A Structured Group Mobility Model for the Simulation of Mobile Ad Hoc Networks

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ABSTRACT

Realistic models for node movement are essential in simulating mobile ad hoc networks. Many MANET scenarios are most realistically represented using group movement, but existing group movement models depict individual group members as independent actors moving randomly. For many scenarios however, group movement implies a common goal or orientation, and hence an inherent structure to the group. We show that this structure can be defined a-priori, and that knowledge of it will result in more accurate simulations. This paper presents the Structured Group Mobility Model (SGMM), which parameterizes group structure and generates movement sequences for use in simulations. We define the model and demonstrate how such a model of node mobility may be used in creating simulations of several MANET scenarios. We compare simulations using the SGMM with other models using various routing algorithms. Our preliminary results indicate that accurate representation of group structure has a significant effect on the overall simulation, particularly in the area of link stability. The results also imply the need for routing algorithms that take group structure into account.

Categories and Subject Descriptors

H.1 [**Models and Principles**]: Miscellaneous

General Terms

Experimentation, Measurement

Keywords

mobility models, group mobility

1. INTRODUCTION

Mobile ad hoc wireless networks (MANETs) are quickly becoming the paradigm of choice where connectivity is required and mobility is a given. Because simulation is often the only feasible way to experiment with new protocols in these complex environments, accurate mobility models are critical. Early models employed random movement, but the situations where nodes move in a genuinely random fashion are fairly limited. More often, nodes will display some form of grouping behavior[13]. Applications for MANETS range from distributed collaborative applications on one hand to complex systems for police, fire and military operations on the other. The U.S. military, in particular, deploys a battlefield digitization system that implements MANETs on large scales, providing real-time situational awareness and operational control for every node in the network[1]. We note that not only do the nodes exhibit group behavior, but the common goal or organization that leads to the group behavior also implies an inherent structure to the group.

Accurate simulations of MANETs require mobility models that correctly capture the node movement. Existing models do this, but the movement of individual nodes within those groups is modeled randomly—a process that fails to capture any inherent structure that exists within the groups of nodes. We have extended current group mobility models by incorporating a-priori knowledge of structure into the movement of groups of nodes. We call the proposed model the Structured Group Mobility Model (SGMM). In it, individual nodes are assigned to groups according to a known organizational structure, and these groups move in concert with other groups in a larger operation. Individual nodes maintain stable relationships within their group, thus preserving overall group structure.

To evaluate the SGMM, we extend the NS network simulator to incorporate physical barriers to wireless signals and to track the effects of movement on connectivity. We implemented several scenarios and compared the performance of the DSDV[16] and AODV[15] routing algorithms while describing movement using the SGMM and RPGMM models. Our preliminary results indicate that the group structure has an effect on the performance of the various protocols, particularly in the area of link stability, and suggests that MANET simulations should capture group structure to accurately evaluate routing algorithms.

The principle contributions of this paper are

- Extensions to NS to capture and trace barrier-induced link breakage, important in accurately evaluating the effects of precise node structures,
- Introduction of the Structured Group Mobility Model, which extends existing models by capturing the organization, strict or loose, inherent in groups, and

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- Presenting simulation results indicating that the internal structure of groups can significantly affect link stability and the performance of routing algorithms.

2. EXISTING MOBILITY MODELS

The study of node mobility is not new, and the literature presents several examples of attempts to model the behavior of nodes in a mobile network. The simplest of all models are those that regard each node as an individual with no connection in terms of movement to the other nodes. More complex models reflect the real-world grouping behavior that is often evident in MANET applications. Such group mobility models vary in complexity, ease of use, and how much knowledge of node mobility is known a-priori.

2.1 Models dealing with nodes as individual agents

Early mobility models were typically aimed at cellular networks and treated each node as an individual agent moving essentially randomly. The simplest model is known as the *Random Walk Method* [10, 14], which dictates that a node moves completely randomly, with speed and direction chosen from a given uniform distribution. There are permutations of the Random Walk Method that limit the selection for a node's next location by limiting the velocity or direction ranges. These models are useful for simulating more realistic node movement, such as automotive traffic on a highway.

Models have also been created that deal specifically with mobility in ad hoc networks. These models differ from those used in cellular networks in that no central station is required, and the notion of a simulation 'cell' denotes only the physical location of a given node as opposed to a relationship to a retransmission tower. The *Random Mobility Model* (RMM)[10] is similar in concept to the Random Walk Method in that a node's next location is determined by selecting a direction and velocity from a uniform distribution, assuming that the node's position is updated at each 'clock tick' of the simulation [17]. Like the Random Walk Method, this model is simplistic and easy to implement but tends to deliver unrealistic results.

