

A Review of Group Mobility Models for Mobile Ad Hoc Networks

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Abstract The importance of accurate mobility models for mobile ad hoc network (MANET) evaluation is widely recognized in literature. Existing MANET mobility models can be generally classified into two categories: *entity* and *group* mobility models. The latter is of particular interest as group motion occurs commonly in scenarios where MANETs are deployed, such as firefighting and battlefield operations. This paper provides a systematic and critical review of recent group mobility models proposed for MANETs. It also discusses the potential of using or adapting these mobility models for other emerging network types.

Keywords Mobile ad hoc network · Group mobility · Routing

1 Introduction

Mobile ad hoc network (MANET) is a form of infrastructureless mobile network with no fixed centralized controller such as base stations for coordinating the communications among the mobile terminals in the network. In MANET, all nodes can be mobile. The nodes cooperate to dynamically form routing paths and relay each other's packets for end-to-end communication [1].

For a thorough performance study of MANET routing protocols, it is important to use mobility models which accurately represent the movements of nodes in the MANET [2]. Existing MANET mobility models can be generally classified into two categories: *entity* and *group* mobility models. In entity mobility models, nodes move independently of each

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other. On the other hand, in group mobility models, nodes tend to cluster and move in groups.

In earlier stages of MANET research, entity mobility models were the most common, if not the only type of mobility models used [2]. However, in recent years, mobile nodes in real-life MANETs were often observed to exhibit some form of group behavior [3, 4]. This motivates the formulation of a variety of group mobility models based on real-life military and civilian application scenarios. The former refers to battlefield operations involving movements by military units such as fighting troops and tank fleets. The latter may include disaster recovery (e.g. firefighting, search and rescue) and law enforcement (e.g. SWAT, crowd and riot control) operations. All of these applications tend to exhibit movement patterns and connectivity characteristics that are quite different from those of entity mobility models. This necessitates the use of a different mobility model for evaluating the performance of routing protocols in such applications. Recently, a number of group mobility models have been proposed and studied with different routing protocols [3–11]. These studies showed that group movements can indeed significantly impact the routing performance.

In literature, there exist a number of survey papers on mobility models for wireless networks. The classification of mobility models into entity and group mobility models was first proposed in [2]. Mobility models have also been classified based on the degree of randomness of node movements such as trace-based, constrained topology based, and statistical models [12]. In [13], the authors reviewed the mobility models for tactical mobile networks, which are one of the common environments where group movements can be found. However, the authors did not focus explicitly or cover in-depth on group mobility. They classified the mobility models according to five types of movement dependencies or restrictions, among which ‘spatial dependencies’ is one that encompasses group mobility.

In this paper, we focus on surveying the state-of-the-art in group mobility models. Specifically, we review seven most well-known and representative group mobility models [3–9]. We first classify the models according to how the mobile nodes move in a group. We then compare the models based on six design features and their target applications. Finally, we discuss the potential of these models to be used or adapted for use in other emerging network types, including vehicular ad hoc networks, mobile sensor networks, opportunistic and delay tolerant networks.

2 Classification of Group Mobility Models

In group mobility models, mobile nodes are divided into groups, each having a coverage area of a certain radius. The mobile nodes located within the coverage area of a group are considered to be the members of that group. Each group can move to any location within the network, whereas members of a group can only move within the group’s coverage area. The most well-known and representative group mobility models in literature [3–9] can be classified according to how the mobile nodes move as a group. In [3, 5–7], the nodes in a group follow a *lead point* whose movement dictates that of an entire group. Here, the “lead point” can be either a real physical node, or more commonly a logical “center” that exists within a group. In this paper, we refer to these models as *point based group mobility (PBGM)* models. In [4, 8, 9], instead of following a lead point within a group, nodes may follow a path through a sequence of regions or areas. We refer to these models as *region*

based group mobility (RBGM) models. Both PBGM and RBGM can be further classified based on the existence of interaction among group members. In [3, 5, 8, 9], group members move independently of each other, and their movements are influenced only by their lead point or targeted regions. These models are said to exhibit *individual group member (IGM)* movements. In [4, 6, 7], the movement of a group member may be influenced by or correlated with other group members due to some interaction or relationships that exist between them. For these models, they are said to exhibit *coordinated group member (CGM)* movements. In summary, the group mobility models can be classified as PBGM with IGM, PBGM with CGM, RBGM with IGM, and RBGM with CGM. This group mobility classification is shown in Fig. 1.

