A Comparative Analysis of Mobility Models for Network of UAVs

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Abstract. Flying Adhoc Network (FANET) is an emerging research area gaining lot of attention of researchers nowadays. FANET as the name suggests, is an ad hoc network of Unarmed Aerial Vehicles (UAVs) flying in the space and forming a connected network to accomplish a common task with cooperation of each other. Mobility of nodes in such networks has always been a challenging task and thus researchers have proposed many solutions over the time for directing nodes mobility within the region of interest. Since, FANET nodes tend to move at much greater speed as compared to nodes in other networks like mobile ad hoc networks (MANETs) and drain more energy pertaining to its self-organizing nature, various new mobility models have been suggested and traditional models for MANET have been modified in accordance with the need of FANETs. In this paper, we present comparative study of both old as well as the new mobility models. A systematic comparative analysis is done based on certain parameters like their ability to cover the area, maintenance of connectivity, collision avoidance and energy consumption. Also, the paper explores some future directions and research problems related to the FANETs.

Keywords: FANET · Mobility models · Adhoc network · UAV · Virtual forces · Area coverage · Connectivity · Drones · Mobile networks

1 Introduction

Unarmed Aerial Vehicles (UAVs) also known as drones, are autonomous aircrafts without human pilot on board, and has become a thriving area in which many researchers want to contribute [1]. The collection of UAVs working together to achieve a single goal is known as UAV Fleet, they all connect and communicate to form an Adhoc network called Flying Adhoc Network (FANET) as depicted in Fig. 1. Usage of multiple nodes has much greater benefits as compared to single node as it allows coverage of large area (multiple nodes can coordinate with each other to cover different coordinates), reliability (if any node fails other can take its place), cost effectiveness (cost for setting single node structure is same as multiple and in the same cost we can have advantage of multiple nodes), unlimited mission duration [2] (if some UAVs are refilling their energy others can continue with the mission), load balancing (collection of data about a mission can be balanced among multiple nodes to maintain energy levels). Flying Networks are very useful in many real world scenarios such as search

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and rescue operations, battlefield monitoring, architecture planning, and firefighting [3]. In many hostile environments, where human intervention is not possible, UAV based networks can be utilize to accomplish applications efficiently. For example a network can be formed for searching a specific target on ground in search and rescues context. In traffic monitoring context, they are able to monitor the road's traffic and can inform appropriate authorities when there is any accident or miss happening. For battlefield monitoring, they can monitor enemy's base area for any unwanted disturbances. It can also be used for monitoring environment using multiple sensors such as pressure, humidity, temperature sensors, etc. Precision farming has also gained a lot of hype in terms of flying network. Similarly, there are various areas where network of flying nodes can be used to achieve great benefits.

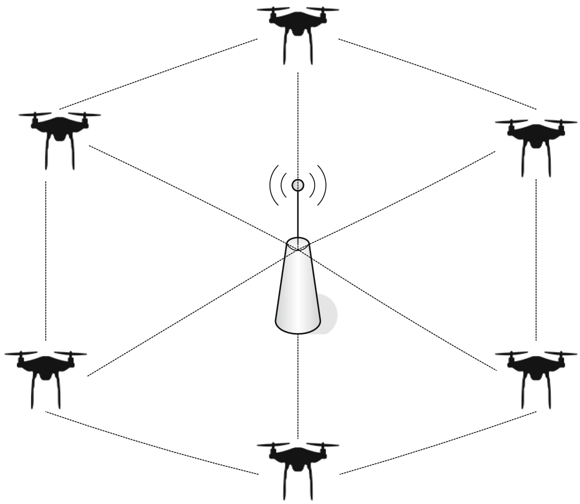


Fig. 1. Illustration of a typical Flying Adhoc Network

The issues pertaining to flying network which differentiate it from traditional MANET networks are high mobility, aerodynamics constraints, and limited bandwidth. High mobility leads to a lot of problems in such networks like breakage of communication and connectivity among moving nodes, sudden topological changes in the network and consumption of lot of energy. A mobility model that can govern the realistic UAV movements and can handle unique attributes of such nodes is a critical requirement for flying network. The importance of a mobility model lies in the fact that field testing is lot costly for evaluation of network performance which can be done in more efficient and cost effective manner using mobility models [4]. A lot of mobility models have been designed by the researchers, but most of these models are remodeled from MANET networks. Not much of research has been done on the mobility models for FANET keeping unique attributes of flying nodes in consideration. A mobility model should consider problems faced in real time scenarios such as sudden change in trajectory, obstacle detection, coverage of large area while maintaining the connectivity, maintenance of required energy levels among UAVs so as to complete mission oriented tasks.

