

Heterogeneous Mobility Models and Their Impact on Data Dissemination in Mobile Ad-hoc Networks

Sven Bittner, Wolf-Ulrich Raffel and Manuel Scholz

Technical Report

August 20, 2004

Abstract

When analyzing dissemination protocols in mobile ad-hoc networks the underlying mobility model is an important factor because it strongly influences the performance of these protocols. So far most of the research only dealt with homogeneous mobility models like the very common Random Waypoint Mobility Model and the Random Walk Mobility Model. In this paper we introduce a new model, the Area Graph-based Mobility Model, which considers the major characteristics of realistic scenarios like their heterogeneity. By analyzing the results of experiments using different broadcast protocols and by comparing our model to the Random Waypoint Mobility Model we examine the characteristics of the Area Graph-based Mobility Model. Furthermore we show, that in heterogeneous scenarios you should use adaptive broadcast protocols, otherwise an efficient dissemination in areas with differing topologies and densities is not possible.

1 Introduction

Due to recent developments in computer technology, such as the advances in the area of small computing devices (laptops, PDAs) and the rapidly growing use of wireless transmission technologies the issue "mobility" becomes more and more important. Thus especially in the area of mobile data management a huge variety of research opportunities are at hand. A current example are Mobile Ad-hoc Networks (MANETs), which are decentralized and unstructured peer-to-peer networks and spontaneously build up connections among mobile devices by using wireless technologies. A typical characteristic of these networks is their dynamic behavior due to the mobility and the unreliability of the network nodes. A MANET has no fixed structure or topology because the connections between

the nodes are changing continuously. Hence many of the well known algorithms for static networks can only be used limitedly or sometimes not at all.

A typical and common operation in MANETs is the broadcast (dissemination to all nodes of the network) of data or messages. Many routing protocols (e.g. DSR [1], AODV [2]) are using broadcasts to establish their routes. Further examples for broadcasts are the dissemination of software updates and the replication of data. To simulate the dissemination of data inside a MANET you always need an underlying mobility model which simulates the motion of the network nodes. In this paper we introduce a new heterogeneous mobility model and show the results of an experimental study of broadcast protocols by using this model.

Today many of the studies of MANETs [3, 4] use homogeneous mobility models such as the Random Walk [5] or Random Waypoint Model [1, 6]. Nearly all of these models have in common that they do not consider many of the characteristics of real scenarios. Other approaches [5, 7] design very specialized mobility models which simulate a specific scenario in a very detailed way. So the experimental results of these models give a very exact picture of the real behavior. But this specialization is also the drawback of these models because they only give results for a special scenario which often cannot be generalized.

The Area Graph-based Mobility Model introduced in this paper, is a model which maintains the main aspects of real scenarios without being too specialized. This mobility model is based on a directed graph with areas of different densities and therefore preserves the heterogeneous structure of real settings which is an important aspect. If you take a look at real scenarios like an exhibition or the campus of a university (where MANETs could build up) you will see that there are many buildings and areas such as exhibition halls and lecture auditoriums in contrast to small aisles and long paths having different network densities.

To show the difference of the dissemination behavior between the heterogeneous Area Graph-based Mobility Model and the homogeneous Random Waypoint Mobility Model we present the results of experimental studies concerning both models. Furthermore we show the necessity of adaptive protocols in case of heterogeneous scenarios.

The paper is structured as follows: In Sect. 2 we give a brief overview of the related work. Section 3 presents the examined broadcast protocols and in Sect. 4 we introduce the new Area Graph-based Mobility Model and remind the Random Waypoint Mobility Model. Section 5 discusses the experimental results using both models. We summarize this paper and give an outlook for future work in Sect. 6.

2 Related Work

Today there are mainly two categories of mobility models: simple homogeneous models and more complex topology-based models.

The most common homogeneous models are the Random Walk Mobility Model [5] and Random Waypoint Mobility Model [1, 6]. They both simulate

the motion of nodes on a rectangular area. The Random Direction Mobility Model [8] is a refinement of the Random Waypoint Mobility Model which determines a random direction instead of a random waypoint. This avoids the typical clustering in the center of the rectangular area [6] when using the Random Waypoint Mobility Model. The Boundless Simulation Area Model [9] extends these models by allowing the nodes to appear on the opposite side of the simulation area if they reach a border.

The City Section Mobility Model [5] simulates motions on a Manhattan topology. In this model nodes move on streets, randomly choose destination points and follow the shortest ways to them. This model only simulates scenarios with a Manhattan topology and thus its results cannot be generalized. In [7] the Obstacle Mobility Model is presented to simulate real world topographies with obstacles and pathways. It is also designed to model very specific scenarios and incorporates the propagation of radio signals according to the obstacles placed.