3 Point Based Group Mobility Models

In PBGM models, each group member follows the movements of a physical or logical lead point that exists within the group.

3.1 PBGM with Individual Group Member (IGM) Movement

In PBGM with IGM models, each group member further moves independently of each other, only to be influenced by the movements of its lead point. The following reviews two prominent examples of such models: RPGM [3] and RVGM [5].

3.1.1 Reference Point Group Mobility (RPGM) Model

RPGM [3] is one of the most commonly used group mobility models for MANETs. At the center of each group's coverage area is a *logical* lead point whose movement defines that of the entire group, including its speed, direction, and acceleration. The trajectory of the lead point can be predefined or obtained based on a particular entity mobility model. Furthermore, each group member has its own reference point that follows the lead point and maintains a constant distance and direction from it. Whenever the reference point of a

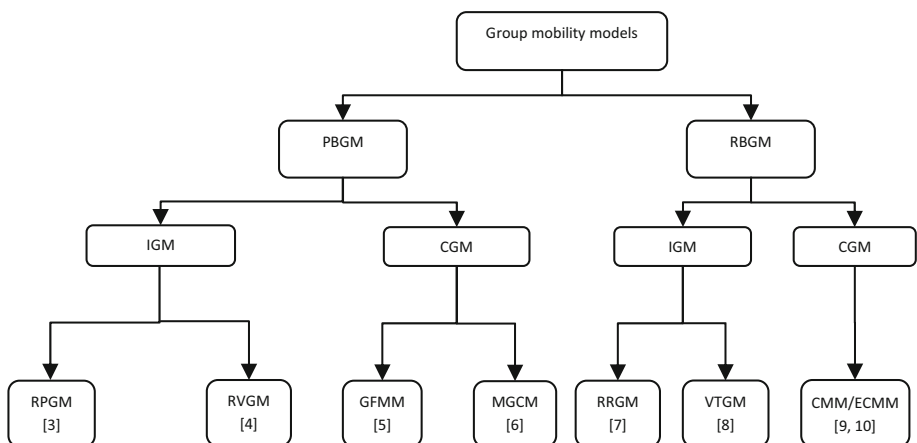


Fig. 1 Classification of group mobility models

group member moves to a new location, this group member also moves to a randomly chosen location within a circular neighborhood of radius R around its new reference point location.

RPGM defines two motion vectors: (1) group motion vector \overline{GM} , which represents the movement of the lead point that characterizes the group movement; and (2) random motion vector \overline{RM} , which represents the movement of a group member with respect to its reference point. The new position of a group member is computed as the sum of these vectors. Figure 2 gives an example of a group moving from time t to time $t + 1$. When a lead point moves from time t to time $t + 1$ based on \overline{GM} , the reference point of each group member also moves to a new location based on \overline{GM} . Then, based on \overline{RM} , the position of each group member will be updated to a new location in the neighborhood of its new reference point location.

In [3], three motion patterns based on RPGM, namely in-place, overlap, and convention, which represent group mobility in battlefield, disaster recovery, and convention scenarios, respectively, were benchmarked against random mobility model and evaluated for their impact on three MANET routing protocols: Ad hoc On-demand Distance Vector (AODV), Hierarchical State Routing (HSR), and Destination Sequenced Distance Vector (DSDV). The results showed that compared with random mobility, group mobility under RPGM leads to a lower rate of connectivity changes. This in turn resulted in higher throughput and lower overhead for AODV and HSR, particularly when communications were confined to within each group. DSDV failed to leverage on group mobility to improve its performance due to its inherent high routing load.

RPGM can be considered as a generic group mobility model, which by changing its parameter values, can mimic group mobility of different real-life scenarios. Firstly, we can arrange the position of each reference point and adjust its radius to generate a particular