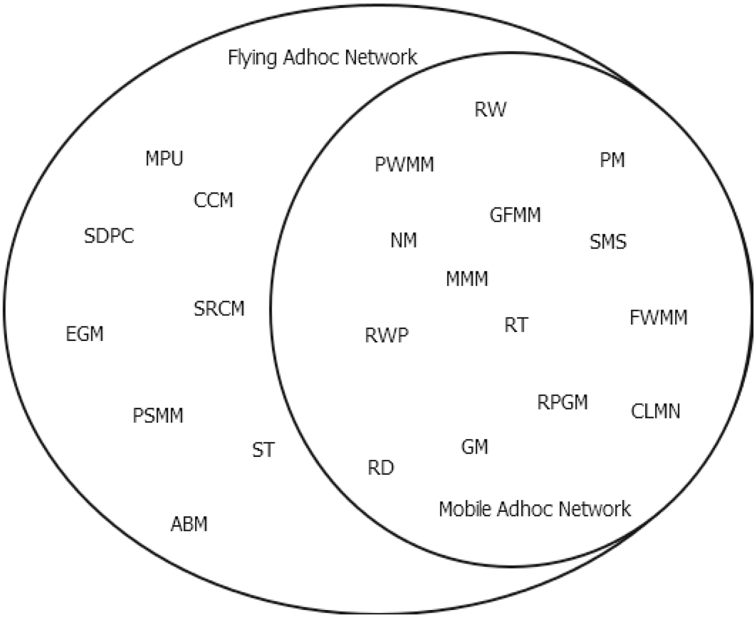
Various mobility models have been adapted from traditional mobile networks in to FANET network. Random Walk (RW) [3, 5], Random Way Point (RWP) [6], Gauss Markov (GM) [7], Column mobility model (CLMN) [3] have been proposed for traditional networks and attuned for flying networks. But the mobility of flying nodes is different and traditional models can not accurately reproduce their behavior. Some of the mobility models like Alpha Based Model (ABM) [8], Multiple Pheromone UAV Mobility Model (MPU) [9], Coverage Connect model (CCM) [10] and Paparazzi mobility model (PPRZM) [11] are designed especially for FANET networks attributing to its distinctive constraints.

The rest of the paper is organized as follows: Sect. 2 presents traditional and new mobility models for FANET and their classifications. Section 3 talks about mobility models designed for FANET networks and their comparative overview. Section 4 presents the conclusion and future scope.

2 Mobility Models and Classification

A mobility model is needed to control various aspects of flying networks such as velocity, direction, location, acceleration over time. A mobility model needs to be good enough for handling criticalities of aforementioned network, arising due to movement of nodes in three-dimensional space at high speed, which otherwise can lead to inaccurate and faulty results. The high mobility can hamper the connections amongst nodes and sometime in worst scenarios even node can become isolated. Therefore, maintaining an adequate level of connectivity and coverage within fleet during operation is really a tedious task. In order to govern the behavior of nodes within a network, many mobility models have been proposed by researchers [3]. However, some traditional MANET based models like Random Walk (RW), RWP (Random Way Point) [4] can be utilized in FANETs also but in some applications scenarios where a coordinated fleet moving is required, they are not able to mock mobility pattern of nodes well and can give misleading results. Thus, over the time, many models for flying network have been proposed like Semi Random Circular Movement (SRCM) [18], Alpha Based Model (ABM), which takes mobility and frequent change in arrangement of flying nodes in consideration. Attempts have been made to fit traditional models in FANETs and new models have been designed specifically for flying network. Figure 2 represents a Venn diagram depicting relationship between existing models adapted from MANET and new models designed specifically for FANET. This section is more focused about the classifications of mobility models as per our study of related work. We consider certain important properties needed for mobile environment and possible application scenarios and based on these properties classify models in different categories.

A mobility model can belong to one or more groups based on its characteristics for example Group Force Mobility Model [22] (GFMM) can be classified as group model as well as connectivity model because it possess characteristics of both the models. Following are the possible classifications.



