

A Group Force Mobility Model

Sean A. Williams and Dijiang Huang

Computer Science and Engineering Department
Ira A. Fulton School of Engineering
Arizona State University
{Sean.S.Williams and Dijiang}@asu.edu

Abstract—Several mobility models attempt to simulate the group mobility model in ad-hoc network simulation. However, most have certain limitations that prevent the model to be an accurate real world representation. There are limitations that a mobility model does not address such as environmental changes that occur that will alter the behavior of mobile nodes (MNs). Also, there are simulation limitations that allow the MNs to overlap or collide which is also more so an unrealistic characteristic. We propose the implementation of a Group Force Mobility Model to address these limitations in an effort to create a more realistic representation of MN behavior in an environment. In addition, to show the simulation results, we also conduct a comparative performance study of our approach with the Reference Point Group Mobility Model.

I. INTRODUCTION

Helbing and Molnár [8] first introduced “social force” for continuous mobility simulation (pedestrians to move continuously in a part of the 2-D simulation area). The social forces do not have a physical source; rather, they reflect the intentions of a pedestrian not to collide with other people in the room or with walls and also to move in a specific direction at a given speed. The social forces are modeled as repulsion forces prevent the pedestrians from colliding with each other or on the obstacles such as the wall. Although the social force model can be used to simulate a few individual behaviors, the mobility modeling technique that can simulate various steering behaviors [12] in more versatile simulation configurations is in great demands. We propose a force-based mobility modeling technique which has the following property:

- The force-based mobility model is not just restricted to simulate repulsion force. Attraction forces also can be simulated. Moreover, the force-based mobility model is able to simulate combined steering behaviors that require combined repulsion and attraction forces. Thus, more complex human behaviors can be simulated.

In this paper, our interest is the group mobility model incorporating the combined repulsion and attraction forces. To analyze the mobile users’ movements, it is a natural way to incorporate forces (repulsion and attraction) among mobile users, which provides a mechanism for a mobile user to avoid collision and congestion. We propose a group force mobility model to illustrate the interactions between the nodes and between nodes and objects. The proposed approach introduces a novel method to emulate users’ behavior in the real world. Our research focuses on two types of groups for mobility simulation:

- (a) When the group members share similar interests but move in a random fashion. We call it as loose group mobility model.
- (b) When the movements of group members are strongly correlated to each other. We call it as tight group mobility model.

We utilize exponential force distribution as the base to modulate a mobile user, i.e., the repulsion force always exists between two mobile nodes and the repulsion force decreases exponentially when the distance between two nodes increases. In this way, we can construct a mobility model to avoid node-collision during the simulation. We also introduce attraction force by combining exponential force and a second force distribution model. The combined force model remains the decreasing property of exponential force model within a small range of distance (0 to 5 meters for tight group and 0 to 15 meters for loose group). When the distance increases (between 5 and 20 meters for tight group and >16 meters for loose group), the force among mobile users are negative, i.e., attraction forces exist among mobile users.

To construct the proposal group mobility model, we utilize the event driven simulation, i.e., NS-2, to conduct our simulation. Moreover, we compare our approach with the reference point group mobility (RPGM) model [9] by evaluating the performance of AODV [11] ad-hoc routing protocol.

The remainder of this paper is organized as follows; Section II briefly discusses related work, Section III illustrates the group force mobility model, Section IV introduces the simulation and results, Section V discusses the performance assessment including comparative analysis with USC’s IMPORTANT, and Section VI concludes our approach.

II. RELATED WORK

There are a wide-range of Mobility models and each try to focus on capturing a specific real world situation or a more general analysis of realistic events. Nevertheless, these models can be grouped into two categories, trace-based and synthetic models [5]. Trace-based modeling requires specific input of mobility traces of a user. This may be good and relevant for a specific isolated case; however synthetic models’ goal is to represent the real world behavior of mobile users.

There are several mobility models that attempt to capture movement and behavior of users. These models include the Random Waypoint Model [4], Random Walk Model [5], Random Trip Model [3], Reference Point Group Mobility Model [5], Obstacle Mobility Model [1], and Pathway Mobility Model [1].

Often scenarios of mobility users will exploit their movement in a coordinated and similar fashion with relatively equal velocities and/or destinations. In order to model such behavior there exist the Reference Point Group Mobility (RPGM) model [2] or similar derivations from this model. The RPGM consists of each group having a center or group leader. This group leader will determine the movement behavior of the MNs in the group [2]. Essentially, the MNs that are a part of that group have velocities reflective and relative to the velocity of the group leader.