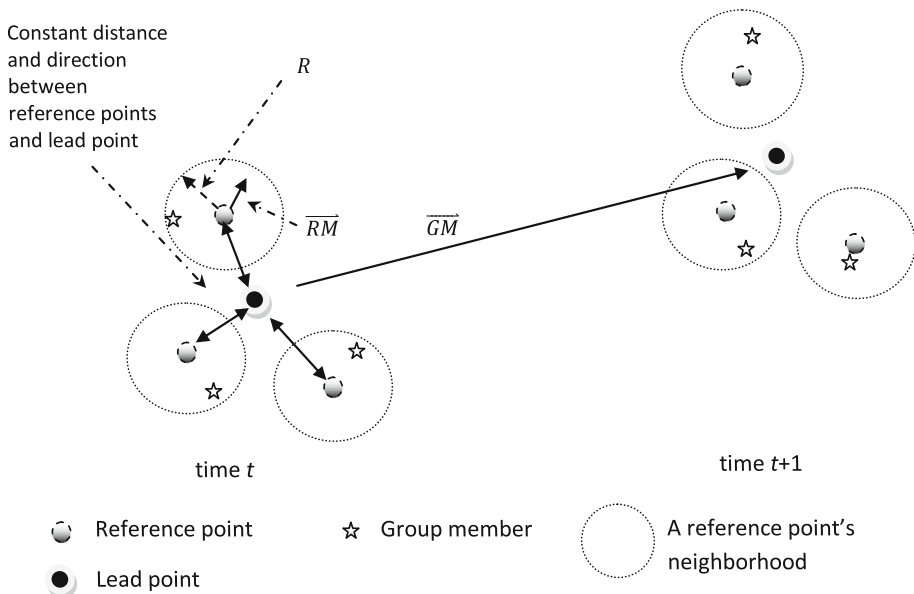


Fig. 2 Movement of group members in RPGM

moving pattern inside a group for a specific operation or activity. Secondly, we can vary the network connectivity among groups by setting the groups' radii. If the group radius is small, a sparse network can be formed. Generally, the smaller the coverage area of a group, the higher the probability the network will be disconnected. Finally, we can define the motion path of each group by specifying manually or automatically using digital maps, the sequence of check points or intermediate locations through which the group will move. This can provide the flexibility for RPGM to be applied in some user-defined scenarios.

3.1.2 Reference Velocity Group Mobility Model (RVGM)

RVGM [5] is an extension of RPGM by replacing the concept of reference point and motion vectors with two velocity vectors to model group mobility. The two velocity vectors are: group velocity of the lead point, and local deviation velocity of each group member. The former defines the movement of the lead point (and thus the group) in terms of speed and direction, and the latter defines the amount of deviation in velocity of a group member from that of the lead point. The movement of a group member is then given by the sum of these two velocity vectors. Similar to RPGM, the movement of the lead point controls the movement of the entire group, and its trajectory can be predefined or based on an entity mobility model.

The occurrence and timing of network partitioning may also be predicted through identifying groups with significantly different lead point velocities. This can assist upper layer routing and other protocols to react early to potential network partitioning and thus minimize the impact of service disruption. However, the circular group coverage and time-invariant group velocity assumptions made by the prediction algorithm of RVGM may not be realistic in some real-life scenarios. A more accurate prediction could be made by using actual information about the group mobility disseminated through some scalable mechanisms. Moreover, in order to always keep the group members to moving within the group, the distribution of the local deviation velocity should be carefully chosen. Otherwise, it may result in the groups to become increasingly loosely connected over time.

3.2 PBGM with Coordinated Group Member (CGM) Movement

In PBGM with CGM model, the movement of a group member is not only influenced by its lead point, but also by other group members.

3.2.1 Group Force Mobility Model (GFMM)

GFMM [6] is similar to RVGM in that the velocity of a group member follows the velocity of its lead point with a small random deviation. However, *forces (repulsion and attraction)* between nodes are introduced to provide a mechanism for nodes to avoid physical node collision and congestion. The strength of force is based on the distance between two nodes and the force distributions. Repulsion force prevents collision between two nodes from any group. As the distance between nodes increases, the repulsion force decreases exponentially to zero and may become attraction force. The attraction force exists only between nodes of the same group. By selecting different *attraction force distributions*, different levels of attraction force can be generated to create different characteristics (from loose to tight grouping).

In [6], three attraction force distributions, namely F, Rayleigh, and Chi Squared, which represent loose, moderate, and tight grouping, respectively, were used to generate three

GFMM mobility patterns. These mobility patterns were benchmarked against RPGM in a MANET using AODV routing protocol. The results showed that compared with RPGM, GFMM can lead to lower spatial correlation between nodes—a similarity measure of the velocity and movement direction between nodes, due to the attraction forces inducing a change in direction of the nodes to avoid collisions. For the same reason, GFMM showed a shorter average link duration as compared to RPGM. These results point towards a more volatile group structure when simulating group mobility under the more realistic GFMM.