RW-Random Walk, RWP-Random Waypoint, NM-Nomadic Community, CLMN-Column Mobility Model, RD-Random Direction, RT-Random Trip, GFMM-Group Force Mobility Model, MMM-Manhattan Mobility Model, FWMM-Free Way Mobility Model, RPGM-Reference Point Group Mobility Model, SMS-Semi-Markov Group Mobility Model, PM-Pursue Mobility Model, GM-Gauss-Markov Mobility Model, SDPC-Self-Deployable Point Coverage, ABM-Alpha based Mobility Model, SRCM-Semi-Random Circular Movement, EGM-Enhanced Gauss-Markov Mobility Model, CCM-Connected Coverage Model, MPU-Multiple Pheromone UAV, PSMM-Particle Swarm Mobility Model, PPRZM-Paparazzi Mobility Model

Fig. 2. Venn diagram representing new mobility models and traditional MANET models applied on FANET.

Group/Spatial Models: In group based mobility models, multiple nodes move together following a common point [3]. Such mobility models are best suited for flying networks as nodes need to move in collaboration and take decisions on their own without human intervention. In such models there is a spatial dependency among flying nodes because position and movement of node is dependent on other nodes [4]. Example: Pheromone mobility model, Nomadic Community [3], Reference Point Group Mobility Model [5] etc.

Entity Models. In entity based mobility model [16] each UAV is independent of each other. In this model a single node is given responsibility of covering a predefined area without any interaction with other nodes. In this model mostly decision making is done by a centralized system located on ground. Example: SRCM [18], Random Model [3] etc.

Temporal Models. Temporal based models [5] are the models in which next movement of the node is dependent on previous timestamp location defining previous direction and speed. Most models in this category try to avoid sharp turns and speed change [12]. Example: Smooth Turn, Gauss Markov etc.

Random Models. UAV selects the direction, velocity and time of movement randomly and mostly independent of each other. Most of traditional MANET based mobility models are based on randomized concept. These models are relatively simple models. Examples: Random Direction [12], Random Walk [3] etc.

Path Planned Models. In Path Planned Models trajectory to be followed by each node is predefined [12]. Each node follows the trajectory till it reaches the end and then changes or start over the same pattern depending on model. Examples: Paparazzi Mobility Model [11], Semi Random Control Mobility [18] etc.

Coverage Based Models. The main aim of coverage based mobility model [10] is to cover the required geographical area with minimum number of nodes possible. To keep the number of nodes in control, overlapping of area coverage by different nodes should be minimized. This model is based on concept of virtual forces [13]. Examples: Multiple Pheromone UAV Mobility Model [9].

Connectivity Based Models. Connectivity oriented approach [10] provides ability to contact any UAV any time in case of emergency. Connectivity oriented mobility model is generally based on spatial mobility models in MANETS i.e. their decision is generally influenced based on local information or neighborhood. In such models main focus is on maintenance of connection among nodes all the time. Example: Group Force Mobility Model [23].

3 Mobility Models for Flying Ad Hoc Networks

MANET mobility models do not fit well for flying environment, due to some unique challenges and high mobility in 3D region of interest. Therefore, new models which can imitate the movement of flying nodes are required. In Flying Adhoc Network, for most of the applications, network needs to be self-organizing and it should cover the area of interest. While covering the area, connection between nodes should not break. Naïve mobility models have been designed keeping above constraints in consideration and some of these models use controlled mobility [2, 17] using virtual forces [8, 13] to maintain both coverage and connectivity. In this section, we explore some of the new FANET mobility models in depth and presented a comparative analysis (Table 1).

Table 1. Comparative analysis of mobility models.

Mobility model	Category	Description	Contributions and limitations	Others
RW [3, 5]	Random, Entity	Memory less model, nodes choose random speed and direction to move for a constant time or distance and change direction randomly	Very simple and doesn't consider sudden stop, change and direction of speed	
RWP [6]	Random, Entity	Similar to RW, considers a pause time and chooses a random destination and start travelling towards the chosen destination	The inclusion of pause time helps to smooth out sudden change in direction but acceleration and deceleration nodes is not taken in consideration	RD [3], RT [5]
MMM [22]	Random, partially Path Planned, Spatial	Nodes move in an urban street like grid, horizontal and vertical lines intersecting each other. On an intersection point UAV can choose any random probabilistic direction for movement	Suits well only in a grid like structure not for other scenarios Sharp turns and change of speed is not considered	FWMM [3], PWMM [5]
GM [7]	Temporal	Temporal correlative movement which is based on Gaussian equations where the change of speed and direction for next move is dependent on a parameter α	Well suited for sudden movements but not perform well for FANET due to constraints in movement	SMS [5], EGM [25]
CLMN [3]	Spatiotemporal, Group	Nodes lying on a straight line but each node move around a reference point randomly. New reference point is created based on previous point	Well suited for FANET network and prevent collisions but sudden change of speed and direction is not considered	NM [3], PM [3], RPGM [5]

