MAC  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557826960 _0_ RTR  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557827448 _3_ RTR  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
r 2.557827452 _2_ RTR  --- 0 AODV 48 [0 ffffffff 1 800] ------- [1:255 -1:255
30 0] [0x2 1 1 [2 0] [1 4]] (REQUEST)
s 2.557827452 _2_ RTR  --- 0 AODV 44 [0 0 0 0] ------- [2:255 1:255 30 1] [0x4
1 [2 4] 10.000000] (REPLY)
s 2.557882452 _2_ MAC  --- 0 ARP 86 [0 ffffffff 2 806] ------- [REQUEST 2/2 0/1]
r 2.558570456 _3_ MAC  --- 0 ARP 28 [0 ffffffff 2 806] ------- [REQUEST 2/2 0/1]
r 2.558570978 _0_ MAC  --- 0 ARP 28 [0 ffffffff 2 806] ------- [REQUEST 2/2 0/1]
```

Figure 4. 7 : Proposed Model Trace File generated after execution of tcl file in NS2

4.3.1.6. Running TCL file in NS2 using AWK Scripts

After that the tcl file was executed with all above mentioned files including awk scripts[13] to generate desired results which will be discussed in next chapter.

4.3.1.7. Running of Network Animator to See Live Simulation of Model

Network animator in NS-2 was used to see the real time movements of nodes in as shown in Figure 4.8 to 4.11. All movements were recorded to keep trace of different behavior of nodes in both column and pursue group mobility models.

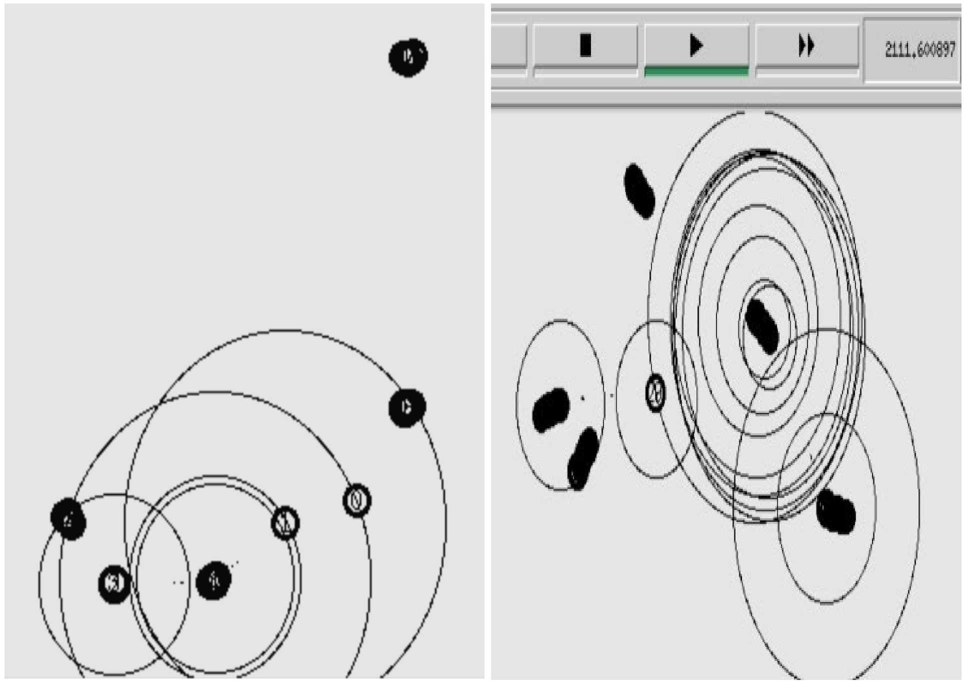


Figure 4.8 : Column Mobility Model Network Animator(NAM) Simulation in NS2

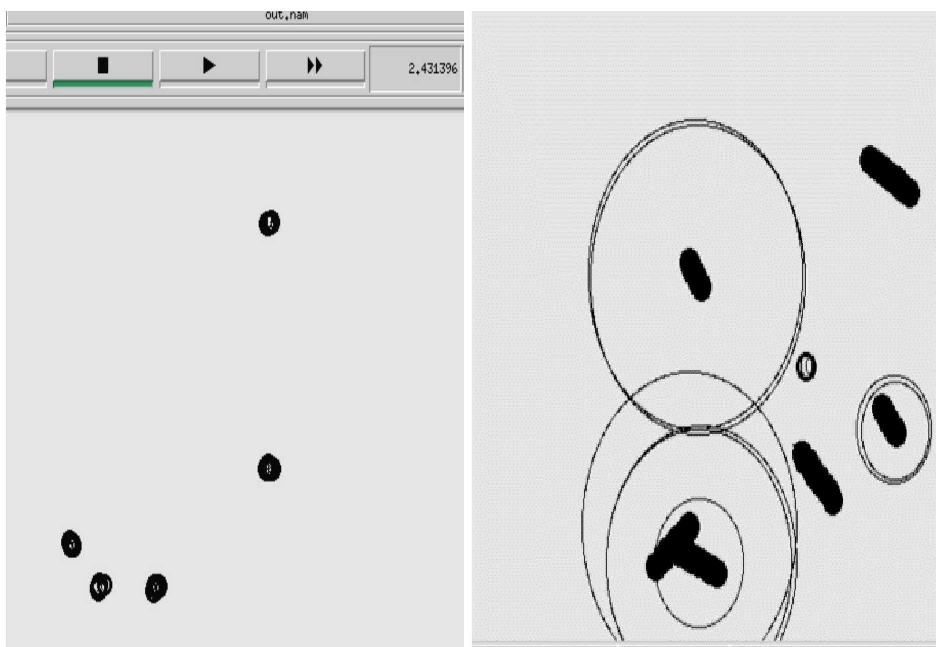


Figure 4.9 : Column Mobility Model Network Animator(NAM) Simulation in NS2

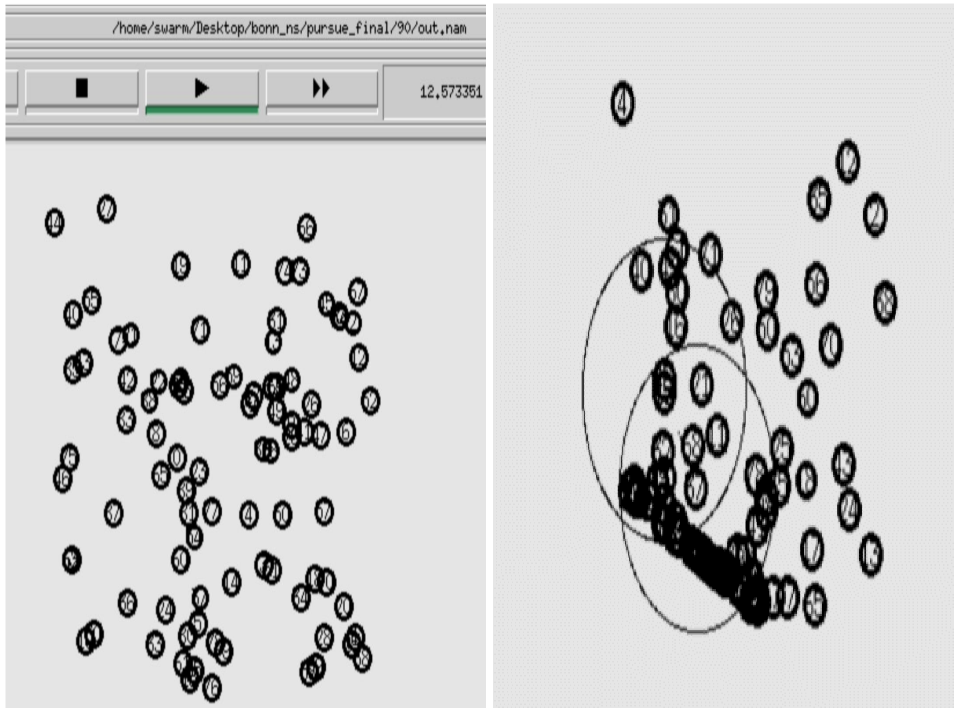


Figure 4. 10 : Pursue Mobility Model with 90 Nodes NAM Simulation in NS2

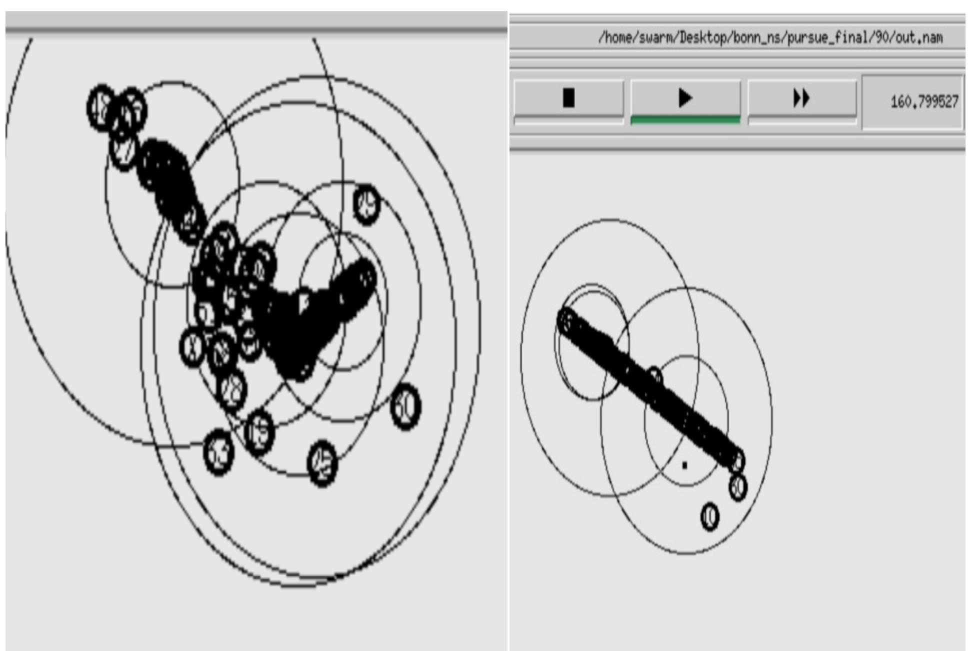


Figure 4.11 : Pursue Mobility Model with 90 Nodes after Some Duration

4.4. Flow Chart

The flow chart devolves around the already elucidated steps which were performed chronologically to implement the proposed GMM Drone Swarm Networks.