The Graph-Based Mobility Model [10] maps the topology of a scenario by using a graph to define the motion of the nodes. It is more flexible than the City Section Mobility Model, but it also does not consider clusters with different topologies and densities.

There are various other models, such as [11,12] which try to simulate different behaviors of the nodes and smooth movements. It is very questionable whether these ideas have a strong impact on the results of simulations because a small change of a node's behavior hardly influences the overall results.

Finally you can say that current mobility models either create homogeneous areas or they are very specialized solutions to simulate very specific scenarios or topologies. A third approach is the detailed simulation of the exact motion of the nodes which does not seem to have a strong impact on the overall results.

What is still missing is a mobility model which maps the reality better than the homogeneous ones but allows more general results than the sophisticated solutions. In the following sections we try to solve this problem by introducing a mobility model that creates a heterogeneous topology but is easy to configure and results in general statements about tested protocols.

3 Broadcast Protocols

When disseminating data in a network (broadcast) it is the primary goal to reach as many nodes as possible. Furthermore the network load (i.e. the number of messages you need to disseminate the data) has to be considered. Especially in mobile networks the network load is a crucial factor because the network nodes generally only have limited resources (bandwidth, energy). Therefore an efficient broadcast protocol should reach many nodes and should have a small ratio between messages processed and number of nodes reached.

In the following subsections we introduce the broadcast protocols which we use in our experiments. We use very common and relevant broadcast protocols [3,4] in order to have a good comparison to other related works.

All network nodes are using a message history. The protocols use this history

to know whether the data of a message is new or has reached the node before. In the latter case the node will not resend the data to prevent infinite message forwarding.

3.1 Simple Flooding

When disseminating data using simple flooding [13] a starting node sends the data to all its neighbors, i.e. all directly reachable nodes. Every node which receives this data is sending the data to all its neighbors as well. Because of the message history of the nodes the dissemination stops at the latest when the data is delivered to all reachable nodes.

Because of its simplicity and the high redundancy of messages the simple flooding protocol is a very robust way to disseminate data in a network and is therefore suitable for highly dynamic and unreliable networks.

3.2 Probabilistic Flooding

When disseminating data using probabilistic flooding [3] a starting node broadcasts the data to all its neighbors. Every node which receives the data is only resending it with a given probability p , but when resending the data the node sends it to all its neighbors. Because of the characteristics of wireless technology (radio signals) this is causing no extra costs. Thus the limitation of the resending nodes is more reasonable than the limitation of the addressed neighbors. The probability value p for resending the data is fixed. If the value is 1, the protocol behaves like simple flooding. Generally you can say that if p has a small value less nodes resend the data and if p has a large value more nodes are resending.

3.3 Adaptive Probabilistic Flooding

Like the probabilistic flooding the dissemination of the adaptive probabilistic flooding is based on a probability value p . Unlike to the probabilistic flooding the value is not fixed but adapts to the local density of the network. It depends on the number of neighbors n_s of the sending node s and the number of neighbors n_r of the receiving (possibly resending) node r . We assume that the number of neighbors is known to the protocol, e.g. by the use of regular hello messages.

The calculation of the probability value p , which is used to determine whether to resend a message or not, is done by a function. This function is limiting the number of resending nodes to a certain value because in dense networks a certain amount of resending nodes is sufficient. This number should be independent of the density and so a threshold value x (> 0) is used to specify the number of resending nodes. A simple function which satisfies these demands would be:

$$f: (\mathbb{N}, \mathbb{N}) \rightarrow (0, 1]$$
$$f: (n_s, n_r) \mapsto p = \min\left(1, \frac{x}{n_s}\right)$$

If n_s is below the threshold value x , i.e. the density is low, the probability value for resending a message will be 1 for all neighbors. Otherwise, the probabilistic value p is calculated that way, that the expected value of resending neighbors matches x .

In cases, in which the sending node has many neighbors, but the receiving has only few neighbors, a resending is very important. So we change n_s in the formula into $\min(n_s, n_r)$ to increase the probability of resending in these cases.

We also add a factor $\frac{\max(n_s, n_r)}{\min(n_s, n_r)}$ to our probability value p to increase the probability value at the transition between areas of high and low density because first experiments showed that they are difficult to handle. So

$$f: (\mathbb{N}, \mathbb{N}) \rightarrow (0, 1]$$

$$f: (n_s, n_r) \mapsto p = \min \left(1, \frac{x}{\min(n_s, n_r)} \cdot \frac{\max(n_s, n_r)}{\min(n_s, n_r)} \right)$$

is the final formula to be used in Adaptive Probabilistic Flooding.