Many group mobility models have been proposed based on RPGM model. There are special cases of the RPGM model such as

the Virtual Track Based Group Mobility [13], Exponentially Correlated Random Mobility Model, Column Mobility Model, Pursue Mobility Model, and Nomadic Community Mobility Model [5]. The Virtual Track Based Group Mobility model [13] is where group models move along the path of a track. Throughout the path there can exist “switch stations” at these stations where large groups can be split up or smaller groups can be joined together. Exponential Correlated Random Mobility Model is based on a function of motion to create movements. A Column Mobility Model is a group of nodes that form a line then uniformly moving in a specific direction. The Nomadic Community Mobility Model is a collection of nodes that move together from one location to another. The Pursue Mobility Model is where a set of nodes follow a target. All of these are some derivation or share some basic foundation with the Reference Point Group Mobility Model.

It is desirable that the movement of a mobile node is adaptable to environmental changes, such as congestion or collision avoidance. Two literature proposals dealing with social force modeling has influenced our proposal to implement force modeling for MN movement. The first was Helbing et al [8] and the proposal of a social force model to simulate humans under stress. In connection with that proposal was Gloor et al [6],[7] who expanded on the idea for pedestrian simulation in the Alps Mountain. Their proposal discussed forces that can affect and alter human behavior. This concept can now be applied to the movement and behavior of MNs to imitate humans and there interactions. These forces can be categorized as:

- The constant force which attracts the MNs to destinations
- The repulsion force between MNs to avoid colliding
- The repulsion force between MNs and boundaries.

Our approach shares the interest of group mobility and the effort to create a more realistic imitation of mobile users based on some behavior that is exhibited. Above mentioned social force-based group mobility models focus on a specific scenario. However, our proposal attempts to focus on a general scenario. As a result, a group force mobility model incorporating these concepts is constructed to provide an optimal representation of MNs and group behavior which focuses on creating a close simulation of the real world.

III. THE GROUP FORCE MOBILITY MODEL

In this section we discuss our proposed group force model. In particular, we address the force between mobility nodes due to the distance changes among them.

A. Force Model Basic

It is important that MNs move in arbitrary directions without artifacts caused by the modeling technique. The social force model (HELBING et al. [8], see appendix A) is a generic coupled differential equation model for MN movement. In this paper, we modify the social force model proposed by Helbing et al. Our focus is the movement directions affected by the environmental changes.

$$\frac{d\bar{r}_i}{dt} = \sum_{j \neq i} \bar{f}_{ij}, \quad (1)$$

In (1), we formulate the moving direction \bar{r}_i of MN i is the accumulated forces between i and j , where $j \in R$ and R is the set including all MNs in the simulation area. Note that, in (1), the term illustrates the force exerted between mobile nodes and how it

affects their direction of movement. Without special notation, the overhead bar represents the term is a vector within a two-dimensional Cartesian plane.

The distance between these nodes is a significant variable which contributes to the calculation of strength of the force, this is vital in the realistic simulation of the force effect between two nodes. As the distance between two nodes increase, the interaction force will exponentially decrease. This is represented in the exponential force decay equation:

$$\bar{f}_{ij} = A_{ij} \exp\left(\frac{d_{ij}}{B_{ij}}\right) \left(\frac{\bar{r}_i - \bar{r}_j}{d_{ij}}\right), \quad (2)$$

here \bar{f}_{ij} is the force exerted on MN i by MN j ; \bar{r}_i and \bar{r}_j are position vectors of the respected mobile nodes; d_{ij} is the distance between the two position vectors, $|\bar{r}_i - \bar{r}_j|$; and A_{ij} and B_{ij} are simulation chosen constants.

B. Group Force Model

One human factor in simulation is group behavior. It is obvious that many MNs will move together and relative to one another based on (a) sharing the same interests, such as having the same destination location, (b) having similar speeds, or (c) bundling by social factors, such as a group of MNs arranged to move together. There are certain characteristics of the movements and the relative distance between each node which differentiates if the group is tight or loose.

Tight groups depict MNs whose movements are interrelated with other MNs in the group. A loose group illustrates that mobile nodes share some similarities such as destination or that they are periodically within a certain range of one another, however, each movement is independent from the movement of the other MN and random. Furthermore, MNs which are a part of one group, but are within some threshold distance x of MNs in another, there exists a force in which we represent as the social force model in (1).

In order to formulate group force among MNs, we inspect two types of forces: (a) repulsion force (positive force), and (b) attraction force (negative force). In both loose and tight groups, repulsion and attraction forces are exerted between MNs within that group. Exponential force, i.e., *Exppdf*(x, μ) shown in (2), decreases when the distance x between two MNs increases. Note that an exponential force is always a positive force, i.e., a repulsion force that prevents the MNs from colliding to each other. To formulate negative force, i.e., attraction force, we propose three force distribution models and individually subtract them from the exponential force to create resulting equations which illustrate both attraction and repulsion forces. These three represent loose and tight groups with the Chi-Squared group force model being the loosest; the Rayleigh group force model being moderately tight, and Fisher-Snedecor or F group force model being the tightest. Figure 1 shows the calculated force distributions for the three equations (3), (4), and (5) with given parameters used in our simulation:

$$\bar{f}_{ij} = A_{ij} \left(\frac{\bar{r}_i - \bar{r}_j}{d_{ij}}\right) \times \left(\text{Exppdf}(x, \mu) - \text{Chi 2 pdf}(x, \nu)\right), \quad (3)$$