The collision avoidance mechanism of GFMM should be easily applied to other group mobility models for modeling the effects of physical interactions between nodes on the group movement in real life.

3.2.2 Multi-group Coordination Mobility (MGCM)

In MGCM [7], all groups move in a coordinated fashion towards a common *object*. A two-level group architecture, *group* and *main group*, is introduced, in which all groups in the network form a main group. Each group has a lead point, and one of the lead points is selected as the lead point of the main group. The lead points of other groups are then treated as group members of the main group. The velocity vector of a lead point for group l , denoted as \overline{B}_l , can be described as:

$$\overline{B}_l = \overline{B}_m + \overline{B}_p + \overline{B}_d \quad (1)$$

where \overline{B}_m is the velocity vector of the lead point for the main group, \overline{B}_p is the force exerted by other peer lead points, and \overline{B}_d is a small random deviation. The force \overline{B}_p is used to maintain a certain distance between lead points to avoid collision among the groups and it only exists when the distance between two lead points is smaller than a predefined threshold. Similarly, the movement of a group member is determined by that of its lead point and further influenced by its peer group members and some deviation.

In Fig. 3, the main group consists of three groups with lead points, a , b , and c . All three groups are moving towards a common *object*. Lead point a is selected as the main lead point. For lead point b , since its distance to a is smaller than the predefined threshold, a peer force from a exists to widen the distance between the groups of a and b . Hence, the velocity vector \overline{B}_b of lead point b is determined by velocity vector \overline{B}_m of main lead point a , force \overline{B}_p from peer lead point a , and a small deviation \overline{B}_d .

In [7], MGCM was benchmarked against RPGM and RRGM. The results on average instantaneous node speed showed that MGCM does not suffer from the well-known average speed decay problem of most random mobility models that makes them less realistic. MGCM also showed a lower rate of link changes than RPGM, but a higher rate as compared to RRGM. The latter was due to all nodes in a group moving at the same predefined speed, while the former was attributed to movement coordination in MGCM which led to a lower degree of freedom for nodes to select a motion direction.

In MGCM, the repulsion existing among groups and group members makes MGCM a better fit for scenarios where collision avoidance is required, such as in vehicular ad hoc networks (VANET) [14]. Moreover, the group coordination exhibited in MGCM tends to keep the entire network connected because all groups are moving in unison towards the same destination *object*.

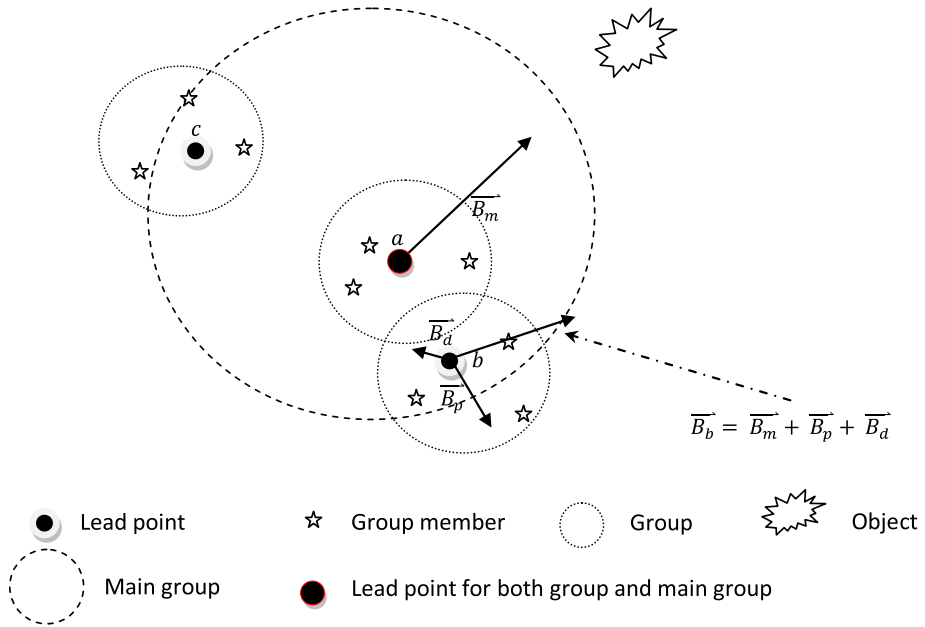


Fig. 3 Movement of groups in MGCM

4 Region Based Group Mobility Models

In RBGM models, each group member may follow a path through a predefined or real-time dynamically determined sequence of regions or areas.