More useful permutations of the RMM have one or more of the three available parameters changing probabilistically; i.e., the likelihood that a node will deviate from its present path by more than a given factor is limited. Thus wild, sudden swings in movement are smoothed out, resulting in more realistic movment.[4].

Probably the most commonly used agent mobility model is the *Random Waypoint* model, as described in [5]. This model has nodes moving from waypoint to waypoint with short pauses between movements. The selection of a node's next waypoint in this model may be via random selection within the simulation field or via random selection of azimuth and distance from the previous location, and the two methods return different movement patterns in actual simulation [5]. This model has been extended in many recent works (eg [6]), and there are several permutations of it that may be selected based on the simulator's environment.

A recent addition to the set of useful models is Jardosh et al.'s *Obstacle Mobility* model[12]. This new model incorporates obstacles into the simulation and alters the network's behavior based on those obstacles. Transmissions may be blocked and links broken by these obstacles. As described, there is no provision for group movement or an expectation that the movement of any one node is related to that of another. Thus, while it is an excellent treatment of the effects of obstacles on network behavior, the OMM is limited in terms of its use for group mobility.

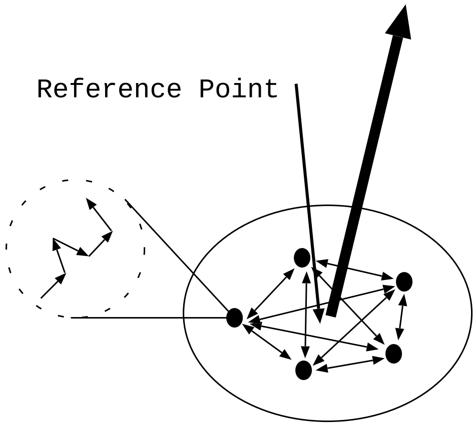

Figure 1: Reference Point Group Mobility Model

2.2 Group Mobility Models

One example of a viable group mobility model is the *Exponential Correlated Random Model* (ECRM)[3], advanced by Bergamo et al. Under the ECRM, the movement of al elements in the simulation—both individual nodes and groups—is governed by two parameters of a complex motion function.

A less complex model is the *Reference Point Group Mobility Model*
(RPGMM)[10]. Under the RPGMM, nodes are grouped prior to the simulation, and each group has a 'center,' or reference point, which could be geographical, logical, or specific (the 'commander' node of the group). The group's reference point describes the overall motion of the group, and may be allowed to move randomly in a macro-RMM fashion or be scripted with waypoints and movement tables. Within each group, nodes move fundamentally randomly as above, provided that they do not move outside of the radius that defines the group. The RPGMM provides an excellent general framework for group movement, but we note that individual nodes continue to move in fully random, unrealistic ways, and we believe the model could be extended to good effect.

A extension of the RPGMM is Wang's *Reference Velocity Group Mobility Model* (RVGMM)[17]. The RVGMM asserts that a more accurate indicator of group behavior is a *group velocity* vector $\overrightarrow{v}$ at time t, where $\overrightarrow{v} = (v_x, v_y)^t$. As Wang himself points out, the RVGMM may be derived from the RPGMM and vice versa, making them essentially the same model approached from different directions.

3. THE STRUCTURED GROUP MOBILITY MODEL

Our observation is that group mobility suggests the existence of task orientation and that this orientation will be known to the individual creating the simulation beforehand. Nodes that move in groups very often indicate the existence

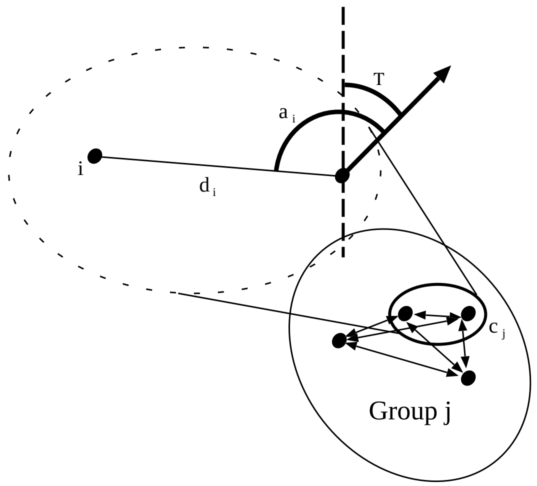

Figure 2: The Structured Group Mobility Model: Placement of node i in a structured group. Node i and c_j of group j are magnified for clarity.

of a common goal, geographic or otherwise. Examples are firefighters in a building, police officers in a crowd control action, or military vehicles on the move. In all these cases and many others, the organizations that the team members belong to impose a structure on the group. The accuracy of a given MANET simulation—particularly when evaluating various routing protocols—would be enhanced by the incorporation of structure to groups, and the *Structured Group Mobility Model* (SGMM) is a generalized way to represent this inherent group structure.