See Figure 1 (a)

$$\bar{f}_{ij} = A_{ij} \left(\frac{\bar{r}_i - \bar{r}_j}{d_{ij}} \right) \times$$

$$(Expdpdf(x, \mu) - Rayleighpdf(x, B)),$$

See Figure 1(b)

$$\bar{f}_{ij} = A_{ij} \left(\frac{\bar{r}_i - \bar{r}_j}{d_{ij}} \right) \times$$

$$(Expdpdf(x, \mu) - Fpdf(x, \nu_1, \nu_2)),$$

See Figure 1(c)

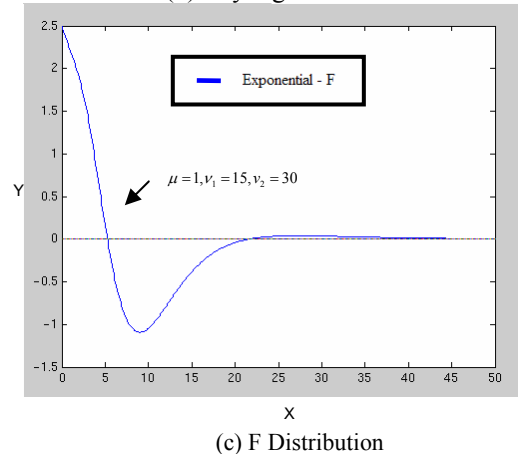
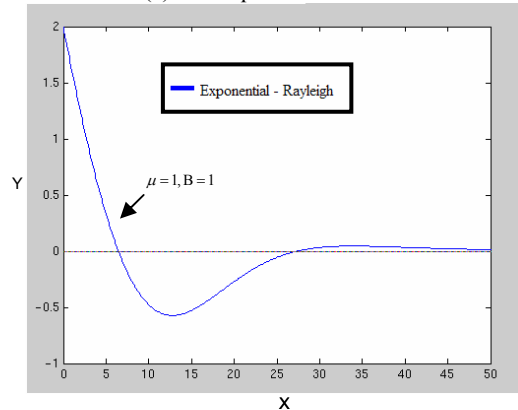
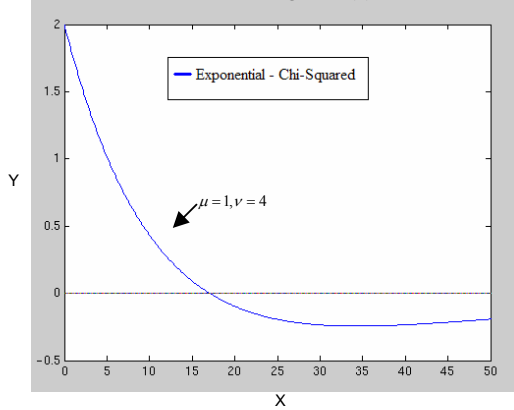


Figure 1. Three Distribution Force Functions

For the descriptions of force distribution models $Chi2pdf(x, \nu)$, $Rayleighpdf(x, B)$, and $Fpdf(x, \nu_1, \nu_2)$, see Appendix B.

The $Chi2pdf(x, \nu)$ function computes the x^2 pdf at each value of x using values in parameter ν , where ν must be positive integers and x is the distance between two MNs. The function $Rayleighpdf(x, B)$ calculates the Rayleigh pdf of each value of x using a parameter B . $Fpdf(x, \nu_1, \nu_2)$, representative of the F distribution, evaluates each value of x using both parameters ν_1 and ν_2 . From Figure 1, we notice, all three combined force distribution models ((1)-(3)) exhibits similar properties when the distance x is small. When the distance x is small the repulsion forces dominate the MNs' behaviors. To realistically demonstrate the behavior of these MN as the forces are applied, there has to exist some distance x in which the forces are negative because the MNs are too far apart. Essentially, that distance x is inversely proportional to the amount of force exerted by one MN on another. As that distance, x , between the nodes decrease the attraction force will increase. In Figure 1, when x increases, the positive forces will change to negative forces, i.e., the attraction forces dominate the MNs' behaviors. The value of negative force represents the tightness of a mobility group. In our example, the $Chi2pdf(x, \nu)$ force model is the loosest one and F force model is the tightest one.

IV. SIMULATION AND RESULTS

To simulate these group force mobility models we use *ns2* which is a commonly used wired and wireless simulator for research. Within *ns2* is a wireless extension created at Carnegie Mellon University known as *setdest*. It is an external application that creates node movement based on the Random Waypoint Model (RWP) and writes it to a file with the *.scen* extension.