4.1 RBGM with IGM Movement

In RBGM with IGM model, each group member further moves independently of each other, only to be influenced by the location of the next region or area to which it is moving. The following reviews two prominent examples of such models: RRGM [8] and VTGM [9].

4.1.1 Reference Region Group Mobility (RRGM) Model

In RRGM [8], the movement path of each group is defined by a sequence of reference regions leading to some target destination. The reference region is a rectangular or circular area whose size is determined by user-specified node density and group size. The location of each reference region is determined in real-time and in sequence such that each is progressively closer to the target destination. Once a reference region is identified, each group member selects a location inside this region and moves towards it. On arriving, the group member will move within its reference region according to random waypoint model while waiting for other members of the same group to arrive. After all group members have arrived in the reference region, they will remain in that region for some time (referred to as *pause time*), before the next reference region is determined. This process repeats until the group arrives at the target destination. At some user-specified time, a new target destination

can emerge to cause splitting of an existing group into smaller groups, one of which will move towards the new destination. Furthermore, groups having arrived at their target destinations for a period longer than the pause time may move to merge into a larger group.

RRGM can well reflect real-life scenarios because it introduces mobility patterns which are extracted from real mission-oriented operations such as firefighting where nodes come together initially and then divided into small groups to execute different tasks in different areas. By providing users with a flexible means of configuring the model parameters, a wide range of realistic group movements including merging and splitting scenarios could be modeled, which broadens the applications of RRGm.

4.1.2 Virtual Track Group Mobility (VTGM) Model

In VTGM [9], each group member moves along a predefined path called *virtual track*, which originates and terminates at some junction points known as *switch stations*. As shown in Fig. 4, a number of *switch stations* are placed at junction points of the virtual tracks, each having a certain track width. Members of the same group are distributed on the same track and move towards the next switch station in a way similar to random waypoint model, but their movements are confined within the virtual track. In addition, the group can merge with other groups or split into smaller groups at *switch stations*. VTGM also introduces non-group nodes, which can remain stationary or move freely without constraints of the virtual tracks and switch stations.

In [9], VTGM was benchmarked against random waypoint model in a MANET operating AODV routing protocol. The MANET topology was abstracted from a highway map where highways and intersections represent the virtual tracks, and switch stations, respectively. The results showed that the performance in terms of packet delivery ratio, throughput, and end-to-end delay, was generally worse in VTGM due to weaker inter-group connectivity as compared to random waypoint model. Thus, additional non-group nodes may be deployed as forwarding nodes outside of the virtual tracks to enrich the connectivity among groups and improve network performance.