The SGMM is shown in Figure 2. Under the SGMM, each group j has a reference point c_j, which may be the geographical center of the group, the location of the leader, or the group's center of mass. Whether it is moving or not, c_j has a directional orientation of angle T from 0 degrees on a global coordinate system. Thus c_j is able to maintain an orientation independent of movement, and subordinate groups and nodes are positioned relative to c_j. Each subordinate groups or node i occupies a location relative to c_j The model derives this position by selecting a distance d_i from c_j from a given distribution D and an angle a_i away from T from a given distribution A.

Each node's relationship to the reference point is maintained by specifying the distributions D and A from which d_i and a_i are selected, and different continuous distributions will lend themselves to different situations. Since all subordinate nodes are dependent on c_j for their position, a simulator need only define the movement of c_j to define the movement of the entire group. Depending on the simulation being constructed, c_j might be controlled by an entity mobility model such as Random Waypoint or even scripted via specific waypoints to follow a predetermined path, as we describe later. A simulator may therefor 'dial in' the correct behavior of group member nodes by simply specifying the appropriate entity mobility model for c_j and the distributions (and means) for A and D.[5]

Thus, in group j, each node i's location is updated over time based on four parameters, and the location at time t can be calculated from a function F such that

$$i(t) = F(c_j, T, D_i, A_i) \tag{1}$$

where

- t is time,
- j is a given group,
- c_j is the location of the designated reference point of group j at time t,
- T is c_j's directional orientation 0 degrees on a global coordinate system
- D_i is the continuous distribution from which d_i is chosen.
- A_i is the continuous distribution from which a_i is chosen.

It is important to note that there is no velocity vector associated with either the individual nodes. The group may move either via waypoints (as in the simulations presented here) or via a mobility model of its own in the form of an entity mobility model for c_j. The locations of the nodes in the group are exclusively determined by their distance and angular relationship to c_j, which are themselves updated through random selections from the distributions A and D.

The SGMM is marginally more complex than previous mobility models, but it offers the advantage that it allows a user to accurately describe the real-world behavior of groups with inherent structure. In particular, the ability to select the distributions that govern the selection of a_i and d_i from the distributions A and D enables the simulator to tailor nodes' behavior to represent a specific situation. If the simulation requires a tight, rigid structure, as in a military unit moving across flat, open terrain, a normal distribution with a small variance may be used for both A and D. Thus, the selection of a particular distribution and its parameters will return the desired behavior, and the model can be made to return node and group behavior that is far closer to real life than previous models.

The SGMM also allows for a tight scripting of a simulation based on the expected behavior of groups executing a given mission, so the behavior of several groups can be controlled with a set of waypoints and associated velocities. For example, a group of military vehicles can easily be scripted to follow an avenue of approach or attack sequence by simply using a series of waypoints as c_j, while the individual movement of the several vehicles will maintain a degree of randomness. Multiple groups can be handled by applying the model recursively, where the members of the main group are themselves SGMM groups. In this sense, the SGMM is self-similar, and lends itself particularly well to representing hierarchical organizations such as command structures. Thus the behavior of many groups can be controlled with only a relatively few parameters.

In practice, we found that the SGMM was not significantly more difficult to generate working movement commands with than the RPGMM, notwithstanding the additional complexity. Both models are easily implemented in software using commonly available programming. For simulations of reasonable size (less than a hundred nodes) viable sets of movement commands for NS under either model could be generated in a few minutes.