3.4 Flooding with Self Pruning

Like the adaptive probabilistic flooding the flooding with self pruning [14] is using knowledge about the network neighbors of a node to broadcast the data more efficiently. By using this protocol we assume both unique identifications for the nodes and knowledge of these identifications of the neighbors in the network.

When a node receives the data it compares the neighbors of the sending node to its own neighbors. If the neighbors of the receiving node are a subset of the neighbors of the sending node, i.e. there is no new node which can be reached, the receiving node does not resend the data. Otherwise it resends the data to all its neighbors.

4 Mobility Models

In order to examine network protocols for MANETs you have to use an underlying mobility model which simulates the motion of the nodes. In this section we firstly introduce the homogeneous Random Waypoint Mobility Model. Secondly we present our heterogeneous Area Graph-based Mobility Model.

4.1 Random Waypoint Mobility Model

In this paper we use the common Random Waypoint Mobility Model [6] as a representative for homogeneous mobility models which are based on random motions inside a rectangular area. The Random Waypoint Mobility Model simulates the motion of network nodes by using uniformly distributed random waypoints on a rectangular plane. When reaching a waypoint a node is waiting for a random time t . After this time t has exceeded the node moves to the next

randomly chosen waypoint. The speed of the node and the waiting time t at the waypoints are random values uniformly distributed in a self-defined interval.

4.2 Area Graph-based Mobility Model

Our proposed Area Graph-based Mobility Model is using a graph as a boundary for the motion of the network nodes. Considering real scenarios you can see that they do not only consist of one area with equal density but of several clusters (with high density) and fixed paths (with low density) between them. Examples are a campus of a university (buildings - paths), a city (malls, cinemas - streets, paths) and an exhibition (exhibition halls - aisles). The characteristics of these scenarios are preserved by the Area Graph-based Mobility Model.

An area graph is a directed and weighted graph. It consists of several rectangular planes (vertices) and direct connections (edges) between them. The clusters are vertices and the paths are edges of an area graph. The weight of an edge is the probability of a network node choosing this edge when leaving the vertex. So the sum of all outgoing edges of a vertex is always 1. Every vertex of the area graph is given an interval which is used to determine the waiting time inside this vertex. The waiting time is chosen uniformly distributed from this interval.

The motion in the Area Graph-based Mobility Model consists of two parts: Motion inside vertices and motion between vertices. The motion inside vertices is according to the Random Waypoint Mobility Model with randomly chosen speeds and waypoints as explained above in Sect. 4.1. Other mobility models (see [5]) could also be used. The model for the motion between vertices behaves as follows: When a network node enters a vertex of the area graph the waiting time inside this vertex is determined randomly. When the waiting time is exceeded, an outgoing edge is chosen randomly concerning to the weights of the edges. Then the network node moves to the connection point of the vertex and the edge and thereafter moves with a randomly determined speed to the vertex chosen. The Area Graph-based Mobility Model only limits the motion of the nodes and not their radio signals. So it is possible to get network connections among different paths and areas even if they are not directly connected.

We now show an example to give a better understanding of the model. In Fig. 1 you can see a part of a typical campus of a university. We assume that the students use PDAs to communicate. There are two institutes, a cafeteria and a library. In this example the probabilities of the edges represent the students' behavior. On average 40% of the students leaving the library go to the Institute of Computer Science, 40% go to the Institute of Mathematics and 20% go directly to the cafeteria. From the cafeteria 20% of the students go to the library and the other students go to the institutes in the same proportions. In the library the students stay 1 - 2 hours, in the institutes they stay 2 - 3 hours and they pause 0.5 - 1 hour in the cafeteria. Also the areas of the buildings and the distances between them are pictured as the sizes of the planes and the lengths of the connections.

This behavior of the students results in 4 clusters and 6 connections between

them as it can be seen in Fig. 1. With the help of the Area Graph-based Mobility Model we can simulate this behavior of the students and retrieve their typical distribution on the campus. In the example the movement inside the building is according to the Random Waypoint Mobility Model. But you could also simulate the students' behavior inside the buildings more detailed with auditoriums and other rooms.