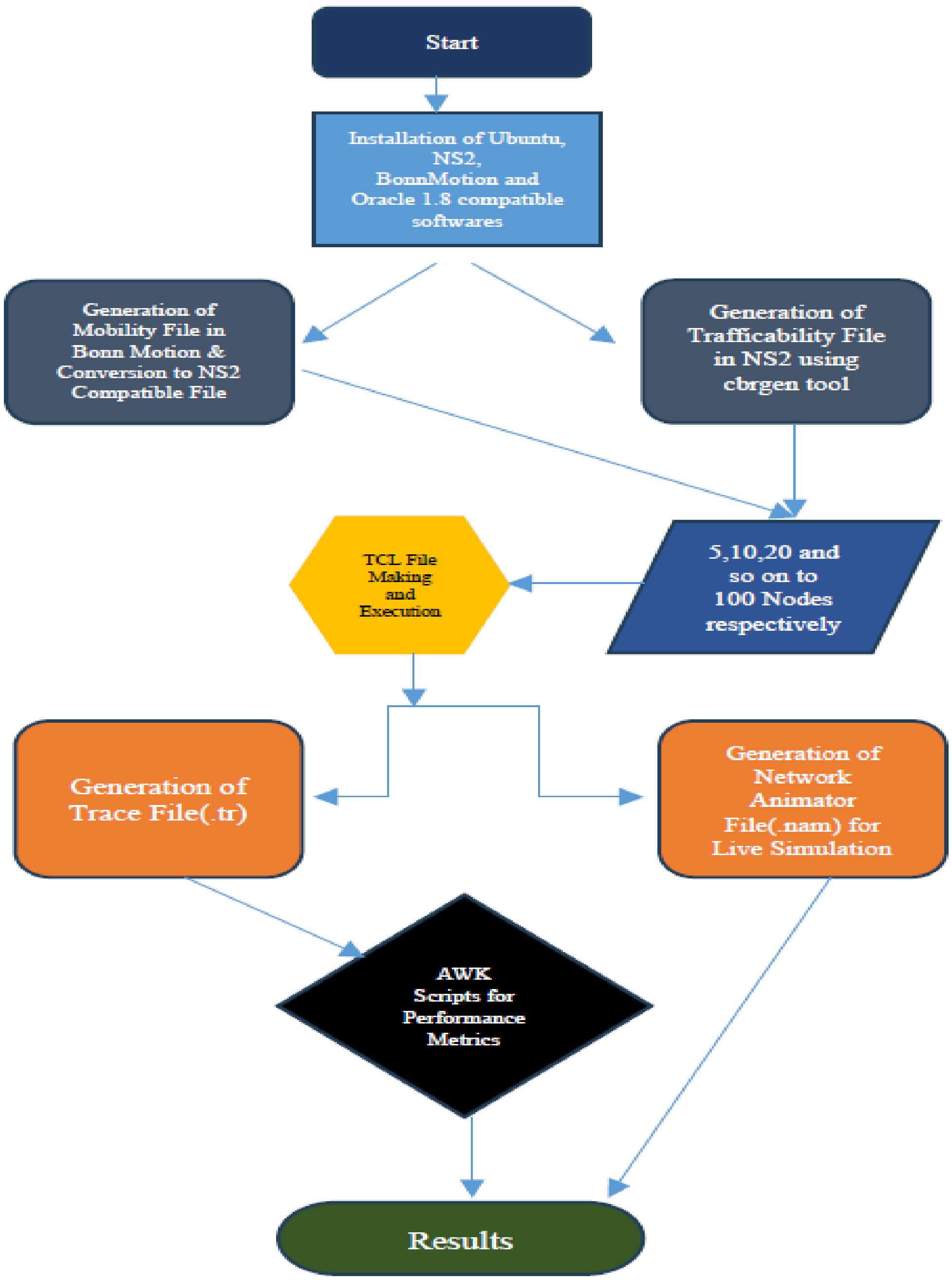


Figure 4. 12 : Flowchart Proposed Group Mobility Model

4.5. Mathematical Equation

In the mathematical model, column mobility model will be used to maintain cohesive and structural formation in movement towards target using smaller columns or subgroups while pursue mobility model will enable individual drone responsiveness, pursuit, target tracking[30] and agile movements.

Column Movement Equations

$$\text{Velocity}, \quad V_c = s_{max} \tag{1}$$

Instantaneous Position,

$$S(t+\Delta t) = S(t) + V_c * \Delta t * [randX(-1,1), randY(-1,1)]] \tag{2}$$

Pursue Movement Equations

$$\text{Velocity}, \quad V_p = s_{max} \tag{3}$$

Direction,

$$\theta = atan2(Y\_target - Y, X\_target - X) \tag{4}$$

Instantaneous Position,

$$S_x(t+\Delta t) = S_x(t) + V_p * \Delta t * \cos(\theta) \tag{5}$$

$$S_y(t+\Delta t) = S_y(t) + V_p * \Delta t * \sin(\theta) \tag{6}$$

During the column behaviour once swarm is divided into column, velocity (Vc) is set to maximum speed(smax) which swarm drones can achieve. At every instantaneous moment (Δt), the position of drone is updated by adding displacement along X and Y axis by ($v*\Delta t$) using range [-1,1] so that drones maintain column formation while moving towards the target whereas during pursue behavior, drones operate independently to pursue a specific target. Velocity is set to maximum speed(smax) but direction (θ) is calculated using atan2 function[12], that gives the angle from the x-axis to a line containing the origin (0, 0) and a point with coordinates (x_num, y_num) i.e. angle between the current position of the drone to target location[12]. Trigonometric functions cos and sin are used to determine position(Sx,Sy)/ displacement at each time step (Δt) based on velocity and direction.

4.6. Loss Function

The Loss function made for optimization and finding out best results for different number of nodes can as as follows: -

Loss_Fn = A * (1 – (Packet Delivery Ratio/100)) + B *(Average End to End Delay/100) + C * (1 – (Average Throughput / 10000)) + D* (Packet Drop Rate / 10000) (7)

- A to D are weights assigned as per the importance of each metric. A can be kept 1.5 while rest can be kept one if we consider pdr as single most important factor over other metrics.
- A* (1 – (Packet Delivery Ratio / 100)) penalizes lower packet delivery ratio. Lower values of packet delivery ratio result in higher loss.
- B* (Average End to End Delay / 100) penalizes higher end-to-end delay. Higher average delay leads to higher loss.
- C * (1 – (Average Throughput / 10000)) penalizes lower average throughput. Lower average throughput results in higher loss.
- D * (Packet Drop Rate / 10000) penalizes higher packet drop rate. Higher packet drop rate leads to higher loss.