We modify the *setdest* program to incorporate our force mobility models to reflect a more realistic depiction of movement of MNs. In understanding its functionality and the principles of the RWP model, the extension randomly selects positions of a given number of nodes and their corresponding destinations. The nodes move with a random speed to the destination; pause for a given time; chose another random destination; and proceed towards that location.

A. Simulation Methodology

To provide a better understanding of the topics in this section some terms need to be defined.

1. *SDR*: Speed deviation ratio, it is a constant used to control the deviation range of speeds of a node from the Group speed. Similar to [2] we chose $SDR=0.1$
2. f : force exerted by a node onto another

Although not going into great detail, there are many modifications of this program to illustrate our group force proposals. The first step is the initial position of the nodes at time, t , and equal to zero. The original code following the RWP model randomly places nodes throughout the simulation area. In order to create groups, the first thing that occurs is the random selection of individual group positions for a random number of groups in the simulation. The next change was an addition to the properties of the nodes. We add an id associated with each node. That id will correlate with one of the randomly generated group positions and we determine the node's position based on the position of the group that matches the id of the node. We calculate it within a 50m range of the group position.

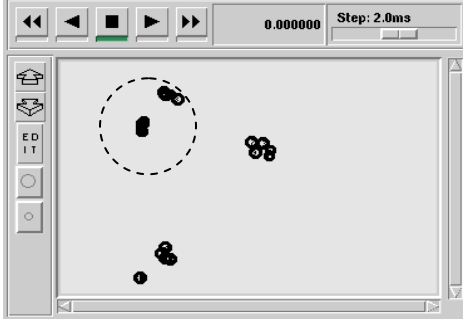


Figure 2. NAM illustrating groups of nodes

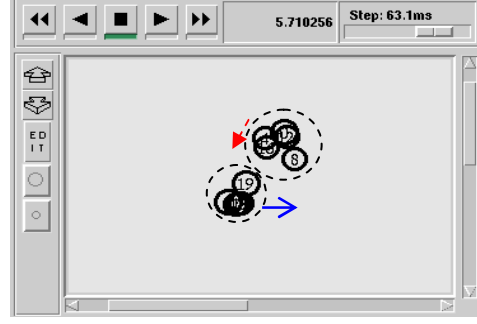


Figure 3. Zoomed in view of two groups

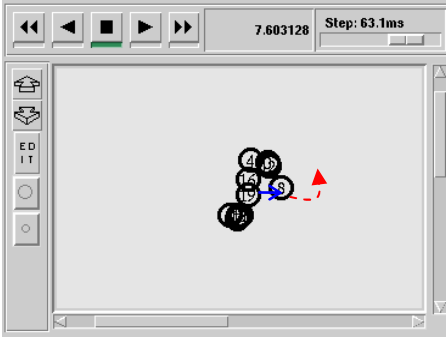


Figure 4. MN 8 changes direction to avoid collision

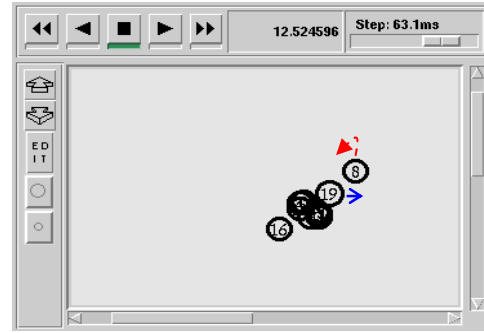


Figure 5. MN 8 starts to return back on path to destination

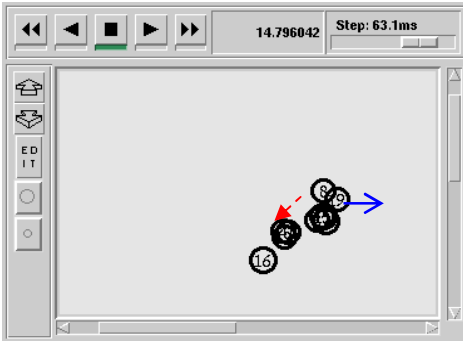


Figure 6. MN 8 and 19 avoid collision

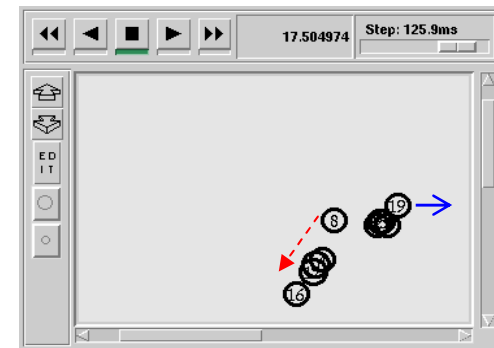


Figure 7. MN 8 continuing on path with rest of group

We calculate the destination and speed of the nodes in a group in a similar way by calculating a group destination position and speed for every group. Then determining the destination of the nodes within the group and calculate based on the corresponding group destination within a 50m range. This concept of determining a node's destination within a radial range simulates a more realistic effect as an opposed to nodes in a group moving towards one specific destination point. We calculate the speed by the following:

$$V_{node} = V_{group} + SDR \times random() \times V_{max} \quad (6)$$

In addition we shorten the discrete event time for each node. This is set to 0.1 seconds. Therefore, every 0.1 seconds the MNs in the simulation updates its position, distance to destination, and direction. The importance of this modification is because as a node moves from position 1 to position 2 within that path and time, another node may appear within the threshold radial distance x and

there must be an evaluation of the force between them. For example, if one node, $n1$, has a direction which we calculate at initial time $t = 0$ and then every 5 seconds, another node, $n2$ can now moved into the path of $n1$ within that time interval ($0 < t < 5$) and there cannot be a calculation of the force exerted by $n2$ onto $n1$ until the next observation interval ($t = 5$). At that time $n2$ may not be within the threshold range nor moving in the same direction as it was prior. So we observe the state of the simulation, the location of the nodes, and the relative distance of the nodes every tenth of a second. In this observation we calculate the distance of each node and its neighbors. If a neighbor's position is within the distance threshold of that node then the force exerted on that node by the neighbor is calculated.

$$f_{tot} = \sum_{\substack{j \neq i \\ j.id \neq i.id}} f' + \sum_{\substack{j \neq i \\ j.id = i.id}} f'' \quad (7)$$

Shown in equation (7), the sum of all the forces of the neighbors of

that node is then evaluated and added to the direction unit vector of the node. f is the force using the normal exponential force model in (2). This is because the node group id does not match the node group id of neighbors. f' is the group mobility force calculated by the Chi-Squared-based distribution equation (3), the Rayleigh-based distribution equation (4) or the F-based distribution equation (5) of neighbors which are in the same group of the node (The distribution is selected based on command-line argument when executing the modified *setdest* program). This illustrates how the direction of a node is dependent upon the forces of neighboring nodes. In addition, because the total force increases as the distance gets smaller the direction of the node will change preventing overlapping or collision.

Since the velocities are random and vary from node to node, one node reaches the destination before the others in the group and pauses. When this happens, a new group destination is determined and all the nodes in the group now move towards the new direction.

B. Simulation Results

The key proof of our results and the proposed research to better emulate mobile user behaviors in such examples as preventing nodes from colliding or overlapping, lies in actually running the simulations and witnessing MNs changing direction based on neighbors and their relative position. Again, this is based on the summation of the forces exerted by neighboring MNs. We observed MNs in which their paths would appear to collide, but now with the exerted force calculated from neighbors and in combination with the MN's desire to reach its destination, the direction of a MN will change and it will maneuver around neighboring MNs exerting the force.

As mentioned in section II, the IMPORTANT framework evaluates the impact of various mobility models such as Reference Point Group Model (RPGM), Freeway, and Manhattan models on the performance of MANET routing protocols [2]. To do so, it uses protocol independent metrics such as mobility metrics, relative speed metrics, and connectivity graph metrics. These are able to analyze the characteristics of different mobility models based on spatial dependence, temporal dependence, relative speed, the number of link changes, and link duration. Our research executes the simulation with the same intent to perform an effective comparison between the RPGM model and our Group Force Mobility Model (GFMM).

Network Animator or NAM is a tool used to simulate NS2 traces (*.scen* files). The following simulation snapshots were generated by NAM and illustrate our group force model and MNs avoiding collisions. We depict MNs randomly selected in groups throughout the simulation area. These specific snapshots show four groups of MNs and in each group the MNs are moving towards a common (but not exact) destination per group.

Figure 2 shows four groups of five MNs. The simulation will randomly generate a number of groups and each group's position. Although the mobile nodes may appear to overlap, once we zoomed in we were able to see that they do not. Further analysis proved this visual assessment by calculating the distance between a node and its neighbors. Nodes that appeared to be significantly close to one another (even appear to overlap) actually had small distances between them. For example, two mobile nodes which possess a distance of 2 meters apart will appear to definitely overlap due to the fact that the radius of the actual circle graphically illustrating the MNs is larger.

As discussed previously, once we zoomed in closer to see MNs and how close they were, they appeared to lie on top. Figure 3 is a closer view of the section inside the dotted line. It shows the moving direction of the two groups and how the circles representing a mobile node can appear to overlap (although the actual distance between them is substantial). Also in the figure, for clarification the red and blue arrows were drawn to explain the direction in which each group moved. The groups appeared to be on a path for collision; in particular, we focused on MNs 19 and 8. The next snapshot (Figure 4) shows MNs 8 and 19 approaching one another. In addition, when the distance between the two decreases, MN 8's path of direction changes. Although the direction of MN 8 changes it still remains persistent to reach its destination. This means that no matter if the direction changes to avoid another node, the MN's destination will not, therefore the MN will attempt to revert back to the path to achieve its destination (as seen in Figure 5).