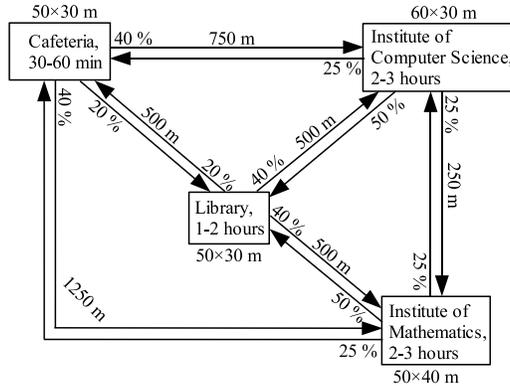


Figure 1: Example of an area graph

Although it is possible to construct such an area-graph which is quite close to a real scenario we avoid this in our experiments to get more general results about the influence of heterogeneity.

5 Experimental Studies

In this section we show the results of our experimental studies using the previously described mobility models. For every scenario we test the following protocols: simple flooding, flooding with self pruning, probabilistic flooding with probabilities p of 20%, 40%, 60% and 80% and adaptive probabilistic flooding with threshold values x of 5, 6, 7, 8, 9 and 10. Protocols with other threshold values x are not tested in detail because first experiments showed that they either reach an insufficient number of nodes ($x < 5$) or produce too many messages ($x > 10$). In the experiments we consider the following values to compare the protocols:

- **Delivery ratio:** The delivery ratio (relative number of nodes reached) indicates how much the data is spread throughout the network by the protocol. The delivery ratio strongly depends on the dynamic characteristics and the density of the network.
- **Message ratio:** The message ratio (ratio between messages processed and number of nodes reached) is a good indicator to show the efficiency

Table 1: Simulation parameters for all experiments

| Parameter | Value |
|--------------------|-----------|
| number of nodes | 2000 |
| transmission range | 30 m |
| bandwidth | 11 Mbit/s |
| message size | 400 byte |

of a particular protocol, i.e. the less messages a protocol needs the better its efficiency.

We run our experiments using both mobility models to compare broadcast protocols in different settings. Thus we obtain information about the influence of the mobility model on the efficiency of the protocols.

5.1 Parameters

Our experimental studies have been done using the simulator OMNeT++ [15]. The simulated network utilizes an IEEE 802.11 [16] conform MAC protocol. This MAC protocol follows a *Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)* scheme. The hidden node problem cannot be avoided that way, so it is still possible for two signals to interfere with each other and thus being destroyed. To avoid collisions because of parallel resending of two near nodes a random sending delay (0 - 0.3 s) is added. Thus the number of collisions has become much smaller in the experiments.

Furthermore we assume that every node has knowledge about the quantity (used by adaptive probabilistic flooding) and addresses (used by flooding with self pruning) of its neighbors. In reality this could be done by using hello messages like they are used in routing protocols (e.g. AODV [2]). For every experiment, i.e. a combination of protocol and scenario, we present the mean values of 500 single runs. In every single run we analyze the data dissemination from a randomly chosen starting node. In Table 1 we show the technical parameters of our experiments. We use 2000 network nodes with a transmission range of 30 m. We further assume a bandwidth of 11 Mbit/s and a message size of 400 byte of user data.

In the next section we describe and evaluate the experiments using the Random Waypoint Mobility Model and in Sect. 5.3 we use the Area Graph-based Mobility Model.

5.2 Experiments with the Random Waypoint Mobility Model

In the first scenario of our experiments we use the Random Waypoint Mobility Model. The scenario is divided into three sub-scenarios with areas of 400×400 m, 600×600 m and 800×800 m respectively. The speed of the nodes is $1 - 4 \frac{m}{s}$.

Table 2: Network density using the Random Waypoint Mobility Model

| Area size | \emptyset no. of neighbors |
|-----------|------------------------------|
| 400×400 m | 32.9 |
| 600×600 m | 14.9 |
| 800×800 m | 8.5 |

There is no waiting time at the waypoints, the nodes move onward at once. The choice of the waypoint is done by randomly choosing a direction, this avoids the problem of density clustering in the center of the area [6]. The measured density values of the three different areas are shown in Table 2 and range from 8.5 neighbors (using the largest area) to 32.9 neighbors (using the smallest area).

The results of the experiments are shown in Fig. 2. Every particular protocol is represented as a point in the coordinate system. The delivery ratio (relative value of nodes reached) is shown on the abscissa and the message ratio (number of messages per node reached) is shown on the ordinate. So a protocol located right and below another protocol is more efficient than the other.

When regarding the single results concerning the delivery ratio and the message ratio you can see that they are quite similar to the results of previous works [3, 4]. With an increasing density of the scenario (smaller area sizes) the protocols reach more nodes. The message ratio of the probabilistic flooding and of the simple flooding is increasing proportionally to the density of the scenario. Furthermore you can observe that using probabilistic flooding a higher probability value p produces a better delivery ratio but a higher message ratio as well.

