

A Group Mobility Model for Ad Hoc Wireless Networks *

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Abstract

In this paper, we present a survey of various mobility models in both cellular networks and multi-hop networks. We show that group motion occurs frequently in ad hoc networks, and introduce a novel group mobility model - Reference Point Group Mobility (RPGM) - to represent the relationship among mobile hosts. RPGM can be readily applied to many existing applications. Moreover, by proper choice of parameters, RPGM can be used to model several mobility models which were previously proposed. One of the main themes of this paper is to investigate the impact of the mobility model on the performance of a specific network protocol or application. To this end, we have applied our RPGM model to two different network protocol scenarios, clustering and routing, and have evaluated network performance under different mobility patterns and for different protocol implementations. As expected, the results indicate that different mobility patterns affect the various protocols in different ways. In particular, the ranking of routing algorithms is influenced by the choice of mobility pattern.

1 Introduction

Ad hoc wireless networks are networks which do not rely on a pre-existing communication infrastructure. Rather, they maintain a dynamic interconnection topology between mobile users, often via multihopping. Ad hoc networks are expected to play an increasingly important role in future civilian and military settings where wireless access to a wired backbone is either ineffective or impossible. Ad hoc network applications range from collaborative, distributed mobile computing to disaster recovery (fire, flood, earthquake), law enforcement (crowd control, search and rescue)

and digital battlefield communications. Some key characteristics of these systems are team collaboration of large number of mobile units, limited bandwidth, the need for supporting multimedia real time traffic and low latency access to distributed resources (e.g., distributed database access for situation awareness in the battlefield).

The hosts in an ad hoc network move according to various patterns. Realistic models for the motion patterns are needed in simulation in order to evaluate system and protocol performance. Most of the earlier research on mobility patterns was based on cellular networks. Mobility patterns have been used to derive traffic and mobility prediction models in the study of various problems in cellular systems, such as handoff, location management, paging, registration, calling time, traffic load. Recently, mobility models have been explored also in ad hoc networks. While in cellular networks, mobility models are mainly focused on individual movements since communications are point to point rather than among groups; in ad hoc networks, communications are often among teams which tend to coordinate their movements (e.g., a firemen rescue team in a disaster recovery situation). Hence, the need arises for developing efficient and realistic group mobility models.

Clearly, mobility models are application dependent. Moreover, we expect that the various mobility patterns will affect the performance of different network protocols in different ways. Thus, we are developing a flexible mobility framework which allows us to model different applications and network scenarios (e.g., individual and group; cellular and ad hoc, etc.) and to identify the impact of mobility on different scenarios. The proposed mobility framework is called Reference Point Group Mobility (RPGM) model. In the model, mobile hosts are organized by groups according to their logical relationships. We study the impact of mobility on: (a) network topology connectivity and; (b) routing protocols. We use DSDV [18], AODV [17] and HSR [16] for the evaluation and comparison of routing scheme performance. Next, as we believe that a clustering infrastructure [9] can reduce the impact of topology changes on routing,

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we study the mobility impact on cluster stability as well.

This paper is organized as follows. A survey of mobility models both in cellular systems and ad hoc networks is given in section 2. Section 3 focuses on group mobility models. The Reference Point Group Mobility model is introduced and several mobility applications are described. The simulation results highlighting the influence of group mobility models on connectivity, cluster stability and routing performance are given in section 4. Section 5 concludes the paper.

2 Existing Mobility Models for Cellular and Ad Hoc Wireless Networks

In a wireless network, mobile hosts (MHs) can move in many different ways. Mobility models are commonly used to analyze newly designed systems or protocols in both cellular and ad hoc wireless networks. In cellular wireless networks, studies for mobility models not only aim at describing individual motion behaviors such as changes in direction and speed, but also consider the collective motion of all the mobiles relative to a geographical area (cell) over time. Models for ad hoc network mobility generally reflect the behavior of an individual mobile, or a group of mobiles. But there is no notion of collective movement of all mobiles with reference to a particular “cell”.