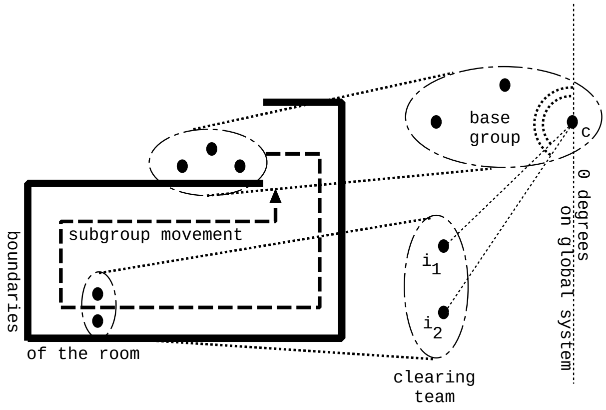

Figure 3: Firefighting team in a building: Clearing a room

4. APPLICATIONS OF THE STRUCTURED GROUP MOBILITY MODEL

The SGMM may be applied to any situation where groups move with a structure that is known a priori. The SGMM would clearly be more useful in those cases wherein group structure is tightly controlled, and we present some examples of possible applications of the SGMM below.

4.1 Firefighters operating in a building

As firefighting agencies become more advanced, they are using sophisticated location determining, tracking and communications systems that are often based on packet radio networks[11]. Firefighting teams themselves are typically small elements of not more than five firefighters, operating in concert with other small teams as they enter buildings and attack the fire. Group structure and control is critical. Individual nodes stay fairly close together in this scenario, but barriers and node failure can easily lead to link breakages that will stress the underlying routing protocol. It is also common for two members to break off from the group to clear a room or search an obscured area, for example[2]. Figure 3 depicts a typical tactic employed by firefighting teams, wherein a command element of a team stations itself at the entrance to a room and a smaller clearing team moves through the room to search for fire and victims. The SGMM could be used to accurately depict these scenarios by tightly controlling the distributions D and A for the 'base' section, and allowing more latitude in both distributions for the 'searching' section. Then, by simply scripting the movement of the reference point node, the entire group may be made to move in a pattern that simulates the interior of a building.

4.2 Military units on the battlefield

Structured groups are very useful in a military scenario involving a digitized battlefield, wherein each vehicle or in some cases each soldier represents a node in a larger tactical internet. Military units are fundamentally hierarchical, and they deploy, move and operate in groups that display tight adherence to a group structure that is known a priori[9, 8]. Figure 4 depicts a tank battalion moving in formation, and illustrates the self-similar and recursive nature of the SGMM. By specifying the distributions D and A at each level, the simulator can tightly control the behavior of all nodes and elements from the whole battalion to the last platoon.

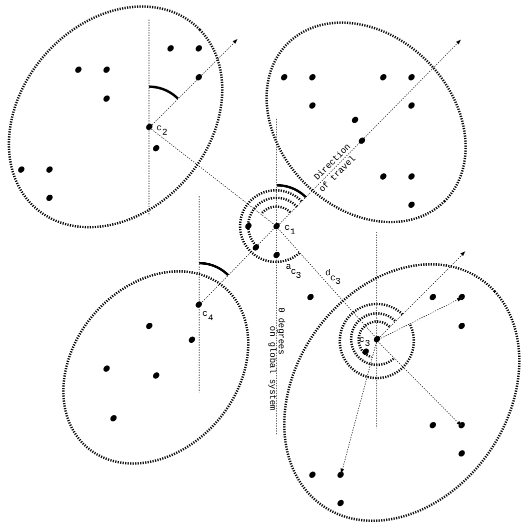

Figure 4: Military units on the move, including subgroups

5. NETWORK BEHAVIOR IN THE FACE OF INDUCED LINK BREAKAGES

The RPGMM and RVGMM offer good platforms from which to observe network behavior in the presence of group mobility. A significant drawback to their use thus far, however, is the fact that they have most commonly been implemented in a flat, obstruction-free simulation environment. Many of the network metrics measured by Hong[10] and Wang[17] are the result of, or are exacerbated by, the rate that links between nodes break and reestablish themselves. Dropped packets, forwarded packets and routing overhead are all directly affected by the quantity and frequency of link activity. Much of the recent research—Jardosh's work[12] being an exception—assumes that wireless links between nodes are broken solely because the nodes in question are no longer able to receive each others' transmissions. This is exclusively a power and distance issue: if transmission power remains constant, then links will break solely when nodes move out of range of each other.

While this model of distance-induced link failures returns adequate results to measure network activity versus mobility (in the case of the RPGMM) or partitioning (in the case of the RVGMM), we believe it is unrealistic in an environment that features structured groups. Such a model ignores the significant effects of barriers and obstructions in the simulation environment. Radio transmissions between mobile nodes operate on line-of-sight, and while it is not uncommon to be able to receive transmissions from a source that is over a hill or around a corner, this is most often the result of signal reflection or some other phenomena that are seldom modeled in existing studies of group mobility. Even Jardosh et al[12] explicitly exclude the possibility of reflected signals, and restrict the non-distance related occurrence of broken links to interruptions of line-of-sight. Thus at a minimum, failure to account for obstacles that induce link breakages appears to be a gap in present research.