(*continued*)

Table 1. (*continued*)

Mobility model	Category	Description	Contributions and limitations	Others
GFMM [23]	Group, Connectivity	Nodes are divided in to groups, nodes belonging to same group apply both attractive and repulsive forces on each other to maintain connectivity and avoid collision respectively and nodes of different groups repel each other	Collision and obstacle avoidance is considered in this model but coverage of the area which is must for FANET network is not taken in to account and also change of a node's group is not considered	
MPUMM [9]	Group, Coverage	Attractive and repulsive pheromone is used to attract and repel nodes to an area of interest	Not suited for real time scenarios as it doesn't consider connectivity and collision of nodes in consideration	DPR [15]
PSMM [16]	Group, Synthetic, Spatiotemporal	The velocity of a node is calculated based on velocity and location of center in previous time slot considering collision free adjustments	Calculation of velocity and waypoints can sometimes converge prematurely arising unrealistic situations. Also it doesn't consider coverage much	
PPRZM [11]	Path Planned, Entity	Paparazzi nodes move based on predefined shapes. Each UAV chooses a movement and altitude which remain fixed during entire simulation	Not suited for most of the FANET applications as it follows a fixed trajectory	
CCM [2]	Group, Spatial, Coverage and Connectivity hybrid, Temporal	Used Ant Colony Optimization and pheromone based approach to attract the UAVs to less covered areas One hop information is used to determine the next position of UAV and best among the viable solution is chosen based on pheromone approach	Good in terms of coverage and connectivity but maintenance of connectivity with small number of nodes is a challenge	SDPC [3, 24]

(*continued*)

Table 1. (*continued*)

Mobility model	Category	Description	Contributions and limitations	Others
ABM [8]	Group, Spatial, Coverage and Connectivity hybrid	The node to be followed is decided based on followship weight which is calculated based on different parameters	Suitable for FANET networks but to determine the value of α is tedious. No emphasis has been given on collision avoidance	
SRCM [18]	Random, Entity and Path Planned	Nodes move in circular motion. On reaching a destination point in circle node chooses another circle with same center randomly and start moving. Clearly ending point of previous period is starting for next period	Avoids collision as multiple UAVS can chooses different circles with different center and cover the area but change in sudden radius while on move is not feasible for FANET	ST [20]

3.1 Pheromone Based Mobility Model

Pheromone based approach is inspired with natural phenomenon of stigmergy used in ant colony [9]. Just as ants deposits pheromones to indicate the already explored area and this pheromone tend to disappear with time. Similar concept is used in Multiple Pheromone UAV Mobility Model [9] (MPU), an attractive chemical called attractive pheromone can be used to attract UAVs to the area where density of nodes is less and a repulsive pheromone can be used to indicate already covered area to repel UAVs from that location. As depicted in Fig. 3, a node gets attracted towards region 2 where number of nodes is less and they spread an attractive chemical to attract more nodes. Repulsive pheromone repels the incoming UAV in region 1.

Another variation of pheromone based model is Distributed Pheromone Repel Mobility [15] (DPR). In this model each node maintains a pheromone map, each cell of which is marked with the timestamp of last time UAV scanned that area. Once an area is scanned local pheromone maps are broadcasted and each UAV merge these map with their own maps. A node tend to move to the area with low pheromone smell as these are the areas which are not recently visited and area outside the search areas are marked with high pheromone smell to avoid those areas.

3.2 Particle Swarm Mobility Model

Particle Swarm Mobility Model [16] (PSMM) is based on temporal as well as spatial relation between the nodes, keeping in account the safe distance between nodes to avoid collision. It is based on PSO [26] (Particle Swarm Optimization) and has two phases (i) Generation of velocities and waypoints (ii) Collision-free adjustments. In first