2.1 Mobility Models Used in Cellular networks

In a cellular wireless network there is a base station in the center of each cell. Calls originate or terminate in the service areas of the base stations. When MHs cross cell boundaries, call hand-offs occur. Based on host mobility, various research topics are addressed, such as, handoff, location management, paging, registration, calling time and traffic load. The mobility models are used for aggregated traffic estimation and for mobility tracking.

The most common model is the random walk model. It has been used by many authors such as Rubin [19], Zonoozi [21], Decker [8] and Bar-Noy [2]. The model describes individual movement relative to cells. In this model, a mobile host moves from its current position to the next position randomly. The speed and direction are picked uniformly from the numerical ranges $[v_{min}, v_{max}]$ and $[0, 2\pi]$ respectively. In a typical Markovian model [2] for one dimensional random walk, a MH in cell i is assumed to move to cells $i + 1$, $i - 1$ or to stay in cell i with given transition probabilities.

The random walk model has been used to investigate a broad set of different system parameters. For example, Rubin uses the random movement assumption to get the mean

cell sojourn time $E(S)$ first, then to derive many other system measures. Zonoozi conducts a systematic tracking of the random movement of a MH. At each instant, he partitions the whole area into several regions according to previous, current and next motion directions of a mobile host. He mathematically gives the conditions for movements from the current region into the next region. His tracking of mobility leads to the calculation of channel holding time and handover number. Decker characterizes an individual MH with the mean duration of stay in the current position and the probability of choosing a moving path. A pre-designed state-transit matrix can give the mobile host a motion pattern such as moving on a highway, on streets or just like a random pedestrian.

Haas [11] presents a Random Gauss-Markov model for cellular networks. His model includes the random-walk model (totally random) and the constant velocity model (zero randomness) as its two extreme cases.

Some mobility studies in cellular system focus on traffic modeling [15, 14] since the motion of mobile hosts affects the traffic load. A simple example [14] of this approach defines traffic passing between cells as a function of cell population. If the population of region i is P_i , the traffic passing between region i and j can be described as $T_{i,j} = K_{i,j}P_iP_j$. $K_{i,j}$ is the transit parameter. The model can be used to different scales, from world wide to nation wide or a metropolitan area.

2.2 Mobility Models Used in Ad hoc Networks

In ad hoc wireless mobile networks, the mobility models focus on the individual motion behavior between mobility epochs, which are the smallest time periods in a simulation in which a mobile host moves in a constant direction at a constant speed.

Many researchers use the random mobility model [21, 20]. According to this model, the speed and direction of motion in a new time interval have no relation to their past values in the previous epoch. This model can generate unrealistic mobile behavior such as sharp turning or sudden stopping.

Some authors use modified versions of the random mobility model. Basagni [3] describes the movement of MHs in their simulation for the DREAM protocol such that a MH has a random direction at every simulation clock tick, but a constant speed during the entire simulation period. The mobility model in Ko's simulation for the LAR routing protocol [13] allows MHs to move along a path which is made up of several segments. The segment lengths are exponentially distributed and the direction of each segment is randomly chosen. Speed is distributed uniformly between $[v - \alpha, v + \alpha]$. In Das's model [7], a node chooses

its speed, direction and distance based on a pre-defined distribution, then calculates its next destination and the time to reach it. When the node reaches that point, it calculates a new destination and time period to reach it again.

Johnson's Random Waypoint mobility model [12] is also an extension of random walk. This model breaks the entire movement of a MH into repeating pause and motion periods. A mobile host first stays at a location for a certain time then it moves to a new random-chosen destination at a speed uniformly distributed between $[0, \text{MaxSpeed}]$. Perkins [17] and Broch [5] also use this model.

Chiang's Markovian model [6] is another way to describe the random motion. States represent motion directions. The probability of maintaining the current state (or moving to another state) is specified in the transit matrix. Once in motion the MH is more likely to keep on going at the current direction and speed. This model is more realistic than the random model.