V. Performance assessment

In this section, we analyze the performance of AODV [2] protocol based on our proposed group force model as well as the comparison to the RPGM model [2].

A. Performance Metrics and Methodology

In our analysis, we utilize the performance metrics defined in [2]. They are:

1. $RD(\bar{v}_1(t), \bar{v}_2(t'))$: Relative Direction (*RD*) (or cosine of angle) between two vectors. $\bar{v}_1(t)$ and $\bar{v}_2(t')$ is given by $\frac{\bar{v}_1(t) \cdot \bar{v}_2(t')}{|\bar{v}_1(t)| \cdot |\bar{v}_2(t')|}$
2. $SR(\bar{v}_1(t), b\bar{v}_2(t'))$: Speed Direction (*SD*) between two vectors $\bar{v}_1(t)$ and $\bar{v}_2(t')$ is given by $\frac{\min|\bar{v}_1(t), \bar{v}_2(t')|}{\max|\bar{v}_1(t), \bar{v}_2(t')|}$
3. Degree of Spatial Dependence ($D_{spatial}$)
4. Degree of Temporal Dependence ($D_{temporal}$)
5. The relative speed (*RS*)
6. Average link duration

For the details of performance metrics, see Appendix C.

To effectively illustrate the comparison based on the protocol independent metrics, we defined them in the same manner as the IMPORTANT research [2], and we use IMPORTANT's *link_analysis* tool to produce the results. USC's IMPORTANT provides this analysis tool which gives the ability to analyze and evaluate mobility metrics of a trace which is generated by the *setdest* program [10]. These metrics include relative speed, temporal correlation, spatial correlation, and average node degree. In addition, the tool calculates the total number of link changes and average link duration [2]. Although we modified the *setdest* tool, we kept the ability to produce the trace file which is the input for the program analysis tool.

Each scenario file executed at various maximum speeds was individually used as input into the *link_analysis* tool, and the results were written to one collective file. From that single file, graphical representations of the results were created. In addition, the RPGM mobility generator provided by IMPORTANT was performed at the same varying maximum speeds and those results displayed on the same graph for each metric.

B. Performance Analysis

The following section provides the results of our Group Force Mobility Model and performs the analytical comparison to the RPGM based on various mobility metrics. The results of the simulations were collected and sorted similar to IMPORTANT's analysis on the RPGM model in [2]. This provides an appropriate comparative domain between our GFMM and the RPGM. Similar to IMPORTANT, our patterns consisted of 40 mobile nodes moving in a simulation area of 1000m by 1000m for a duration of 900 seconds. Four groups of ten mobile nodes were used for both models. The pattern used for the RPGM model was generated by the *ns2*-provided *setdest* tool and the GFMM model pattern was created by our modified *setdest* tool. The SDR was set to 0.1 and the maximum velocity V_{max} varied from 1, 5, 10, 20, 30, and 40 meters per second for each model. In addition, constants A and B were set to 20000 and -150000, respectively. The large negative B value is set to normalize the exponential force equation (2). It was evident based on the protocol independent metrics that the characteristics of each model was different and that our model showed a more stable and realistic representation of MNs moving in a group and relative to one another.

B.1 Spatial Correlation

The first metric comparison was of Spatial Correlation. As defined, it is the likeness of the velocity of two nodes whose distance between them is not too large. For our simulation, in order to calculate spatial correlation, the distance between them cannot exceed the threshold distance range of 20 meters. Furthermore, the higher the spatial correlation, the more the nodes are moving in the same direction. The graphical representations of these results consist of calculating this spatial correlation over the various maximum speeds set for the simulations.

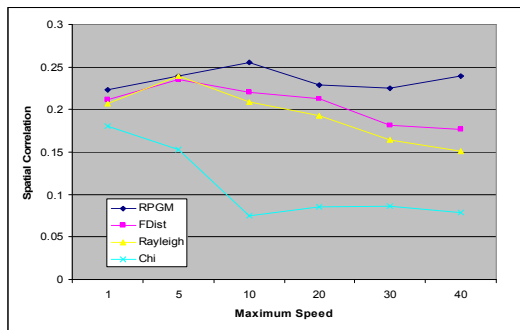


Figure 8. Spatial Correlation Comparison

Figure 8 is the first graphical illustration of the comparison between the three distributions of the GFMM and the RPGM. It shows that our model with these three distributions represents a more realistic representation of mobile movement. Per the definition of spatial dependence, the F, Rayleigh, and Chi-Squared distributions of the GFMM explains that two nodes will not travel in the same direction or speed. Thus the three plots on the graph are lower than the RPGM model. The three distributions are lower because in the GFMM, our calculation when generating a scenario file considers that a neighbor can exert a force on a node within a threshold distance. As explained, this force can change the direction of the nodes preventing overlap and collision. Also, the figure explains the loose and tight characteristics of a group based on our distribution functions. Figure 8 directly reflects the graphs in Figure 1. (In order from bottom to top) The Chi-squared equation represents a loose group format of the nodes. Explained