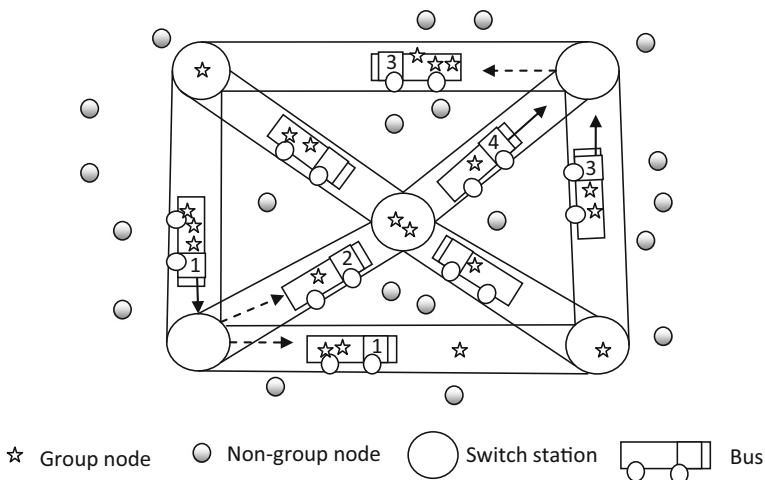


Fig. 4 Movement of group and non-group nodes in VTGM

VTGM can precisely mimic a number of practical scenarios involving constrained node movements. For example, *switch stations* can be regarded as gathering points for commuters and *virtual tracks* can be viewed as streets. Groups' movements can be treated as buses with on-board passengers traveling along the streets and non-group nodes can represent other motorists or pedestrians within the area. As shown in the lower left corner of Fig. 4, some passengers in one bus may alight (group splitting) and board the other at gathering point (switch station). Similarly, passengers of a pre-terminating bus, e.g. due to accident or breakdown, may board an alternative bus at gathering point (group merging) as shown in the upper right corner of Fig. 4. The use of this model is not necessarily limited to the vehicular context. The virtual tracks may also represent the planned paths to be taken by a walking tour guide leading a group of tourists to visit the various attractions (switch stations) within the locality. VTGM's concept of tracks to constrain nodes' trajectories could be made even more realistic by incorporating some additional rules for avoiding physical collisions among individual nodes and between groups.

4.2 RBGM with CGM Movement

In RBGM with CGM model, the movement of a group member is not only influenced by the location of its current and neighboring regions or areas, but also by other group members.

4.2.1 Community Based Mobility Model (CMM)

CMM [4] is one of the earliest proposed mobility model based on social network theory. In CMM, each community is defined as a group of nodes that have strong social links with each other, and consequently a likelihood of being co-located together. An interaction matrix (IM) where each element has a value ranging from 0 to 1 (low to high) is used to represent the degree of social interaction between any two nodes. This IM is then converted into a connectivity matrix (CM) where each element is a binary value that indicates whether or not the associated pair of nodes should be socially linked or connected. Consequently, the highly connected set of nodes will be grouped together to form a community. Each community is associated with one specific region inside the network area, and each member of the community is randomly placed within its community region as an initial location.

In addition to identifying community or group memberships, movements of the nodes are also influenced by the social links between them. A node will move to a randomly selected location within a community region to which it is most socially attracted. The *social activity* (SA) of a community region to a node is defined by the average strength of the social links between this node and members of that community. The target location chosen by each node for its next movement can be inside its current community region or in other community region, depending on which region exerts the highest SA on the node. Once a location is chosen, the node can move towards that location based on any entity mobility model.

It is worth noting that under CMM, although nodes are grouped and co-located together by their social relationships, their movements may not result in a group movement since each node moves according to its own social relationship with other members of the same or different group. An enhanced version of CMM (ECMM) was recently proposed which incorporates a feature that encourages group mobility [10]. This is achieved by introducing

a group movement encouragement factor k . A high k value strengthens the social attraction of nodes that have chosen to commute to another community region for their next movement. This increases the tendency for some nodes to be attracted to and follow those which are commuting to another community region, resulting in a group movement. However, it should be noted that ECMM only encourages and not enforces group mobility, and the resulting group movement typically does not involve all but only a subset of members of the group.

In [10], the mobility traces generated by ECMM were compared against CMM and HCMM (Home Cell Mobility Model—an extension of CMM incorporating social attractions exerted by physical spaces) as well as two sets of real mobility traces collected from human subjects in a conference context. The results showed that the mobility traces of ECMM resembled more closely to the real ones in terms of their inter-meeting time and contact duration distributions. The former refers to the time interval between two consecutive meetings between two nodes, while the latter refers to the duration for which two nodes maintain radio contact. It was further found that group mobility encouragement factor k does not affect the inter-meeting time, but prolongs the contact duration as k increases.

5 Abstraction of Design Features in Group Mobility Models

From our discussed models in Sects. 3 and 4, six design features can be identified as follows:

1. *Spatial constraints*: These refer to constraints imposed by the nodes' spatial environment that restrict their movements in a certain way. Such constraints may include roads, walkways, rail tracks, and transportation structures such as bridges and tunnels. VTGM is an example of a model that incorporates spatial constraints in the form of virtual tracks.
2. *Collision avoidance*: This refers to controlling the movement of a node to avoid physical collision with other nodes. GFMM introduces repulsion force between neighboring nodes to achieve this goal. MGCM similarly adopts the repulsion force approach for collision avoidance among groups.
3. *Stable group structure*: This refers to maintaining the relative distances and positions among the group members during a group movement, such as when a group of nodes (e.g. troops, tanks, robots) move in formation, or on-board a transport carriage (e.g. bus, truck, train). RPGM can provide a stable group structure by properly placing the reference points and limiting their coverage radius. VTGM can also provide such a feature by limiting the degree of internal random mobility.
4. *Group destination*: This refers to the target destination of a moving group, which can be randomly chosen or predefined. In models such as RPGM and RVGM, the groups do not have any restrictions in choosing a target destination. Thus, they are free to move to anywhere inside the network area. In other models such as MGCM and RRGM, each group moves toward a particular destination that is usually defined a priori. In VTGM, all switch stations are potential destinations for the groups.
5. *Group coordination*: This refers to the existence of some cooperation or interaction among groups, which allows the movement of these groups to be coordinated. Such coordination exists in real-life scenarios such as that exhibited between groups when