Similar to Chiang's Markovian model, other models [20, 10] consider the relationship between a mobile host's previous motion behavior and the current movement in speed and/or direction. In particular, Haas [10] presents an incremental model in which speed and direction of current movement randomly diverge from the previous speed and direction after each time increment. Namely, speed v and direction θ are expressed as below:

$$v(t + \Delta t) = \min[\max(v(t) + \Delta v, 0), V_{MAX}] \quad (1)$$

$$\theta(t + \Delta t) = \theta(t) + \Delta\theta \quad (2)$$

where Δv and $\Delta\theta$ are uniformly picked up from a reasonable data range of $[-A_{max}\Delta t, A_{max}\Delta t]$ and $[-\alpha\Delta t, \alpha\Delta t]$. A_{max} is the unit acceleration/deceleration and α is the maximal unit angular change.

Further, Sanchez [20] studies the relationship among MHs. This relationship exists while MHs move with the same purpose. As we can see in a disaster recovery, or a military deployment, several mobile hosts most likely move with a common objective. Two examples given by Sanchez are the Pursue model, where MHs try to move towards a target, and the Column model, which represents a searching activity.

From the above review we note that most existing cellular and ad hoc wireless mobility models describe independent motion behavior. In the next section we will develop a group mobility model for dependent behavior, which captures both motion dependence over time epochs and a relationship among MHs.

3 Group Mobility Model

As we mentioned in previous sections, the collaboration among members of the same team is common in an ad hoc

network (e.g., searching for a target). This team relationship makes it possible to partition the network into several groups, each with its own mobility behavior.

3.1 Previous Work

One of the first examples of group mobility is the Exponential Correlated Random (ECR) model proposed by BBN [4]. The model reproduces all possible movements, including individual and group, by adjusting the parameters of a motion function. The new position $\vec{b}(t + 1)$ is a function of the previous position \vec{b} , to which a random deviation \vec{r} is added.

$$b(t + 1) = b(t)e^{-\frac{1}{\tau}} + (\sigma\sqrt{1 - (e^{-\frac{1}{\tau}})^2})r, \quad (3)$$

Where: $b(t) = (r_t, \theta_t)$ is defined for a group or a node at time t ; τ adjusts the rate of change from old to new (small τ causes large change); r is a random Gaussian variable with a variance σ .

The parameters τ and σ vary from group to group. They drive the groups into different moving patterns. The ECR mobility model requires a complete set of (τ, σ) (one per group) to define the motion of the entire network. The drawback is that it is not easy to force a given motion pattern by selecting the parameters.

3.2 Reference Point Group Mobility model

The group mobility model we proposed here is called Reference Point Group Mobility (RPGM) model. Each group has a logical "center". The center's motion defines the entire group's motion behavior, including location, speed, direction, acceleration, etc.. Thus, the group trajectory is determined by providing a path for the center. Usually, nodes are uniformly distributed within the geographic scope of a group. To node, each is assigned a reference point which follows the group movement. A node is randomly placed in the neighborhood of its reference point at each step. The reference point scheme allows independent random motion behavior for each node, in addition to the group motion.

Figure 1 gives an example of a two-group model. Each group has a group motion vector \vec{V}_{g_i} . The figure also gives an illustration of how a node moves from time tick τ to $\tau + 1$. First, the reference point of a node moves from $RP(\tau)$ to $RP(\tau + 1)$ with the group motion vector \vec{GM} (Here, $\vec{GM} = \vec{V}_{g_i}$). Then the new node position is generated by adding a random motion vector \vec{RM} to the new reference point $RP(\tau + 1)$. Vector \vec{RM} has its length uniformly distributed within a certain radius centered at the reference point and its direction uniformly distributed between

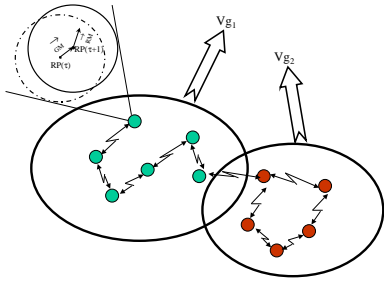


Figure 1. Group Mobility Model

0 to 360 degree. This random vector \overrightarrow{RM} is independent from the node's previous location.