4.7. Summary

This chapter amply covers all proposed GMM and implementation details/ all steps for one proposed GMM that were performed to achieve the desired results duly optimized keeping in view various routing protocols and even designing of a loss function after normalizing of various performance metrics after seeing their upper limits in results. All files which were generated in each iteration of the methodology were shown to better assimilation of the process involved besides flow chart of complete methodology and mathematical equation.

CHAPTER 5 : EXPERIMENT & RESULTS

This chapter covers all the statistical and practical results that were received after taking into consideration all steps that were performed and enumerated in previous chapter. It took a lot of time to get the desired results through an iterative process and reaching of various inferences as elucidated in this chapter.

5. Results

Two iterations were performed for each column and pursue behavior using two different routing protocols. The final results were based on eleven iterations each for column and pursue behaviour for different number of nodes ranging from 5 , 10 , 20 and so on till 100.

5.1. Results and Findings for Column Mobility Model Using AODV RP

5.1.1. AODV routing protocol was used to simulate the column mobility model which performed well when nodes were less i.e. 5. Packet delivery ratio was 100% as there was no dropped packet. Avg end to end delay was also very less.

5.1.2. The packet delivery ratio was totally degraded for 10 nodes which further kept on improving till it reached more than 96% for 100 nodes which is a very good result.

5.1.3. Packet generation is getting increased by increasing duration of simulation. Maximum dropped packets were there when nodes were 30 followed by next maximum dropped packets when nodes were 40 as duration was suddenly increased on 30 packets and onwards. Dropped packets are getting reduced as we increase number of nodes showing cohesion and indicative of good communication among nodes.