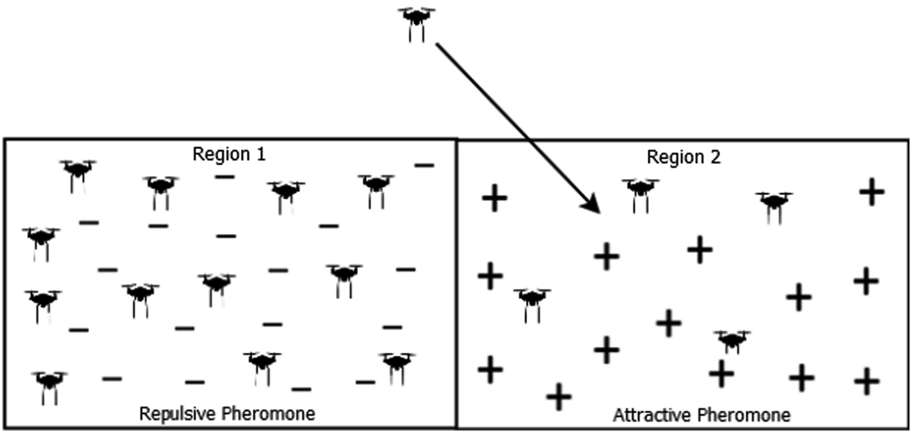


Fig. 3. A UAV getting attracted towards Region 2 because of the attractive pheromone.

step, the path or trajectory of node is assumed to be sequence of waypoints at discrete times. The next waypoint to be followed at time t is dependent on velocity at time t − 1 (temporal dependency) and the location of center at time t − 1 (spatial dependency) as depicted in Fig. 4(a).

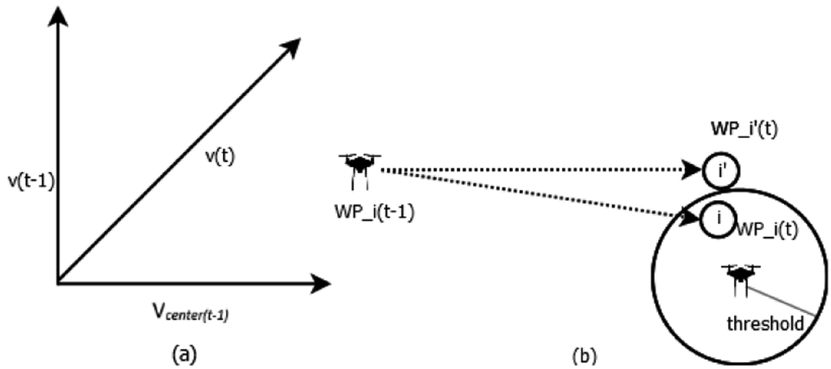


Fig. 4. (a) Velocity at time t is resultant of velocity at t − 1 and guidance of center location (b) A collision free adjustment for node i.

In second phase nodes which are not at a safe distance are identified and necessary adjustments are made to avoid collision keeping change in spatiotemporal properties as minimal as possible. These adjustments are made assuming nodes are sharing information among group, initial distribution of nodes is safe and collision if happen in between time interval t and t + 1 is not considered. In Fig. 4(b), a node i can move to position WP_i(t) in next time stamp and can collide with node j, a collision free adjustment is made and node can now move to WP_i′(t).

3.3 Paparazzi Model

Paparazzi model is kind of path planning mobility model. PPRZM [11], paparazzi UAV can make five movements Stay-At, Eight, Waypoint, Oval and Scan as depicted in Fig. 5. Each node is given a particular shape and altitude for movement which will remain same for whole simulation. Probability of node moving in Stay-At, Oval and Scan is high compared to eight and way-point.

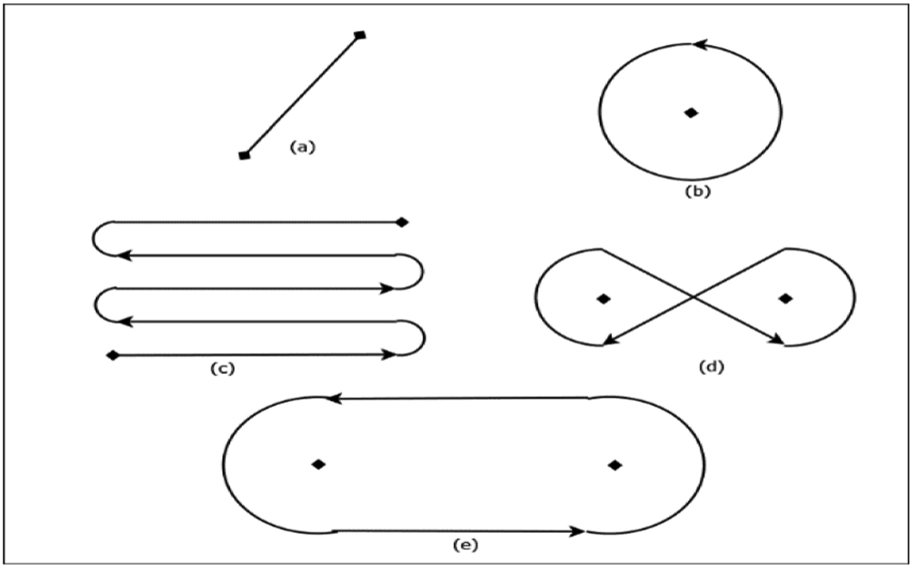


Fig. 5. PPRZM path schemes: (a) Way Point, (b) Stay-At, (c) Scan (d) Eight, and (e) Oval