The RPGM model defines the motion of groups explicitly by giving a motion path for each group. A path which a group will follow is given by defining a sequence of check points along the path corresponding to given time intervals. As time goes by, a group moves from one check point to the next on a continuing basis. Each time the group center reaches a new check point, it computes the new motion vector $\overrightarrow{V_{g_i}}$ from current and next check point locations and from the time interval.

By proper selection of check points, one can easily model many realistic situations, where a group must reach predefined destinations within given time intervals to accomplish its task. The check point scenario file has the advantage of decoupling the motion pattern from the model itself. Many methods can be used to generate a scenario file, such as, typing in manually, digitizing a route from a map, using outputs from a program or a profile from real world. The model has the advantages of providing a general and flexible framework for describing mobility patterns, which are task oriented and time restricted as well as easy to implement and verify.

3.3 Various Applications of the Reference Point Group Mobility Model

By proper selection of check point path and initial group location and parameters in the RPGM model, it is easy to model various mobility applications. In this section, we illustrate the use of RPGM in a few representative cases.

The first model is a geographical partition model (see Figure 2). The entire area is divided into several adjacent regions, with a different group in each region. This model can be used to model a battlefield situation, where different battalions are carrying out same operations(e.g., land mine search) in different areas. Each group is in charge of one partition. Another application can be large scale disaster recovery, where different paramedic, police, firemen teams work in separated neighborhoods. We call this model an

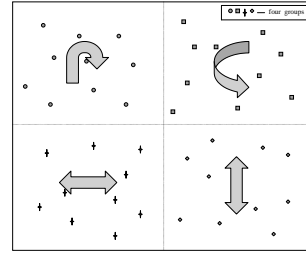


Figure 2. In-Place Mobility Model

In-Place Group Model. Figure 2 gives an example of four groups working in four adjacent areas, with different motion patterns.

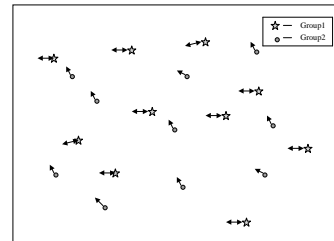


Figure 3. Overlap Mobility Model

The second model describes an overlapped operation. Different groups carry out different tasks over the same area. However, the distinct requirements of each task make their mobility pattern quite different. For example, in a disaster recovery area, the rescue team, the medical assistant team and the psychologist team will be randomly spread out over the area. Yet, each group has a unique motion pattern, speed, scope etc.. In Figure 3, there are two groups working in the same area. We call this model the Overlap Mobility Model.

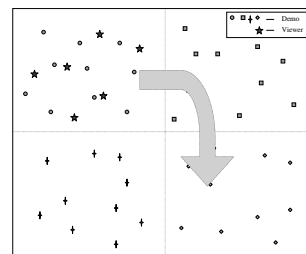


Figure 4. Convention Mobility Model

The third model is a convention scenario. It mod-

els the interaction between exhibitors and attendees. In a convention, several groups give demos of their research projects/products in separate but connecting rooms. A group of attendees roams from room to room. They may stop in one room for a while and then move on to another room. Or, they may pass through one room quickly. Figure 4 shows a group of attendees roaming around four exhibit rooms. This is called the Convention Model.

Other more complex scenarios which can be modeled with RPGM include: (a) a military maneuver with joint aircraft, tank and infantry operations. Each asset has a different mobility pattern which can be handled with check point path profiles; (b) a two-level mobility model, for example infantry and helicopters, with slow and fast nodes, etc..

A road map can be easily translated into RPGM check point format. Thus, mobility on highways can also be modeled by RPGM. For example, the Convention Model could also be used to reflect the roaming behavior of drivers on a road network.