6. SIMULATIONS WITH STRUCTURED GROUPS

The goal of the SGMM is to provide more realistic network behavior than more stochastic models such as the RPGMM and RVGMM, especially in an environment where obstructions induce link breakages between nodes. We expect that the added stability that structured groups provide should reduce the rate of link breakages due to distance and transmission power. In this section, we detail our simulations to evaluate the impact of Structured Groups and barriers on the performance of two wireless routing protocols: AODV and DSDV.

6.1 Simulator

We used the NS2 discrete-event network simulator[7]. To simulate the existence of barriers that would induce link breakages, we exploited NS2's ability to read a *Digital Elevation Model* (DEM), and we altered the NS2 code that governs the receipt of wireless packets from the MAC layer to make use of this topographical data. Because the propagation models that NS2 uses cannot account for three dimensional data[7], we modeled barriers to be simple walls of infinite height that block all wireless traffic. We assume that the nodes are transmitting omni-directionally, and we assume that the radio 'shadow' that the obstacle creates is of infinite duration. Put simply, if between any two nodes there is an obstacle, then the two nodes cannot communicate.

Our new code in NS2's mobilenode MAC layer reads the packet header of each incoming packet and checks for the existence of a barrier anywhere on the path between it and the packet's last hop. Where a barrier exists, the packet is dropped at the MAC layer, and this event constitutes a broken link. The software records the broken link event in a 'links-down' table, and higher layers of the protocol handle routing table updates and data retransmission. If on the other hand a barrier does not exist then there must be a valid link between the source and destination nodes. Before passing the packet up the stack normally, the software checks the links-down table for the presence of the link between the source and destination nodes and, if the link is found, removes it. This event constitutes the reestablishment of a valid link, and both link-down and link-up events are recorded.

6.2 Movement Patterns

We created three simulations intended to represent movement of military vehicles toward an objective[9]. The topography for each simulation was represented in a DEM file of 3000m × 3000m. The location of the barriers was chosen somewhat arbitrarily, and then the movement was created with the position of the barriers in mind.

Each movement pattern represents a unit of 14 vehicles engaged in a tactical movement across that particular topography. To create the movement instructions, the group structure of the unit was decided and the waypoints were created for each topography. A script was used to create the precise node-by-node movement instructions used by NS for the simulation. The script implements the SGMM and RPGMM, taking the waypoints and automatically generating either structured movement or random movement around the command vehicle. Figures 5, 6 and 7 show the waypoints and general movement patterns for each simulation. Each of the three movement patterns lasted approximately 1000 seconds within the next-event simulation, depending on how far the nodes were required to move at 6m/s.

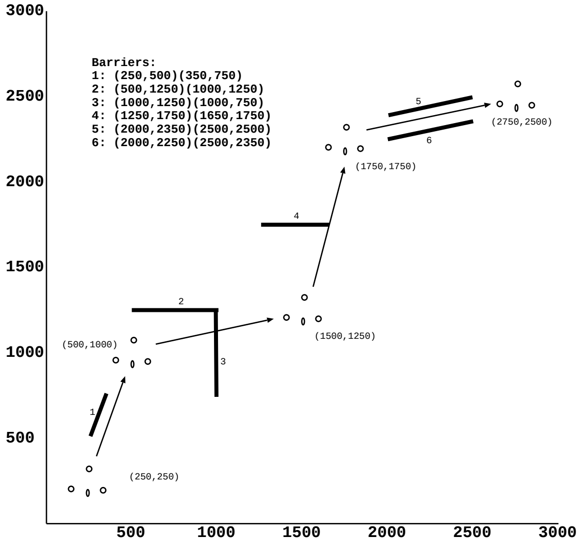

Figure 5: Structured groups moving via waypoints, around and through obstacles. The unit moves toward an objective, passing over escarpments, next to buildings and through valleys.

For these simulations, the DEM file topography represents barriers to communication, but not necessarily to node movement. This type of barrier would represent a realistic feature such as a large hill or a dense line of trees that vehicles might be able to cross, but would generally try to avoid crossing. Thus, for the purposes of radio transmissions, a single barrier would realistically model a steep ridge, such that nodes at the bottom of the ridge—in the valley—would not be able to communicate with nodes that are over the crest of the ridge. Before beginning movement, each node establishes an FTP connection with every other node, and initiated constant, low bitrate FTP traffic for the length of the simulation.