5.1.4. Average end-to-end delay also increasing as nodes are increasing thereby showing latency issues on scalability of this model. However, end-to-end delay is maximum for 30 nodes as duration for simulation was suddenly increased.

5.1.5. Average throughput also increasing as duration for simulation has been increased besides number of nodes.

Table 5.1 : Performance Metrics Evaluation - Column Mobility Model - AODV RP

Ser	Duration	Nodes (nn)	Generated Packets	Received Packets	Packet Delivery Ratio (pdr)	Total Dropped Packets	Avg End-to-End Delay (ms)	Avg Throughput (kbps) (CBR)
1	200	5	793	793	100	0	5.81468	49.99
2	200	10	4328	2441	56.4002	1803	5.75649	192.53
3	200	20	10319	7918	76.7322	2274	6.73849	551.77
4	3000	30	250000	191941	76.7764	58191	54.0704	1059.74
5	3000	40	250000	211510	84.604	38542	28.9014	1064.15
6	3000	50	250000	228928	91.5712	21275	25.1342	1144.85
7	3000	60	250000	230100	92.04	20109	35.1047	1162.44
8	3000	70	250000	217843	87.1372	32317	41.1738	1091.63
9	3000	80	250000	220998	88.3992	29078	20.9973	1117.20
10	3000	90	250000	237683	95.0732	12325	23.5772	1228.82
11	3000	100	250000	240982	96.3928	9053	49.6567	1256.89

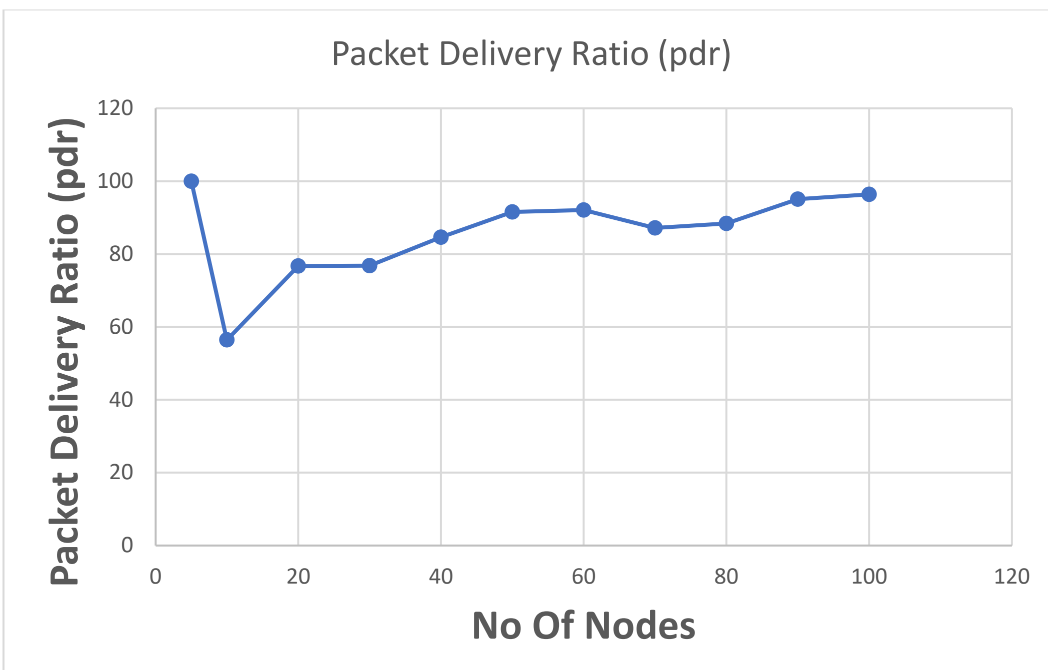


Figure 5.1 : Packet Delivery Ratio Column Mobility Model Using AODV RP

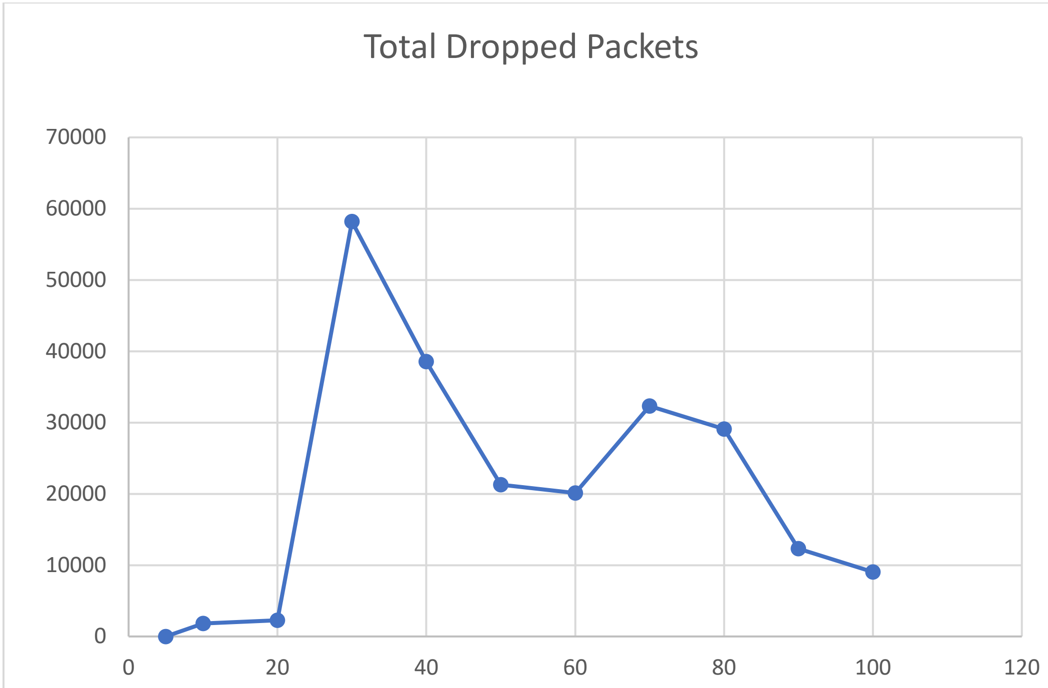


Figure 5.2: Total Dropped Packets Column Mobility Model Using AODV RP

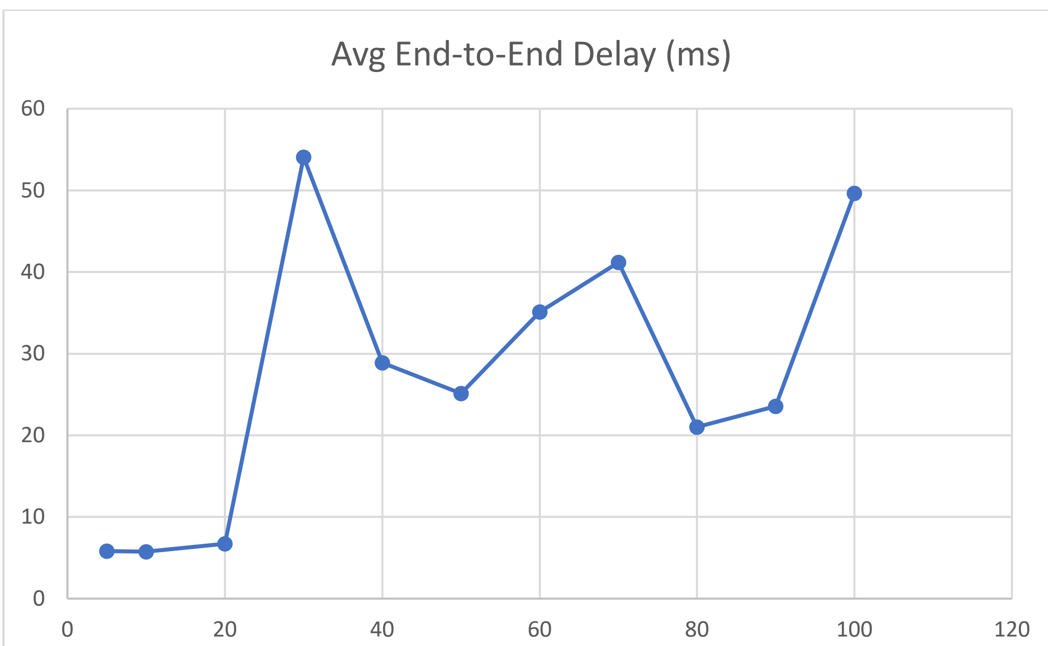


Figure 5. 3 : Avg End-to-End Delay Column Mobility Model Using AODV RP

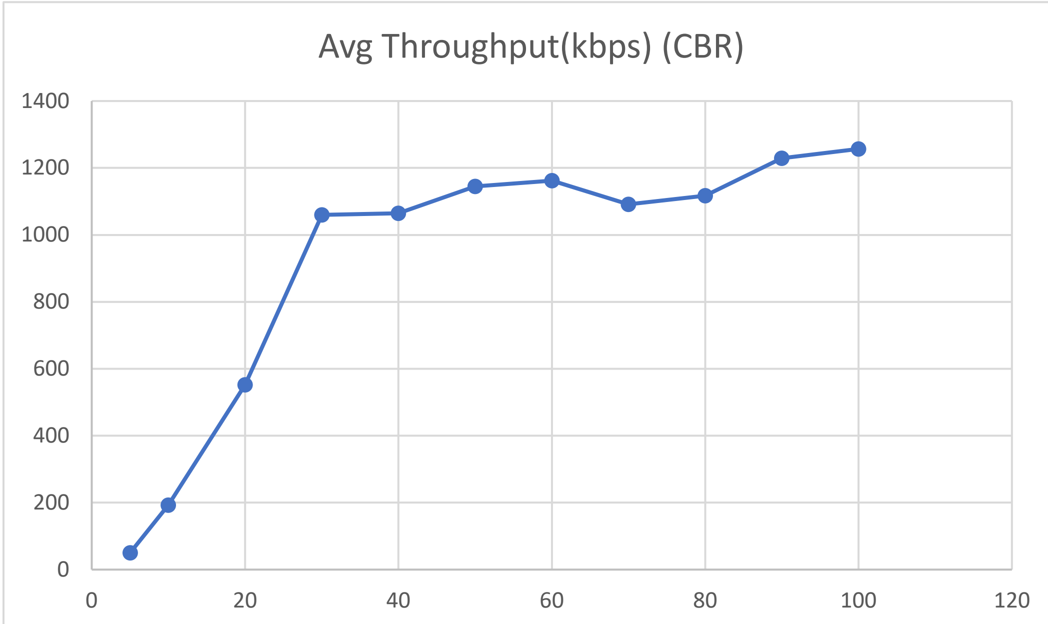


Figure 5.4 : Avg Throughput Column Mobility Model Using AODV RP

5.2. Results and Findings for Pursue Mobility Model Using AODV RP

5.2.1. AODV routing protocol was used to simulate the pursue mobility model which performed well when nodes were 40 as packet delivery ratio was 99.89%. Packet delivery was degraded the most when there were only 5 nodes indicative of all nodes too far apart leading to poor packet delivery.

5.2.2. Dropped packets were maximum on 70 nodes however still far lesser than dropped packets in column mobility model. Hence pursue behavior is far more optimized than column behavior as far as dropped packets are concerned but it can't be useful inference but holds good for only first three iterations as simulation time for remaining iterations was much higher for column behavior, this generating more packets and more losses.