in the context of spatial dependence-this means that a loose group distribution is a greater representation of nodes not travel in the same direction or speed. Thus the spatial correlation of the Chi-squared distribution is the least of all the plots. The Rayleigh distribution is slightly tighter than the Chi-squared plot, and the F Distribution is the tightest of the three. Again, since the RPGM model is less realistic and allows nodes to overlap, collide, and not change direction, it has the highest.

Similar to the evaluation done for the IMPORTANT framework the temporal dependence and link changes didn't prove to show a difference in the RPGM and GFMM patterns.

B.2 Average Link Duration

The *link_analysis* tool also calculates the time in seconds that there is a communication link between a pair of nodes. This is averaged over the total number of link pairs. This is categorized as link duration.

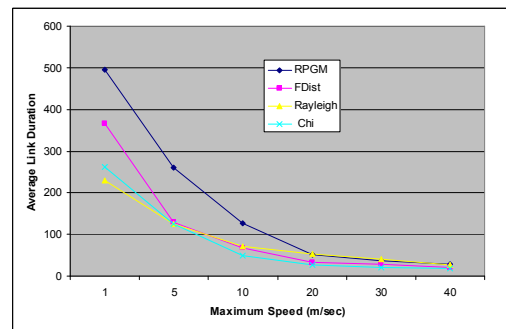


Figure 9. Average Link Duration

Figure 9 represents the duration (in seconds) of the communication between two nodes. Since our results are lower, this shows that a node pair will communicate and remain connected for a shorter amount of time throughout the movement of the group for all three distributions. Again this is a more realistic representation of the activity between mobile nodes or users. The RPGM model has a higher duration because this value is related to the relative speed of the nodes and the direction of motion [5]. In the RPGM model the relative speed of the nodes is a small deviation from the group leader, and the direction of motion for nodes in a group does not change significantly. Essentially, a smaller deviation in speed from the group leader and less change in direction of motion equates to a larger value for the average link duration because there are more nodes that remain in a communication threshold. Ideally, nodes in a group should have a larger degree of freedom for relative speeds since the velocity of the nodes may have to change to avoid one another. In addition, for the GFMM the nodes will constantly change direction to avoid collisions with other nodes and resulting in the link duration being less as the nodes move.

VI. CONCLUSION AND FUTURE WORK

In this paper, we propose a new methodology to simulate a more realistic model to illustrate mobility in nodes. In conjunction, we eliminate some limitations that which many mobility models fail to address and that is the ability to adapt to an environment stimuli. These environmental changes, as discussed previously, are such things as collision avoidance and congestion.

Furthermore, we examine group behavior between MNs and introduce a force model concept. This concept explains the characteristic of MNs exerting forces between one another within a

threshold radius. As a result this causes the MN to change direction either permanently or temporarily to avoid simulation overlap or collision.

To explain the effectiveness of the newly proposed methodology a comparison of protocol independent metrics of the Reference Point Group Model examined in [2] versus our Group Force Mobility Model. The results concluded that our system introduces a more stable and realistic simulation of group mobility based on spatial correlation and link duration. Future work plans to demonstrate this further with more comparative metrics and enhancements to the model.

In summary, we propose a new methodology which uses force mobility to capture a more realistic depiction of real world interaction between mobile users and directly address some limitations that previous simulations did not. Such limitations are collision avoidance, congestion avoidance, and the overall interaction between MNs in a group that is tightly or loosely coupled.

Currently, the mobile nodes in the GFMM only change direction based on these attraction and repulsion forces from other nodes. In the future, we plan to program the MNs to change its velocity in accordance to the activity of neighboring nodes. Realistically, in addition to changing direction, a mobile node may have to increase or decrease its speed to avoid collision with other mobile nodes; to avoid overlapping; or even to leave a group or to join a desired group moving to a shared destination.

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APPENDIX

A. Social Force Model

In our situation, it is important that agents can move in arbitrary directions without artifacts caused by the modeling technique. The social force model (HELBING et al., [8]) is a generic coupled differential equation model for pedestrian movement. We propose the modified model as following:

$$m_i \frac{dv_i}{dt} = m_i \frac{v_i^0 - v_i}{\tau_i} + \sum_{j \neq i} f_{ij} + \sum_W f_{iW} ,$$

where m_i is the mass of the pedestrian and v_i its velocity. v_i^0 is its desired velocity.