Table 1 Comparison of the models based on their design features and applications

Model	Spatial constraints	Collision avoidance	Stable group structure	Group destination		Group coordination	Group merge/split	Target applications (with links to known implementations)
				Random	Predefined			
RPGM			✓	✓				Battlefield operation, disaster recovery, convention mobility Similar to RPGM Any application requiring non-colliding interaction between nodes Military applications requiring motion coordination among multiple groups
RVGM				✓				
GFMM		✓		✓				
MGCM		✓			✓			
RRGM				✓			✓	Applications requiring group splitting and merging, including search and rescue, battlefield, exhibition hall visiting
VTGM	✓		✓		✓		✓	Any applications requiring nodes to move on predefined paths, including roads, trails, highway systems with intersections
CMM/ ECMM					✓		✓	Scenarios where nodes gather and interact socially with each other, such as in conference venue, school, and workplace ^c

^a <http://net.cs.uni-bonn.de/wg/cs/applications/bonmmotion/>

^b <http://mile.cise.ufl.edu/important/software.htm>

^c <http://sourceforge.net/projects/ecmm/>

moving through a road traffic intersection. MGCM is an example of a model that incorporates group coordination.

6. *Group merging/splitting*: This refers to the provision for two or more groups to merge into one when they come together, or for a group to split into two or more smaller groups, each moving towards a different destination. RRG, VTGM, and ECMM are models that incorporate such a feature.

A comparison of the discussed group mobility models based on their design features and target applications is provided in Table 1. Note that none of the models include all the six design features as not all features are required by the applications for which they are designed for. Our aim is to provide users of these models with the list of design features to consider when adapting them, or creating new models with the desired set of features to suit their specific applications.

It should be noted that even though these group mobility models [3–10] have been proposed mainly for the performance study of MANETs, they can be used or adapted for use in the performance study of other network types that involve group mobility. For example, in VANETs [14], vehicles entering a street or highway are modeled to move in the same direction for some time, which resembles a group movement that can be modeled using a group mobility model such as VTGM incorporated with a street map and collision avoidance. In mobile sensor networks where nodes move in groups such as in monitoring sensor tagged animals that live in groups, existing models such as ECMM that considers the social influence on node movement could be used as a basis for developing group mobility models for specific wildlife communities. The performance of opportunistic and delay tolerant networks (DTNs) [15], which are characterized by intermittent communication opportunities, frequent disconnection, and long delays, have been mostly studied based on entity mobility models. Thus, it would be interesting to also investigate the performance of such networks, their protocols and applications under different group mobility patterns. Another potential direction for future research is the design of a generic parameterized group mobility model with an automated mechanism to populate the model parameters based on mining captured datasets of real mobility traces. Such a model can facilitate the automatic modeling of any new types of group mobility patterns of existing or new mobile entities (e.g. tactical drones) that may emerge in the future.

6 Conclusion

In this paper, we have reviewed some of the most representative group mobility models proposed for MANET research. We classified the models into four categories based on the movement of the group members: PBGM with IGM, PBGM with CGM, RBGM with IGM and RBGM with CGM. We first concisely described how the group and group members move in each model based on our classification, including our insights from analyzing each model. We then summarized and compared the models based on six design features and their target applications. The list of design features is provided for users of these models to consider when adapting them or creating new models with the desired set of features to suit their specific applications. Finally, we discussed some directions for future research on modeling group mobility patterns not only for MANETs, but also other types of networks.

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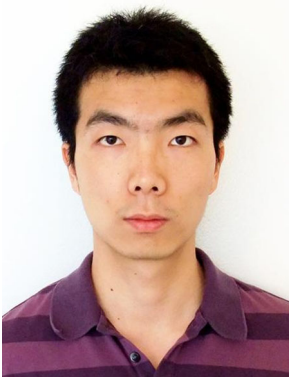
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