5.2.3. Average end-to-end delay was maximum for 5 nodes followed by 100 nodes and 90 nodes respectively indicative of saturation in scalability to an extent i.e. performs acceptably well till 80 nodes.

5.2.4. Throughput is continuously increasing as we are increasing the nodes.

Table 5. 2 : Performance Metrics Evaluation - Pursue Mobility Model – AODV RP

Ser	**Duration**	**Nodes (nn)**	**Generated Packets**	**Received Packets**	**Packet Delivery Ratio (pdr)**	**Total Dropped Packets**	**Avg End-to-End Delay (ms)**	**Avg Throughput (kbps) (CBR)**
1	200	5	1551	889	57.3179	625	559.758	69.60
2	200	10	4306	4229	98.2118	76	53.3626	268.17
3	200	20	10324	10283	99.6029	74	22.4289	963.13
4	200	30	12844	12813	99.7586	43	21.6173	1085.64
5	200	40	12811	12797	99.8907	23	37.3641	1193.45
6	200	50	12863	12800	99.5102	81	42.2391	1200.65
7	200	60	12870	12674	98.4771	162	44.8442	1094.01
8	200	70	12816	11442	89.279	1431	78.5758	1229.62
9	200	80	12783	12697	99.3272	95	53.3127	1195.09
10	200	90	12797	12044	94.1158	696	342.047	1077.02
11	200	100	12869	12202	94.817	697	399.852	1262.70

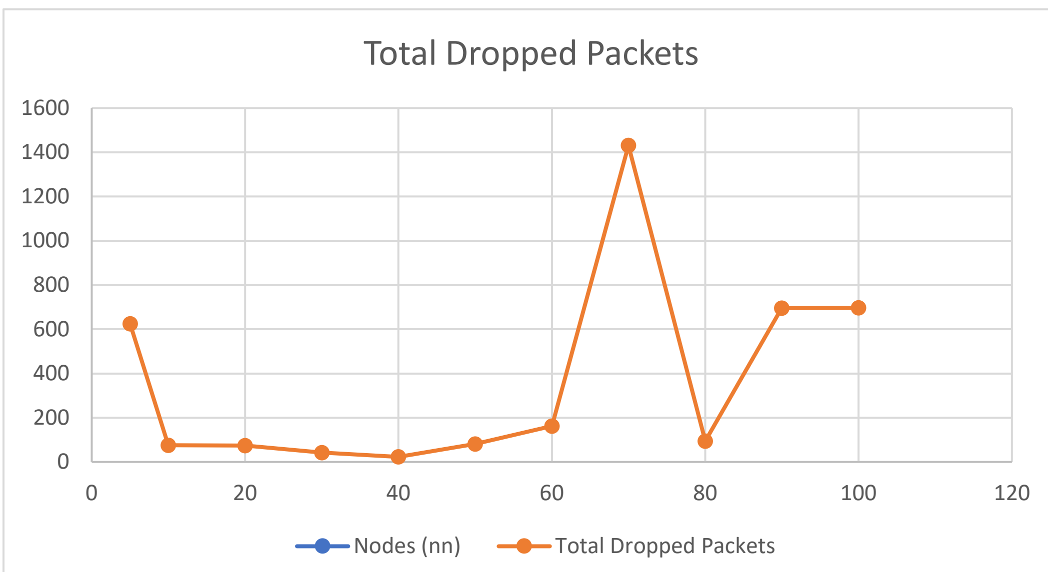


Figure 5. 5 : Total Dropped Packets Pursue Mobility Model Using AODV RP

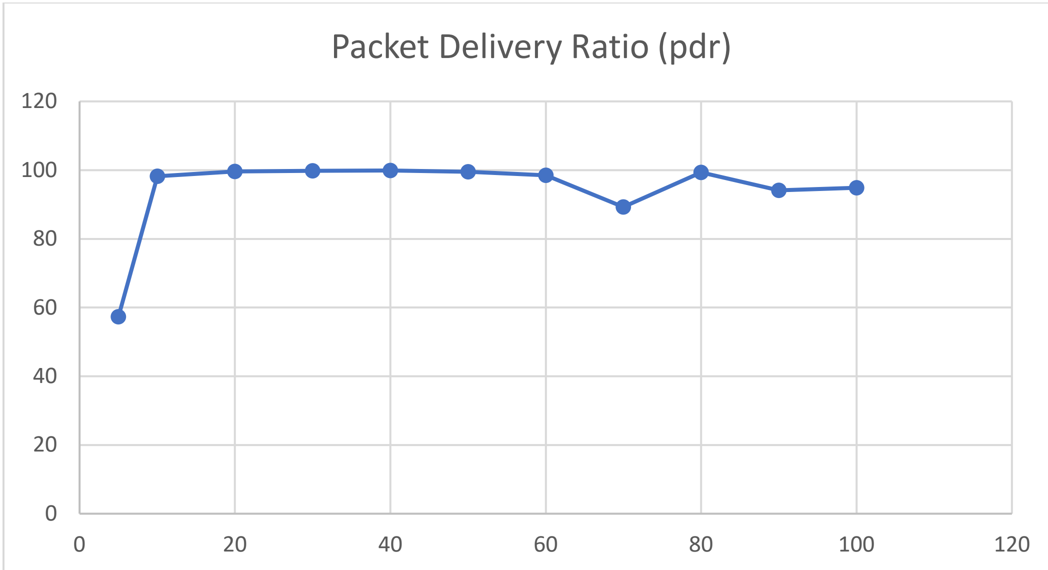


Figure 5. 6 : Packet Delivery Ratio Pursue Mobility Model Using AODV RP

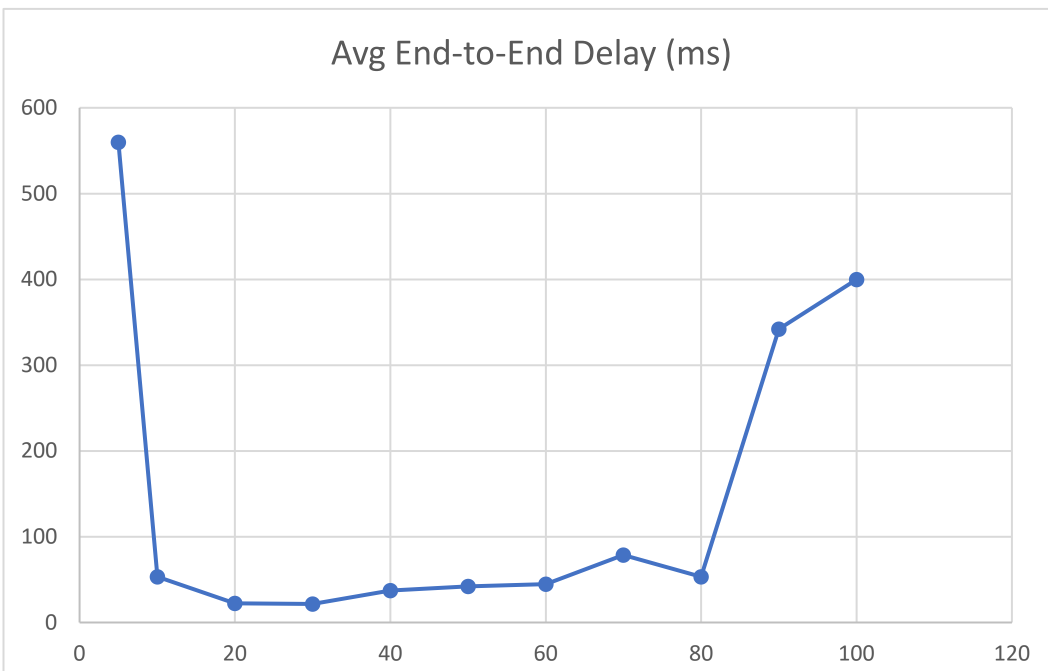


Figure 5. 7 : Avg End-to-End Delay Pursue Mobility Model Using AODV RP

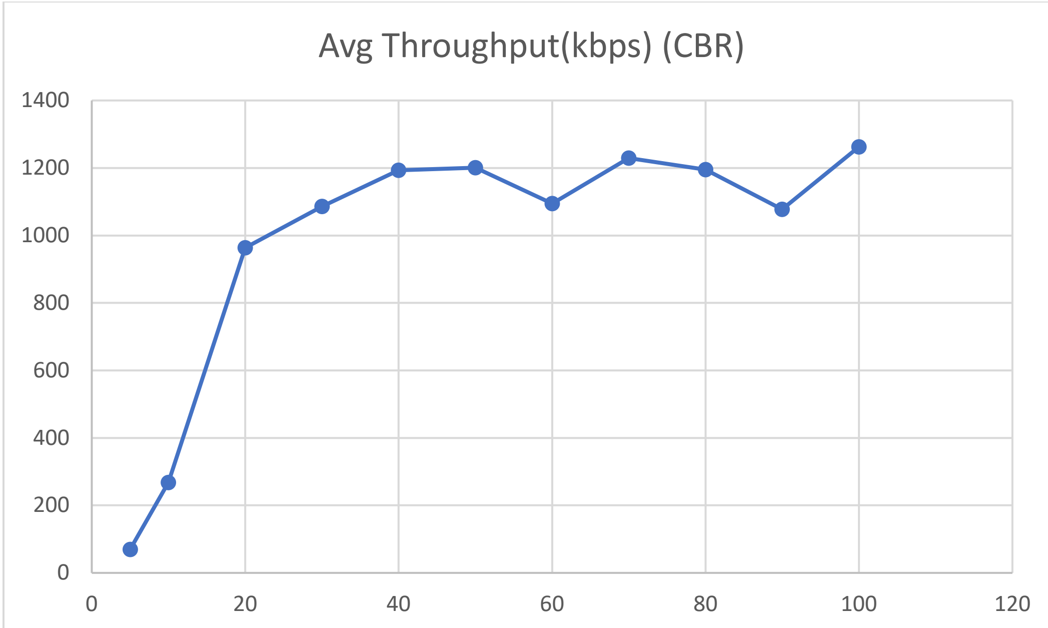


Figure 5. 8 : Avg Throughput Pursue Mobility Model Using AODV RP

5.3. Results and Findings for Column Group Mobility Model Using OLSR RP

5.3.1. Packet delivery ratio is very less using OLSR RP and column mobility model. Though it improves for 50 nodes but still its very less.

5.3.2. Dropped packets are also too much besides average end-to-end delay is also too much especially for 50 nodes. However, dropped packets are getting less as we increase number of nodes.