4 Performance with Group Mobility

In a wireless, ad hoc multi-hop network, even relatively small movements of the nodes can cause noticeable changes in network topology and thus affect the performance of upper layer protocols, such as, throughput and delay. Ad hoc networks are more sensitive to mobility than cellular wireless networks since in the latter the topology changes only when a node leaves the cell, irrespective of relative connectivity with other mobiles. Using the group models introduced in the previous section, we study in this section the impact of mobility on the performance of various architectures, protocols and communication patterns.

4.1 Performance Metrics

Here we define several metrics related to mobility. We first monitor the change in link status (up, down) caused by the motion of nodes. When two nodes previously within the transmission range (assuming they have same transmission range) move far away, the connection is lost. This event increments a link down counter. Vice versa, when two nodes move into the transmission range, a connection is gained. This is a link up case. So we evaluate how the mobility affects the link up/down dynamics.

Then, we will look at how mobility affects a clustered infrastructure. As the clusterhead [9] serves as a regional broadcast node across clusters and as a local coordinator of transmissions within the cluster, we evaluate the clusterhead change rate. A high clusterhead change rate means an unstable network infrastructure for upper layer.

Finally, we observe how routing schemes will perform under various mobility models. We evaluate the perfor-

mance of routing protocols in two ways: (a) end-to-end throughput (kbits over 200-second simulation period) and; (b) control overhead. The control overhead is measured as megabits per second per cluster in the cluster infrastructure. With mobility, physically available routes may become invalid (i.e., may not be found by the routing algorithm), causing packets to be dropped and leading to throughput degradation and increasing control overhead.

The routing protocols used are Destination-Sequence Distance Vector (DSDV) [18], Ad hoc On Demand Distance Vector Routing (AODV) [17], and the Hierarchical State Routing (HSR) [16]. Since only mobility will produce link up/down and will affect clustering, the choice of a specific routing protocol has no effect on link up/down and cluster metrics. Thus a simple Bellman Ford routing scheme is used in the two latter experiments.

The mobility reported in the performance diagrams is based on average group speed and on mean motion displacement of nodes around their reference points.

4.2 Simulation Environment

We use a multi-hop, mobile wireless network simulation model with a clustered infrastructure. The simulator is written in the parallel simulation language Maisie [1]. The network consists of 100 mobile hosts roaming in a 1000x1000 meter square with a reflecting boundary. The radio transmission range is 120 meters. The data rate is 2Mb/s. Packet lengths are 10 kbits for data, 2 kbits for clusterhead neighboring list broadcast, and 500 bits for MAC control packets. The buffer size at each node is 100 packets. Data packets are generated following a Poisson process with an average interval of 50 ms. The experiments will transmit a file of 1000 packets from 10 sources to 10 destinations in 200 seconds, and measure the effective throughput with increasing mobility range.

We use four groups in the In-Place Model. The simulation area is divided into 4 regions as shown in Figure 2. Each group moves around in one region. We also use four groups in the Overlap Model, but each group scatters over the entire area. Two of the four groups move in a circular pattern in different direction. One group moves linearly, back and forth. The last group is almost static. In the Convention Model, we have four exhibitor groups moving slowly in each of the four partitions as in the In-Place Model. We also have one viewer group, which roams around the entire area. For the experiments with HSR, we choose the fixed logical subnet size, i.e., 25 members in each subnet and a total 4 subnets. To make the results comparable, group configurations and paths are identical for the three routing protocols.

4.3 Simulation Results

4.3.1 Network Topology

Figure 5 shows the result of the link up/down experiment. When mobility increases, all the models show an increase in the link up/down rate. As expected, the random mobility model has a higher link change rate than the group mobility models. The Convention Model shows the smallest link change rate, since the four exhibit groups move slowly. The In-Place Model and Overlap Model have different motion patterns, but they have similar link change rates.