In consequence, the first term on the models is the exponential approach to the desired velocity, with a time constant τ_i . The second term on the model is the interaction between mobile users; and the third item on the model is the interaction of the mobile user with the environment. The specific mathematical form of the interaction term does not seem to be critical for our applications as long as it decays fast enough. Fast decay is crucial in order for the users to cut off the interaction at relatively short distances. This is important not only for efficient computing, but plausible with respect to the real world. For instance, mobile users at a distance of several hundred meters will not affect a mobile user even if they are at a very high density level.

Exponential force decay is given as follows:

$$f_{ij} = A_{ij} \exp\left(\frac{r_{ij} - d_{ij}}{B_{ij}}\right) \frac{r_i - r_j}{d_{ij}} ,$$

where f_{ij} is the force contribution of mobile user j to mobile user i ; r_i and r_j is the position of mobile users i and j , $d_{ij} = |r_i - r_j|$, $r_{ij} = r_i + r_j$ is the sum of their radii, A_{ij}, B_{ij} are constants.

For the environmental forces, f_{iW} is given as follows:

$$f_{iW} = A_{iW} \exp\left(\frac{r_{iW} - d_{iW}}{B_{iW}}\right) \frac{r_i - r_W}{d_{iW}} ,$$

where W represent environmental object force, such as walls.

B. Distributions of Force Model

Here, we present the force distributions (*Exppdf(x,μ)*, *Chi2pdf(x,ν)*, *Raleighpdf(x,B)*, and *Fpdf(x,ν1,ν2)*) used in our group force model. For detailed presentation on these distributions, see Appendix B. All parameter values can be vectors, matrices, or arrays of multiple dimensions (all with same size). The probability density functions for equations (3) thru (5) are as follows:

Chi-squared pdf is

$$y = f(x | v) = \frac{x^{(v-2)/2} e^{-x/2}}{2^{v/2} \Gamma(v/2)}, \quad (8)$$

where $\Gamma(\dots)$ is the Gamma function.

Rayleigh pdf is

$$y = f(x | b) = \frac{x}{b^2} e^{-\frac{x^2}{2b^2}}. \quad (9)$$

F pdf is

$$y = f(x | v_1, v_2) = \frac{\Gamma\left[\frac{(v_1 + v_2)}{2}\right]}{\Gamma\left(\frac{v_1}{2}\right)\Gamma\left(\frac{v_2}{2}\right)} \left(\frac{v_1}{v_2}\right)^{\frac{v_1}{2}} \frac{x^{\frac{v_1-2}{2}}}{\left[1 + \left(\frac{v_1}{v_2}\right)x\right]^{\frac{(v_1+v_2)}{2}}}, \quad (10)$$

where v_1 and v_2 are positive integers and x exists in the interval $[0 \infty)$.

C. Performance Analysis (Definitions and Terminology)

The following is a list of definitions and terminology explained in [2] that will aid in understanding our methodology and results.

1. V : velocity of a node and $\vec{v}_i(t)$ is velocity vector for a node indicated by i at a time t .

2. SDR: Speed deviation ratio, it is used to control the deviation range of speeds of a node from the Group speed.

3. $RD(\vec{v}_1(t), \vec{v}_2(t'))$: Relative Direction (RD) (or cosine of angle) between two vectors. $\vec{v}_1(t)$ and $\vec{v}_2(t')$ is given by $\frac{\vec{v}_1(t) \cdot \vec{v}_2(t')}{|\vec{v}_1(t)| * |\vec{v}_2(t')|}$.

4. $SR(\vec{v}_1(t), \vec{v}_2(t'))$: Speed Direction (SD) between two vectors $\vec{v}_1(t)$ and $\vec{v}_2(t')$ is given by $\frac{\min|\vec{v}_1(t), \vec{v}_2(t')|}{\max|\vec{v}_1(t), \vec{v}_2(t')|}$

5. Degree of Spatial Dependence is the likeness of two nodes velocity if they are not too far distant from one another.

$$D_{spatial}(i, j, t) = RD(\vec{v}_i(t), \vec{v}_j(t)) \times SR(\vec{v}_i(t), \vec{v}_j(t)) \quad (11)$$

$D_{spatial}(i, j, t)$ will increase when both nodes i and j travel in virtually the same direction and speed. Consequently, if the Relative Direction or Speed Ratio decreases, then the $D_{spatial}(i, j, t)$ will decrease.

b. Degree of Temporal Dependence is the likeness of the speed of a node at a time t and t' .

$$D_{temporal}(i, t, t') = RD(\vec{v}_i(t), \vec{v}_i(t')) \times SR(\vec{v}_i(t), \vec{v}_i(t')) \quad (12)$$

$D_{temporal}(i, t, t')$ will increase when node travel in virtually the same direction and speed between a specific time interval.

Relatively, if the Relative Direction or Speed Ratio decreases, then the $D_{temporal}(i, t, t')$ will decrease.

c. The average link duration is the average time a link exists between two nodes.