5.3.3. Average throughput is increasing gradually.

Table 5. 3 : Performance Metrics Evaluation - Column Mobility Model - OLSR RP

Ser	Duration	RTR	Nodes (nn)	Generated Packets	Received Packets	Packet Delivery Ratio (pdr)	Total Dropped Packets	Avg End-to-End Delay (ms)	Avg Throughput(kbps) (CBR)
1	3000	8510	30	296660	190024	64.0545	60043	8.9291	1017.43
2	3000	1725	40	313130	210929	67.3615	39087	11.2866	1063.38
3	3000	4768	50	332087	227658	68.5537	22373	29.8448	1124.54
4	3000	1388	60	345138	228565	66.2242	21452	7.30094	1115.69

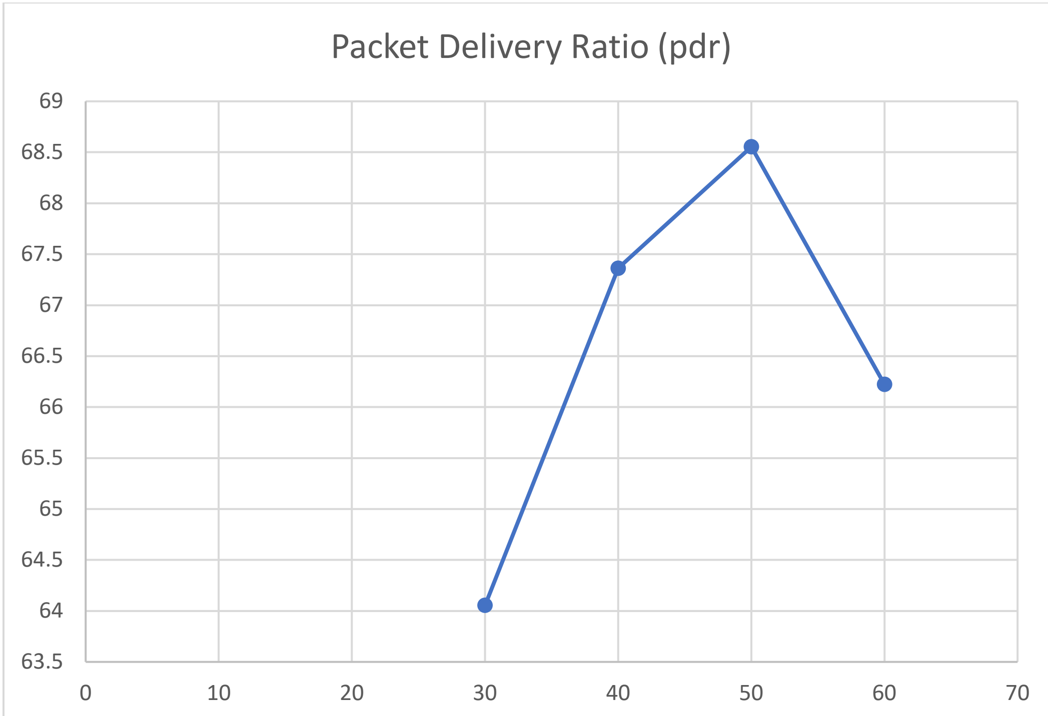


Figure 5. 9 : Packet Delivery Ratio Column Mobility Model Using OLSR RP

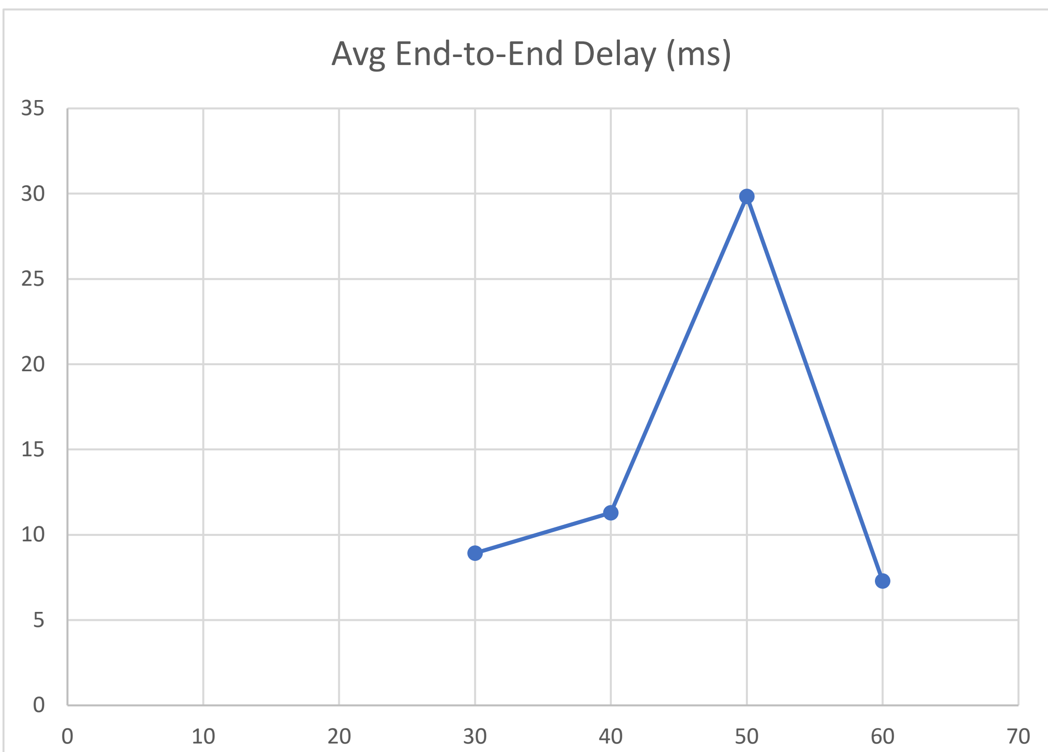


Figure 5. 10 : Avg End-to-End Delay Column Mobility Model Using OLSR RP

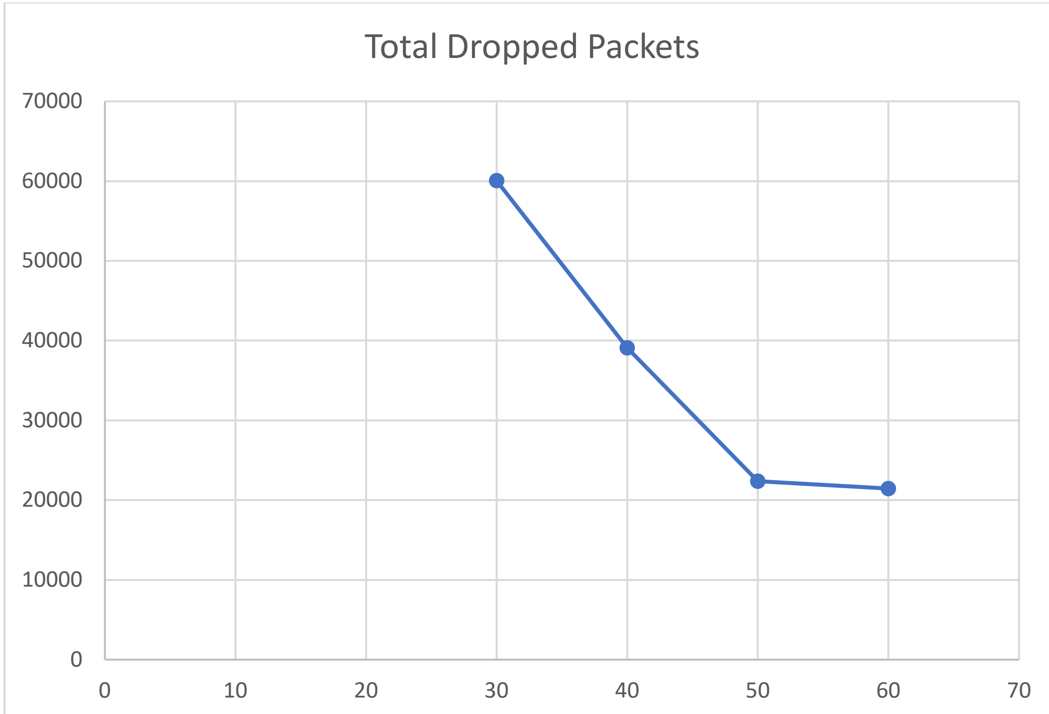


Figure 5. 11 : Total Dropped Packets Column Mobility Model Using OLSR RP

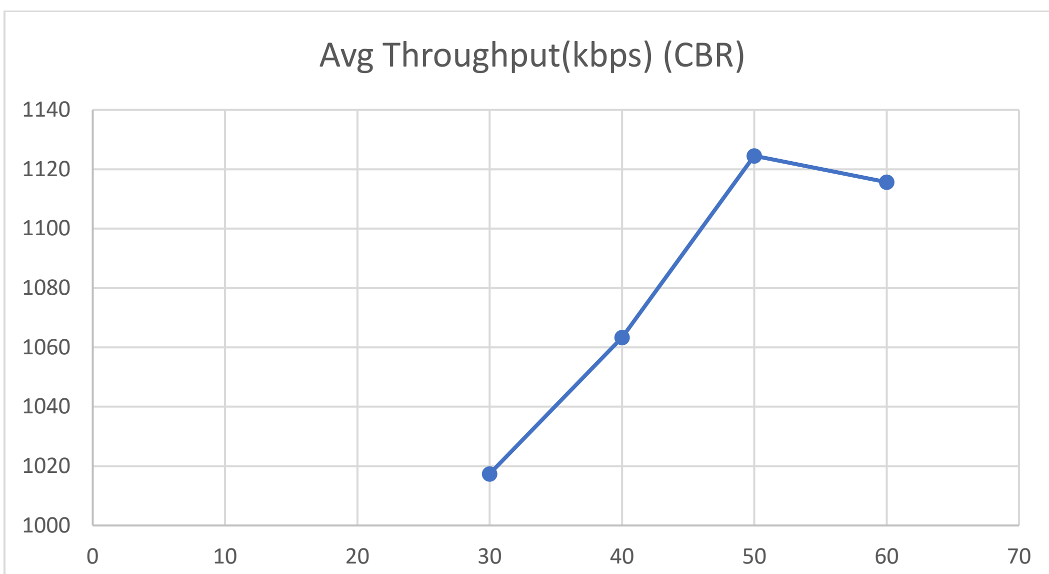


Figure 5. 12 : Avg Throughput Column Mobility Model Using OLSR RP

5.4. Results for Pursue Group Mobility Model Using OLSR RP

5.4.1. Packets have substantially dropped on increasing of nodes in OLSR model using our Pursue Mobility Model which clearly indicates that this model is not scalable with OLSR routing protocol.

5.4.2. Packet delivery ratio is also decreasing as we are increasing the number of nodes thereby indicating the same as mentioned above that its not scalable and going for packet losses or network congestion due to which packets are getting discarded or are under retransmission as RTR also increasing with increased number of nodes.

5.4.3. Average end-to-end delay is also increasing with increased number of nodes.

5.4.4. The average throughput increases till 40 nodes but suddenly decreases as we increase nodes to 50 indicative of network congestion and collision. Hence proposed GMM is not scalable with OLSR RP.