3.4 Alpha Based Mobility Model

Apart from considering connectivity and coverage, energy is also accounted to be an important factor while making the decision of next move in alpha based model [8] (ABM). After every t update second, each node update its neighbor table based on the information gathered. In the next step, value of followship (α) weight is calculated for each UAV based on (i) hop count (ii) number of neighbors (iii) energy. Followship weight (α) represents node's willingness to be followed by adjacent nodes.

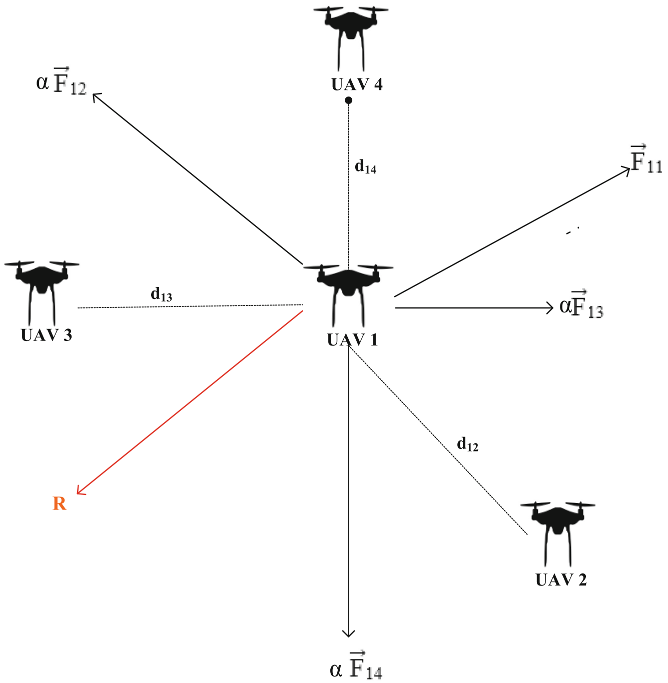


Fig. 6. UAV 1 is moving in direction F_{11} and αF_{1i} is the force applied by UAV_i on UAV1 and UAV1 will choose its next direction based on the resultant of these forces i.e. R

Its value is calculated for each node and can vary from 1 to 10. 1 represents the least recommended node to be followed while 10 represents most recommended node. Three evaluation levels, big, small and medium are proposed based on the three parameters mentioned above. Big and small represents the neighbors high and low level of followship weights and medium corresponds to undecided or neutral level of followship weights. The value of α is computed locally based on information of neighbor nodes and a force of magnitude equivalent to α is applied on UAV by each of the neighboring nodes. Node with high α value has greater impact than node with smaller value and each UAV also applies a force vector in the direction of current movement. Resultant of all the forces will determine the next direction and movement of UAV. Figure 6 depicts the forces applied on UAV1. Length of force vector indicates the magnitude of force. UAV 1 will choose its next direction based on resultant of forces i.e. R.

3.5 Connected Coverage Model

Connected Coverage model (CCM) [2] is based on three steps (i) neighborhood selection (ii) computing viable alternative (iii) selecting best alternative. In the first step appropriate neighborhood is selected based on the hop count. In step (ii) the future position of the node is considered and if the node is going out of transmission range in any of the scenarios that alternative is discarded. Out of available situations best alternative is selected in (iii) step based on pheromone based approach i.e. by moving in a direction where number of node is less to maintain appropriate density of nodes at a particular region. As depicted in Fig. 7. Circles represent the radio range of nodes and their next direction of movement is shown with arrows. Node in consideration can go up, down and right. The alternative which becomes out of range is discarded and out of available alternatives one which will not go out of range in near future is chosen as best alternative and is followed by node in consideration.