6.3 Evaluation

We ran each simulation using the AODV and DSDV protocols respectively for a total of twelve simulations. Each simulation produced a tracefile that we processed for the needed data.

Our goal in this evaluation is to determine the impact of the mobility model on the results of the simulations, rather than attempting to evaluate the routing algorithms themselves. Our argument that structure is important to evaluating ad hoc protocols will not be measured strictly in terms of raw performance, but rather in terms of differences in link behavior that are achieved by the same routing algorithm under different mobility models.

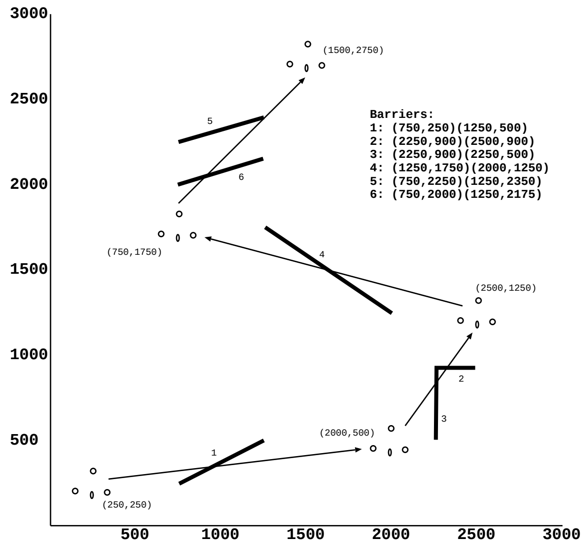

Figure 6: Structured groups seeking contact, moving over various terrain features

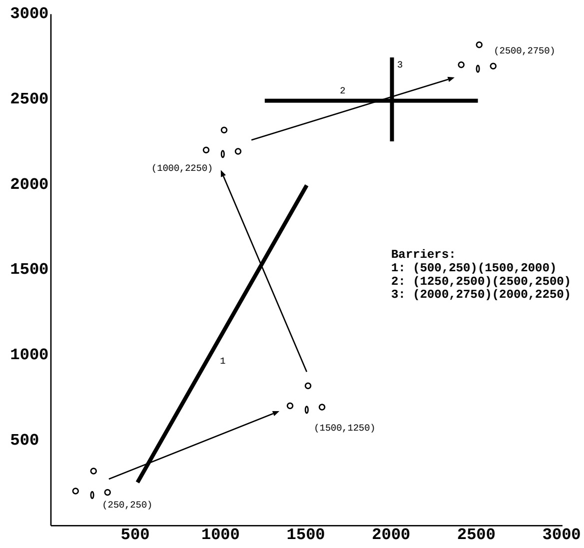

Figure 7: Structured groups moving toward an objective, passing down and then back up a ridge, then over a steep hill

Thus, the primary metrics that we measure deal with changes in link status, both those caused by distance and those caused by barriers. Because the SGMM is less stochastic than the RPGMM, we would expect there to be fewer barrier-induced link breakages than with the RPGMM. For our simulations, the selection of a particular routing protocol should not affect the rate of link breakage, but it will affect the rate of convergence, or link reestablishment. Note, however, that because we filter traffic for barriers *after* the destination MAC address has been checked, links are only noted to be broken upon an attempted unicast transmission to the node or a broadcast by the routing protocol.

We also examine the relative routing performance for the two protocols that results from using structured versus unstructured groups. We measure the total number of packet forwards, dropped packets, and received packets. We measure the routing overhead as the number of routing packets sent.

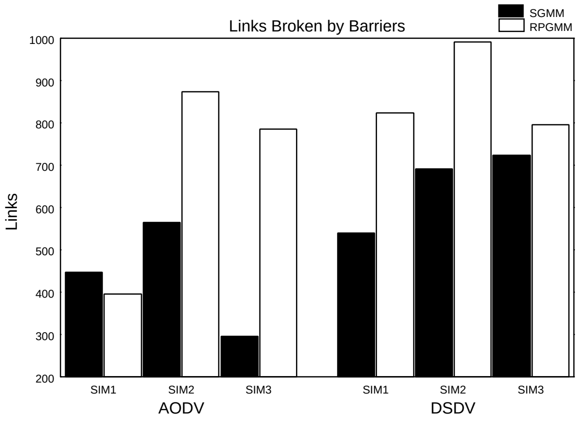

Figure 8: Links broken by a barrier

7. RESULTS

For reasons that will become clear, we present the results for each simulation run rather than attempting to summarize them. In each graph, the left six bars show results from the AODV routing protocol and the right from DSDV. For each topography/movement dataset (labeled SIM1, SIM2, and SIM3) the results from each of the mobility models are shown together. The SGMM results are solid black and the RPGMM results are hollow.