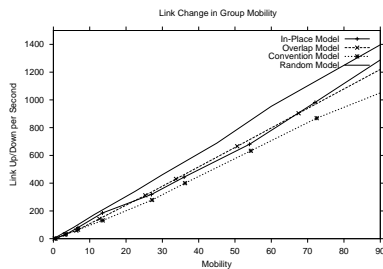


Figure 5. Link Up/Down vs. Mobility

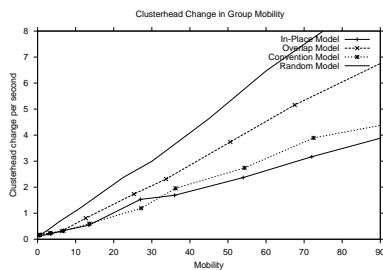


Figure 6. Clusterhead Changing vs. Mobility

The result of clusterhead change rate is shown in Figure 6. From Figure 6, we can see that the Random mobility model has a higher change rate than the group mobility models as already noticed in the link up/down experiment. However, in this case different group mobility models can have different effects on the change rate. The rate of the Overlap Model is much higher than in the In-Place Model and the Convention Model. According to the model description of the Overlap Model, many groups (four groups in simulation) have activities in the same field. Thus, the intermixing of the four groups generates more opportunities for cluster re-election (recall that the clusterhead is the node with lowest id among its neighbors [9]). Contrarily, the In-Place Model only allows each group to move within its own geographical area, with fewer cluster change opportunities.

4.3.2 Throughput of Routing Protocols

In most experiments for performance evaluation, we assume that members communicate randomly across group, with uniform probability. However, since the very notion of groups suggests that the interaction (i.e., communications) is mostly within each group, it is natural to consider also the case of intra-group communications only. We use the Convention Model for this experiment, with traffic only within the roaming group (“Local Scope Model”). While the roaming group comes in contact with other groups or subnets, the members of other groups will affect its topology and change the internal routing tables. But will not interfere with its traffic.

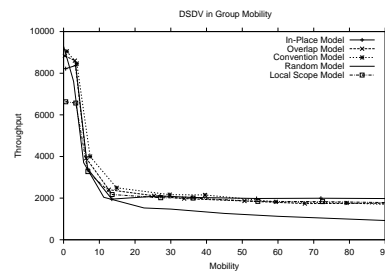


Figure 7. Throughput of DSDV vs. Mobility

In Figure 7, the throughput results of DSDV are reported. DSDV degrades fast when the mobility increases no matter which mobility model is used. The throughput remains at a low level after mobility exceeds 15 km/h. As expected The Random mobility model is worse than the group models. DSDV’s poor performance is due to heavy control message overhead.

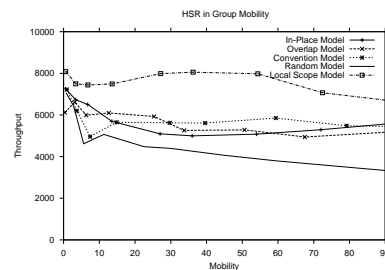


Figure 8. Throughput of HSR vs. Mobility

The throughput of HSR is given in Figure 8. The random mobility model has lower throughput than the group mobility models. This is because the subnet hierarchical structure of HSR can match well the group motion. The throughput of group mobility models does not decrease too drastically when the mobility increases, though the clusterhead change

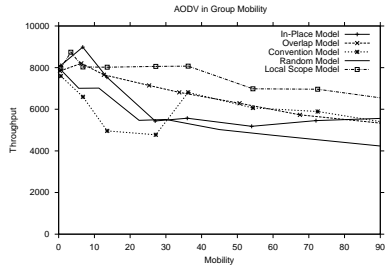


Figure 9. Throughput of AODV vs. Mobility

rate increases when the mobility increases. This stability comes from the subnet hierarchical structure and the home agent facilities [16]. When the traffic is restricted within a group in the Local Scope Model experiment, the throughput is the highest as expected.

Figure 9 presents the throughput of AODV in various mobility models. When the routing requests and destinations are localized within the roaming group (i.e., Local Scope Model), AODV has very good performance. In the other models, the sessions are generated between arbitrary pairs of nodes across the entire network. Recall that AODV does not maintain background routing tables. Rather, it computes routes for each new request. The performance curves for different mobility patterns are thus more irregular than those for DSDV and HSR. For the Local Scope Model, performance of AODV is enhanced by the fact that paths are preserved (and therefore remembered) longer than in the other cases. Thus, routing is more effective and fewer packets are dropped. In general, AODV provides a throughput level comparable to HSR.