Table 5. 4 : Performance Metrics Evaluation - Pursue Mobility Model - OSLR RP

Ser	Duration	RTR	Nodes (nn)	Generated Packets	Received Packets	Packet Delivery Ratio (pdr)	Total Dropped Packets	Avg End-to-End Delay (ms)	Avg Throughput(kbps) (CBR)
1	3000	4135	30	298766	249690	83.5738	310	10.2711	1195.11
2	3000	21497	40	315592	249810	79.156	194	12.1134	1247.36
3	3000	5105	50	330720	240261	72.6479	9756	10.6842	1161.07

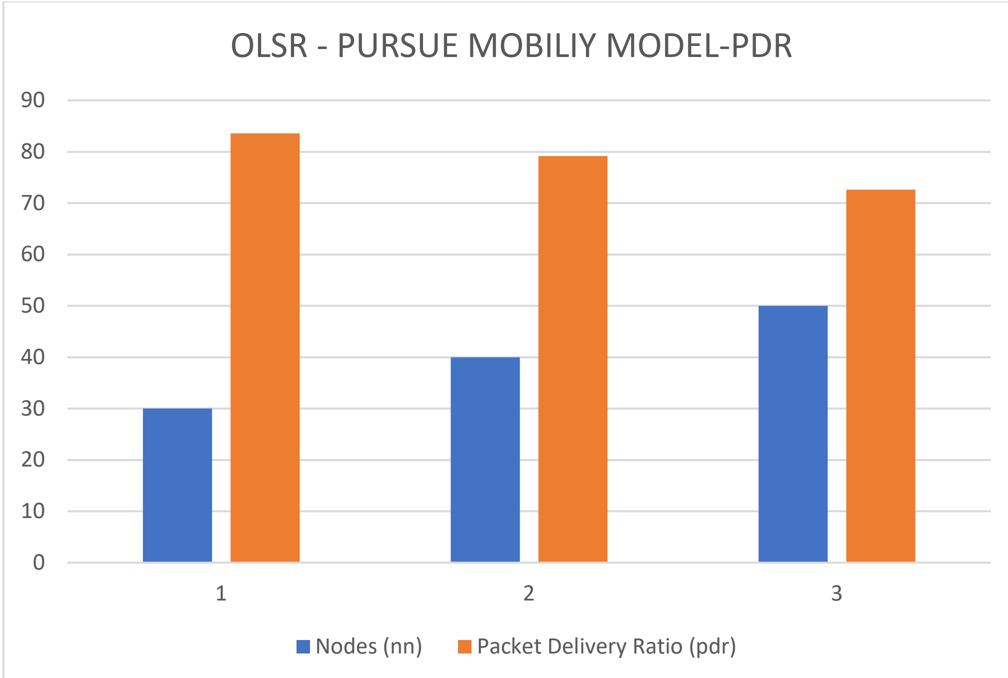


Figure 5. 13 : PDR Pursue Mobility Model Using OLSR RP

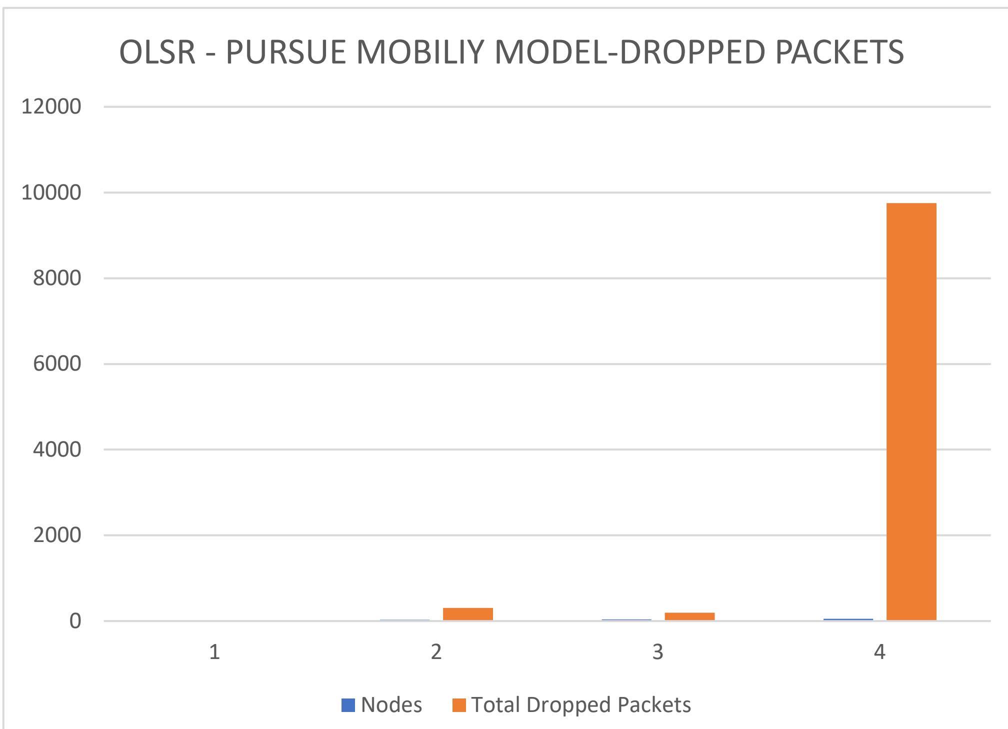


Figure 5. 14 : Dropped Packets Pursue Mobility Model Using OLSR RP

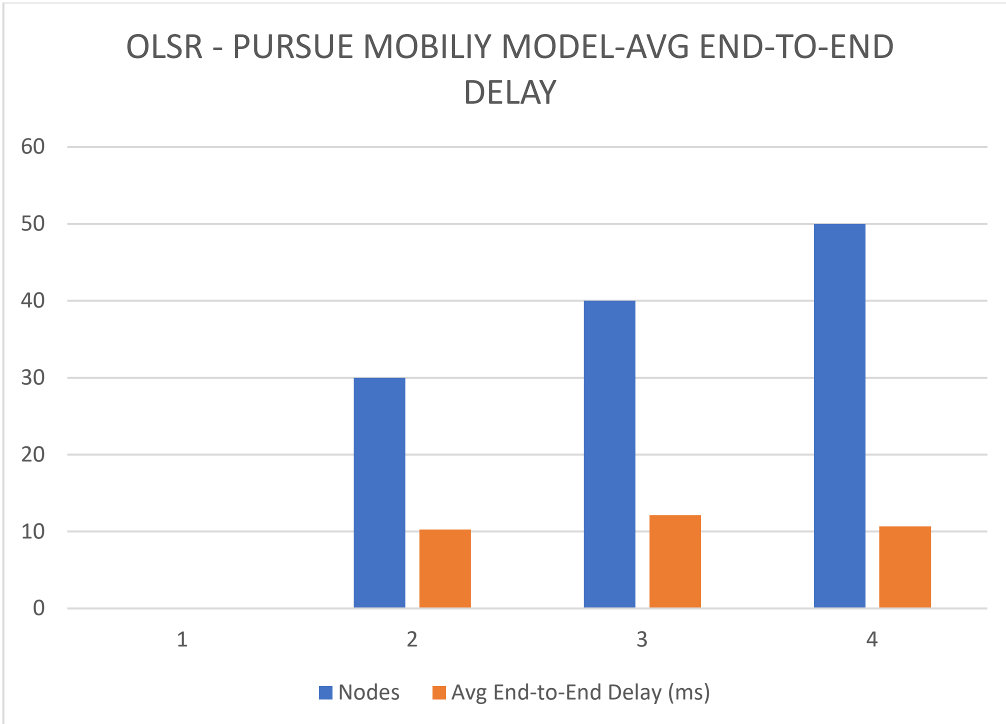


Figure 5. 15 : Avg End-to-End Delay Pursue Mobility Model Using OLSR RP

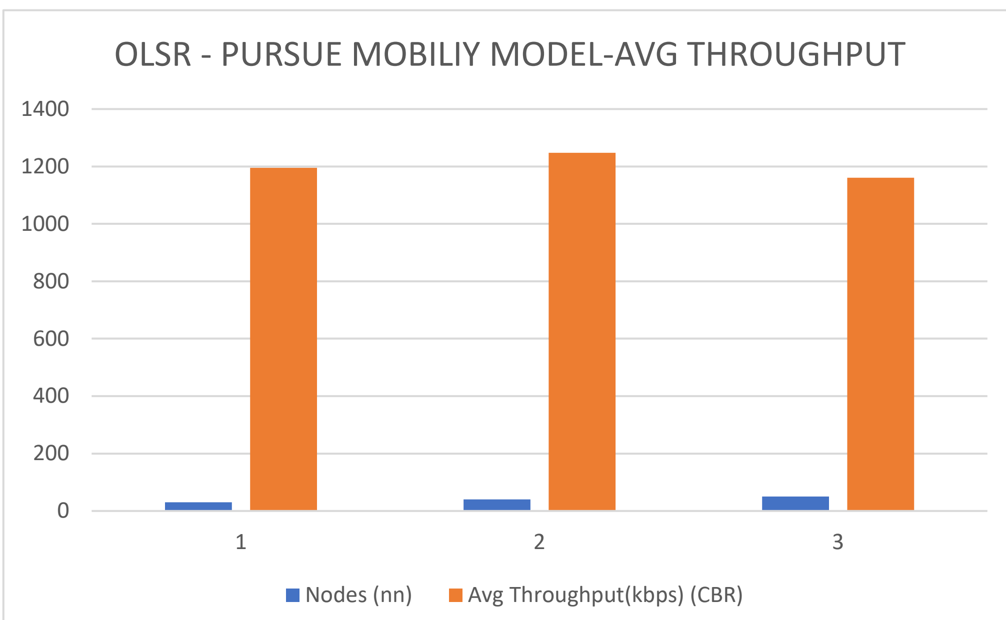


Figure 5. 16 : Avg Throughput Pursue Mobility Model Using OLSR RP

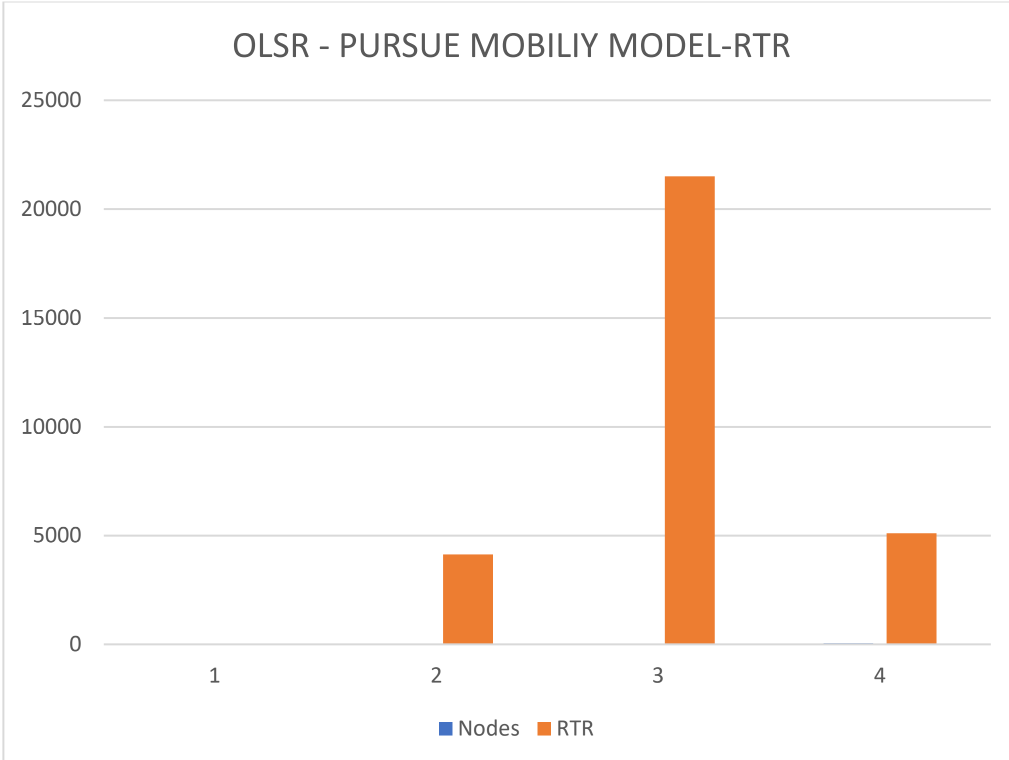


Figure 5. 17 : RTR Pursue Mobility Model Using OLSR RP

5.5. Summary

AODV has performed far better in our proposed group mobility model **Hybrid Column and Pursue Mobility Model for Search and Pursuit Military Operations.** Traffic was generated using CBR. OLSR totally fails for above mentioned proposed group mobility model drone swarm networks due to loss of packets and very low packet delivery ratio. Although OLSR performs a bit better in Pursue Mobility Model as part of the current hybrid model but still performance is not at par with AODV routing protocol. OLSR is opting for lot of RTR as compared to AODV which is causing sufficient end-to-end delay.

CHAPTER 6 : CONCLUSION

6. Conclusions

The proposed GMM Drone Swarm Network was successfully implemented and simulated using AODV routing protocol with optimum results. The research was very time intensive and background study was very important to keep up with the latest trends and developments in Drone Swarm Networks as it is continuously evolving day by day and in near future swarm drones will be doing lot of tasks where we are presently employing human work force. The subject model can be used by law enforcement agencies and even military for search and pursuit operations. Various other models have also been proposed in this thesis but implementation of those models would have been a cumbersome task keeping in view the limited scope of current research work. However, other proposed group mobility models can also be implemented by researchers and can be food for thought or jump of point for next level research.

There is no denial that future warfare will be swarm drone based and complete warfare tactics have been changed after the world witnessed Nagorno-Karabakh drone war and Azerbaijan military superiority in the battlefield due to use of drones in offensive with shrinking their causalities in the battlefield. Similarly, China[14] demonstrated the use of a drone swarm to deliver food to soldiers on the frontline during the standoff in Ladakh. Research in this area was the utmost need of time to cater for future warfare needs.

6.1. Research Limitations and Real-Time Challenges for Future Work

Some of the key research challenges include: -

6.1.1. Scalability

As the number of drones in a swarm increases, maintaining efficient group mobility becomes challenging. Researchers need to develop group mobility models that can scale to accommodate large drone swarms while ensuring effective coordination and communication among the drones.

6.1.2. Heterogeneity