Our initial analysis focuses on the broken link event counts. Figure 8 shows the number of times a link was broken by a barrier and Figure 9 shows the number of times a link was broken by excessive distance. It is very clear that there are more links broken by barriers in the RPGMM-based simulations than in the SGMM simulations. This result confirms our assumption that the structure in the SGMM creates greater link stability—because the nodes remain in formation, they do not cross the barriers independently but stay with the same subgroup.

The results for links broken by distance are similar, with one exception. In five cases, the number of links broken by distance are either very close or significantly greater for the RPGMM. In the sixth case, the RPGMM experienced a significantly lower number of broken links. Intuitively, the SGMM—where the distance separating nodes is governed by the model parameters— should experience fewer links broken by distance, whereas the RPGMM should experience them more often as the random motion within the group leads some nodes away from others.

We find these results generally agree with our intuition, but we are exploring the underlying causes of the results in more detail. More specifically, we have found that because the links are determined to be broken after the MAC layer has determined whether there is a destination match, the results are strongly influenced by the number of broadcasts done by the routing protocol. We are planning a future study where all nodes regularly send out broadcast packets to track link connectivity without influence of the routing protocol.

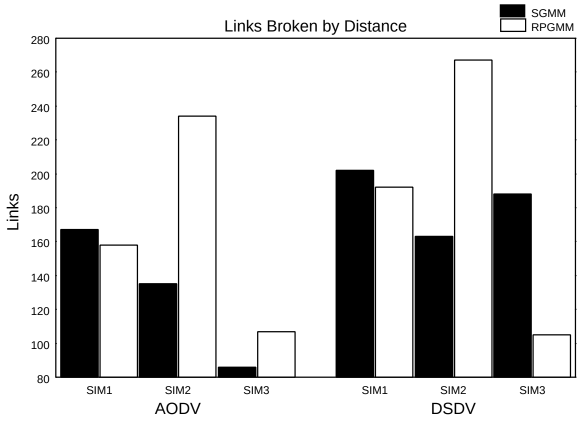

Figure 9: Links broken by distance

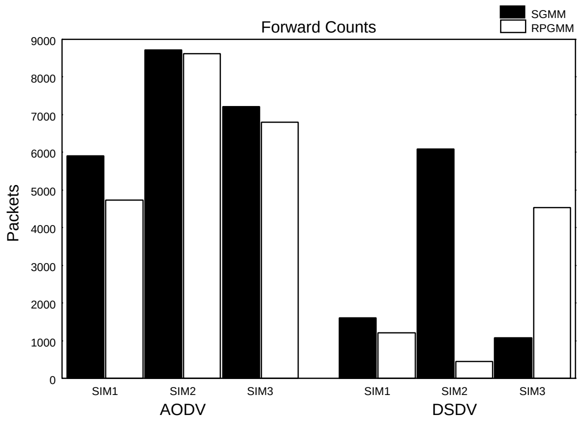

Figure 10: Total packets forwarded from any node

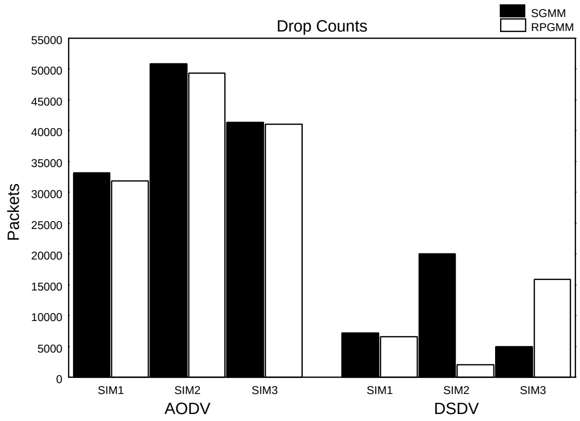

Figure 11: Total packets dropped for any reason

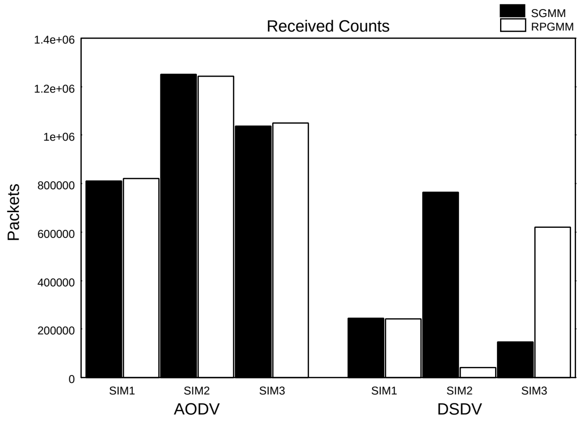

Figure 12: Packets received at destination

Figures 10, 11, 12, and 13 show the results for the routing performance. The results here are more surprising. Although there was a substantial difference in the number of broken links observed during the AODV runs, the actual routing performance numbers remain remarkably similar. We believe that AODV's timer-based broadcasts to refresh routes are responsible for these performance numbers[6], both in terms of the the numbers of broken links and for the very large number of packets sent during the simulation.

The DSDV results are more challenging to draw conclusions from. In SIM1, the protocols perform similarly, in SIM2 SGMM forwards more data, and in SIM3 RPGMM forwards more data. We observe that the routing performance numbers appear to be inversely correlated to the number of links broken by distance, but have no current explanation for this result.