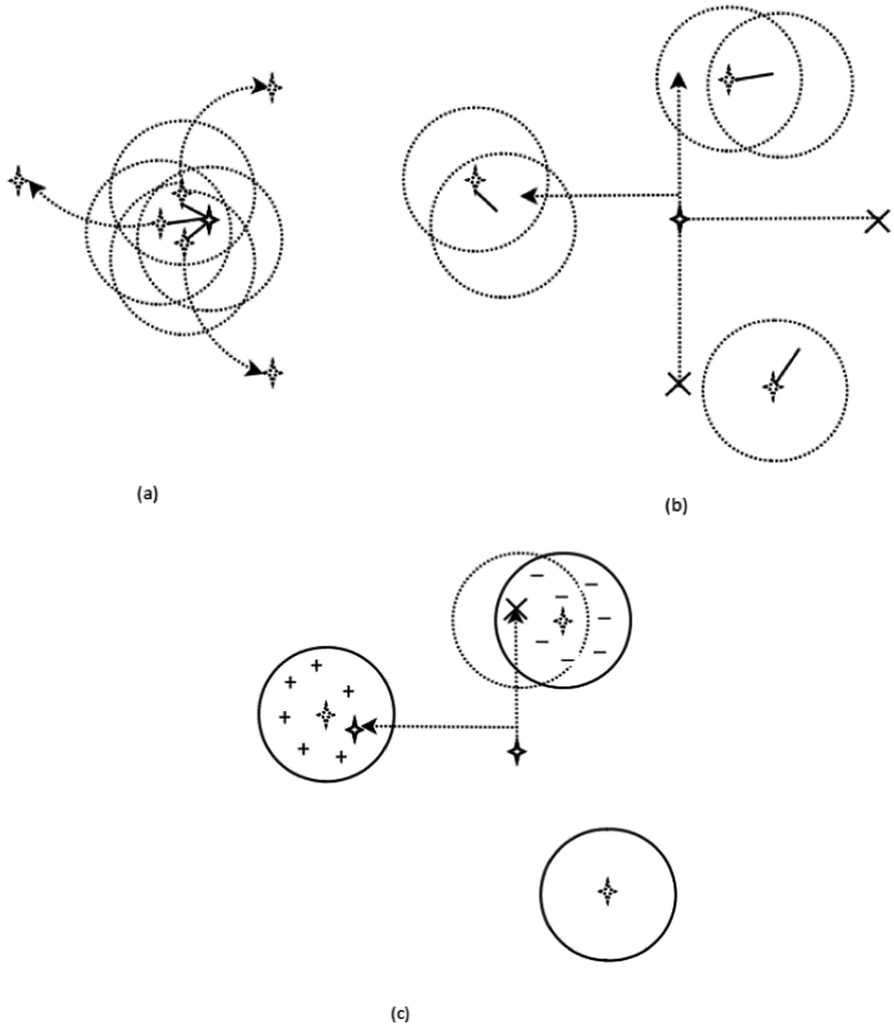


Fig. 7. Computation of viable alternative and Selection of best alternative in CCM.

3.6 Semi Random Circular Movement

Semi Random Circular Movement (SRCM) [18] model is designed especially for FANET network and is an enhancement to its predecessor models Random Direction Model and Random Way Point Model.