4.3.3 Control Overhead of Routing Protocols

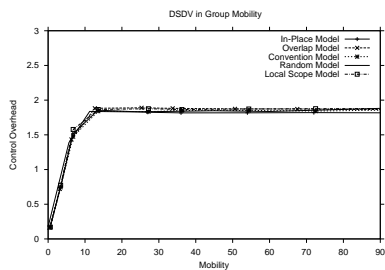


Figure 10. Control Overhead of DSDV vs. Mobility

Figure 10 shows the overhead in DSDV. DSDV has high control overhead because of the exchange of routing updates. Overhead traffic peaks at 15 km/h, where it takes

over just about all the available bandwidth (2Mbps/cluster)! The results is consistent with DSDV throughput (Figure 7). DSDV's excessive route control overhead is practically independent of the mobility pattern.

The overhead of HSR is given in Figure 11. The overhead of all the mobility models increases when the mobility increases. But the level of overhead is very low, less than 10 percent of cluster capacity. For the Local Scope Model, the overhead is the smallest. The features of HSR reduced the impact of topology change and clusterhead change on control overhead.

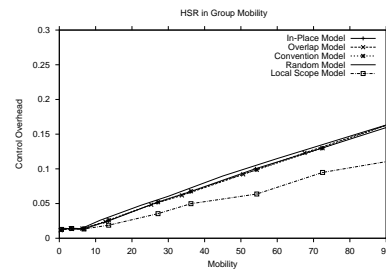


Figure 11. Control Overhead of HSR vs. Mobility

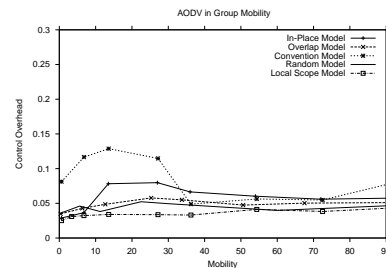


Figure 12. Control Overhead of AODV vs. Mobility

Figure 12 presents the control overhead of AODV in various mobility models. In Local Scope Model, AODV has very low overhead. It is quite reasonable according to the scenario and is consistent with the high throughput shown in Figure 9. With the remaining mobility patterns, the overhead behavior is consistent with the throughput behavior, i.e., it is more irregular than those for DSDV and HSR.

These experiments show that the mobility models will affect different protocols in different ways. It appears that the Random Model leads to the worse performance in most cases (at least for the set of routing protocols selected in this comparison). Group mobility can improve performance

considerably, especially if the routing protocol can take advantage of some of the group mobility features (as is the case of HSR and AODV with Local Scope Model).

5 Conclusion

In this paper we proposed a group mobility model - Reference Point Group Mobility model. The model organizes mobile hosts into groups according to their logical relationships. Simulation results show that the choice of the mobility model makes a difference in the physical link dynamics and the cluster stability. The Random model generates higher rate of change in connectivity than group models. Likewise, Random and Overlap models cause more intermixing (than other group models) and thus more cluster-head changes. Further, different routing protocols have different reactions to the mobility models. In AODV and HSR when communications are restricted within the scope of a group, the throughput improves. DSDV, on the other hand, shows little sensitivity to group mobility and to localized communications.

These results show that, when an ad hoc network is deployed in a real situation, it is not sufficient to test it with random walk type mobility models since the motion pattern can interact in a generally positive, but sometimes negative way with network protocols.

Further work is in progress in several directions. Multicast protocols are being tested, as they stand to get the most impact from group mobility. Home Agent schemes and Resource Discovery techniques are also influenced by group mobility. The impact of motion on channel propagation must be investigated (by using appropriate radio propagation models) in order to obtain a realistic match with actual testbed experiments. Finally, terrain models (hills, rivers, highways, urban roads, buildings, indoor partition layouts, etc.) must be accounted for in that they both constrain movements and influence the propagation models.

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