Our results, particularly the broken link events, indicate that there are significant differences between the communication environments experienced by nodes in structured and unstructured mobility models. That these differences do not show up in a consistent fashion in routing algorithms is surprising, but the wide range of behaviors observed during the DSDV simulations is intriguing. We are planning further work to identify the exact cause of the performance differences and to separate out the broadcasts from the unicast packets to better identify the impact of structure on routing performance. We also need to better characterize the effects of the randomness in the RPGMM, as the results may be significantly influenced by the nature of the random movements generated for each simulation.

8. CONCLUSION AND FUTURE WORK

This paper presents a study of real-world group movement scenarios for mobile ad hoc networks. The collected data and experiments dictate two conclusions.

- Groups in real-world MANET scenarios exhibit internal structure.
- A mobility model that captures structure inherent in groups produces different results than those that do not capture structure.

These conclusions suggest that simulations of mobile ad hoc nodes should be designed with consideration for possible structure inherent in the environment being simulated.

To effectively model the structure inherent in groups and to simulate its affects on routing performance we

- introduce the Structured Group Mobility Model (SGMM), which allows a parameterized description of group structure dependencies for generating movement traces, and

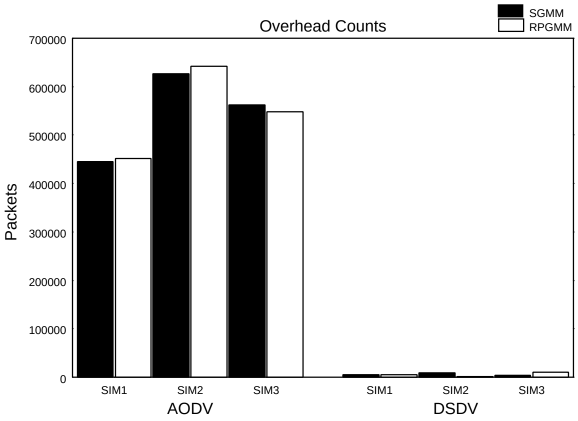

Figure 13: Routing overhead packets

- extended NS to utilize barrier information described in DEM files and to determine link blockage at the MAC layer.

The SGMM is more complex to use due to the need to develop parameters describing the formation of the group. Once that task is accomplished, however, group movements can be specified using only waypoints for the reference point. Calculating the movement traces for the SGMM is somewhat more complex than for other mobility models, but we have found that time to be insignificant in the simulation process.

Our research presents interesting results, but raises an even larger number of questions. First, we need to develop techniques to better quantify the influence of the group structure on routing protocols. Secondly, the barriers had a significant effect on the performance of the protocols, but our current model is somewhat simplistic in how they are modeled. We need to incorporate uncrossable barriers into our implementation of the SGMM and RPGMM, and we intend to automate the generation of movement traces so we can generate longer duration simulations. An ideal simulation would also have a more detailed signal propagation model, but we expect that current simulation capabilities will restrict us to communication barriers for the near future.

In the future, we will continue to refine the SGMM with an eye toward broadening its application. In particular, although we described four real-world scenarios where groups move with internal structure, we have only simulated hierarchical military vehicle movements. We are currently implementing a simulation of freeway traffic patterns and other environments where many nodes move in a loosely coherent manner. To that end, we will compare the results of simulations using the SGMM in a traffic environment with observed behavior to quantify how closely the SGMM models actual behavior.

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