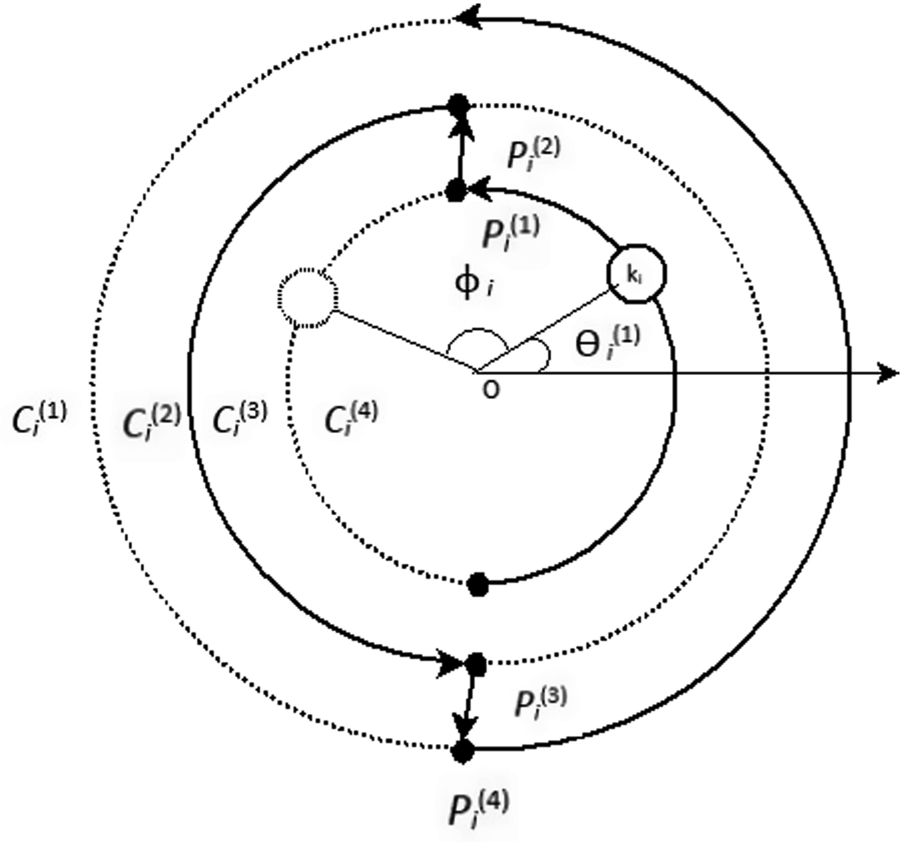


Fig. 8. Movement of a node k_i using SRCM mobility model.

It is an entity based model designed specifically for the curved movement and sudden turns of flying nodes. As the name suggests, this model has both random and non-random properties. It follows a predefined circular path say C_i for a node k_i at a velocity v_i which can vary from $[v_{min}, v_{max}]$ from an initial point P_i and take the next step on the same circle based on the step point, step time and step length calculations but it can choose to move to different radius after reaching a destination point P_i randomly. The starting point of the current period is the destination point of the previous period. Figure 8 represents a node k_i travelling in circles centered O with step angle ϕ_i.

3.7 Comparative Study and Discussion

FANET has different constraints compared to other Adhoc network. Table 2 shows analysis of new FANET mobility models based on connectivity, coverage, and energy and collision avoidance and neighbor awareness.

1. Connectivity Awareness: Because of its high mobility and unstable nature connection between the nodes tends to break. Pheromone, Particle Swarm, ABM, CCM and SRCM models are designed to avoid sudden connection breakage.
2. Energy Awareness: Energy is an important resource for flying network because of its application in hostile environments where battery cannot be charged. ABM keeps constraint of energy in consideration while deciding next move [8].
3. Collision Avoidance: Nodes should avoid collision with each other while moving. PSMM model avoids collision in collision adjustment phase [16] and due to circular movement SRCM model also partially avoids it [3].

Table 2. Comparison of new FANET specific Mobility Models.

Mobility model	Connectivity awareness	Energy awareness	Collision avoidance	Global coverage	Neighbor awareness
Pheromone [9, 15]	No	No	Yes	Yes	Partially
Particle Swarm [16]	Yes	No	Yes	Yes	Yes
Paparazzi [3, 11]	No	No	No	No	No
Alpha Based [8]	Yes	Yes	No	Yes	Yes
Connected Coverage [2]	Yes	No	No	Yes	Yes
Semi Random Circular Movement [18]	No	No	Partially	Yes	Partially

4. Global Coverage: Main aim of UAV network is to cover whole area of interest. Except PPRZM [11] all other models described above try to cover the maximum area.
5. Neighbor Awareness: Most of the application scenarios for FANET require group movement which in turn demands knowledge about neighboring nodes. MPU, DPR and SRCM models have partial neighbor awareness. ABM, PSMM and CCM are having full neighbor awareness.

4 Conclusion and Future Research

This paper presented a useful insight towards study of mobility models for flying adhoc networks. A mobility model helps in accurately handling the movement of nodes in real time scenario. An inappropriate model can give inaccurate results and can be misleading. In this paper, we have discussed about various mobility models for FANET, some of them are adapted from traditional mobile ad hoc networks and some are new models designed for flying network. Mobility models are classified based on different characteristics such as a model's ability to cover or connect, movement in group or as single entity, motion in fixed trajectory or randomly etc. The mobility models are compared with their contribution and limitations in tabular form. New FANET models are examined in length and a comparative study of models is discussed based on its ability to cover an area, maintenance of connectivity, energy efficiency etc.

As per our study, very few/limited work is found which considers energy as a decision parameter. Hence, in the future, more mobility models can be designed keeping energy consumption in consideration. Also, some clustering based approaches can be applied for movement of UAV network. Furthermore, applying machine learning approaches a good mobility models can be designed or existing models can be improved while considering sudden change of direction, acceleration and deceleration of moving nodes. Finally, work can be carried out using concept of virtual forces and controlled mobility. An attempt towards designing a mobility model which will consider coverage, connectivity and energy constraint while moving can be appreciated.

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