Drone swarms can consist of drones with different capabilities, including varying speeds, communication ranges, and payload capacities. Designing group mobility models that account for the heterogeneity of drones is essential to optimize the swarm's performance.

6.1.3. Decentralization

Centralized control of drone swarms may not be practical in many scenarios due to communication constraints and potential single points of failure. Researchers need to explore decentralized group mobility models that allow drones to make local decisions based on shared information.

6.1.4. Adaptability

Drone swarm networks often operate in dynamic and unpredictable environments. Group mobility models should be adaptive and capable of responding to changing conditions, such as weather, obstacles, or mission objectives.

6.1.5. Communication and Connectivity

Effective communication among drones is critical for coordinated movement. Researchers must consider the communication protocols and connectivity challenges when developing group mobility models.

6.1.6. Energy Efficiency

Drone swarms are constrained by limited onboard energy. Developing energy-efficient group mobility models that optimize drone movements and minimize energy consumption is essential to prolong the swarm's operational duration.[26]

6.1.7. Collision Avoidance

Ensuring collision avoidance among swarm drones is crucial for safety and mission success. Group mobility models need to incorporate collision avoidance algorithms to prevent mid-air collisions.

6.1.8. Mission-Specific Objectives

Different applications of drone swarm networks require specific mission objectives. Researchers should explore group mobility models tailored to different mission types, such as surveillance[1], search and rescue, or disaster response.

6.1.9. Robustness and Fault Tolerance

In dynamic environments or under adversarial conditions, drones may face challenges like communication disruptions or drone failures. Developing robust group mobility models that can tolerate faults and recover from disruptions is vital.

6.1.10. Validation and Real-World Deployment

Evaluating the performance of group mobility models in real-world scenarios is essential. Researchers should validate their models through simulations and real-world experiments to ensure their effectiveness and practicality.

6.1.11. Real-world Complexity

Simulating and modeling real-world environments accurately is challenging. The dynamics of outdoor environments, weather conditions, and obstacles are difficult to capture comprehensively, making it harder to validate the group mobility models in realistic scenarios.

6.1.12. Dynamic and Unpredictable Environments

Drone swarm operations often take place in dynamic and unpredictable environments, such as disaster zones or military operations. Designing group mobility models that can adapt and respond effectively to rapidly changing conditions is a significant challenge.

6.1.13. Ethical and Legal Considerations

Swarm drone networks raise ethical, moral and legal concerns, especially regarding privacy, safety, and potential misuse. Incorporating ethical considerations into the design of group mobility models is a challenging but essential aspect of research.

6.2. Way Forward

Addressing these research challenges will advance the state-of-the-art in drone swarm networks' group mobility models, enabling more efficient and reliable swarm operations for various applications and domains. The group mobility model drone swarm networks which have been proposed in this research work can pave way for future researches.

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