In the scenario with a 400×400 m area (Fig. 2(a)) a probability value p of 40% is sufficient for a delivery ratio similar (less than 1% deviation) to flooding, but the message ratio is significantly better. In the scenario with a medium density (area of 600×600 m, see Fig. 2(b)) a probabilistic value p of at least 60% is needed for a similar delivery ratio and in the scenario with the low density (area of 800×800 m, see Fig. 2(c)) only the protocol with a probability value p of 80% has a delivery ratio similar (1% deviation) to flooding. Since the protocol with a probability value p of 80% has a high message ratio in the other sub-scenarios (400×400 m, 600×600 m), none of the probabilistic protocols is efficient in all of the three sub-scenarios.

Unlike the probabilistic protocols the message ratio of the adaptive probabilistic protocols is quite steady (maximum deviation 20%) and not behaving proportional to the network density. The reason is the probabilistic limitation of the number of resending nodes by the threshold x . Despite the low message ratio (especially for the dense scenario) all the adaptive probabilistic protocols have a delivery ratio similar to flooding (maximum deviation 2.8%). The lowest message ratio can be observed for the protocol with threshold value $x = 5$ because less neighbors resend the data.

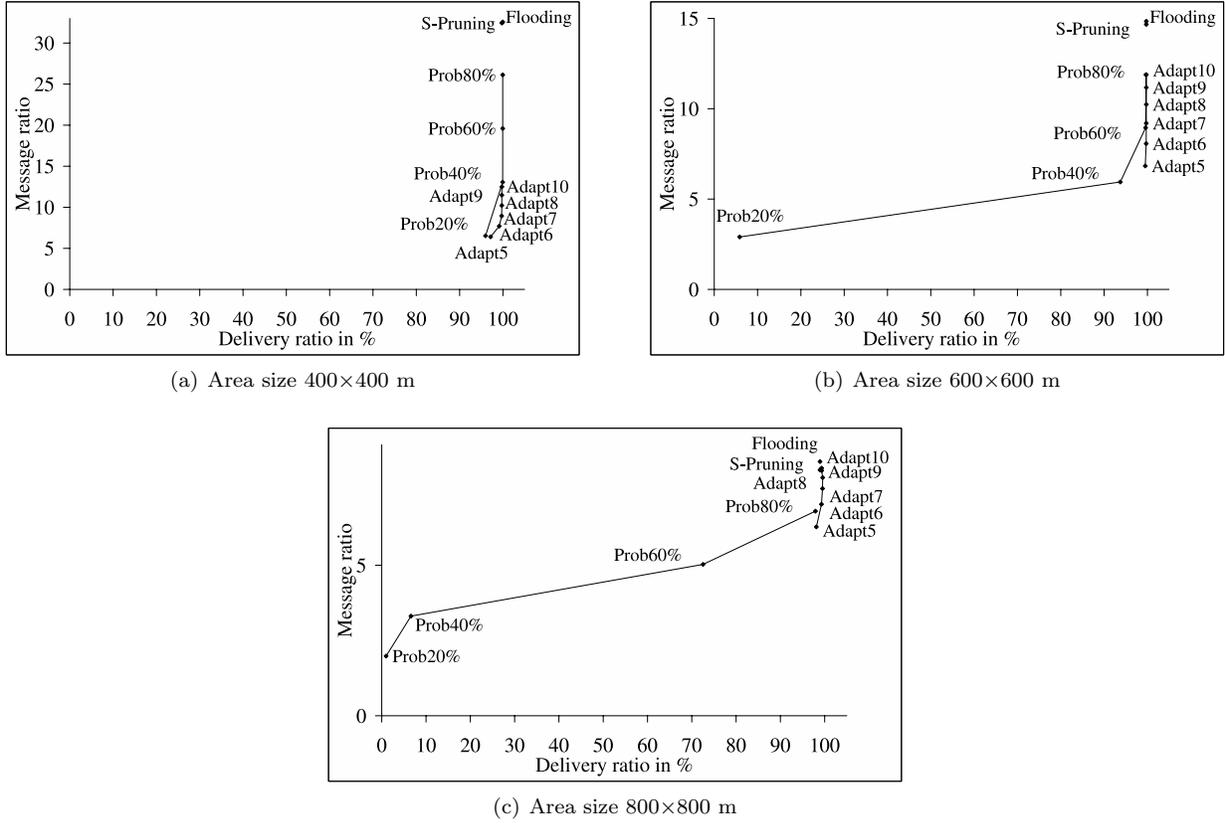


Figure 2: Results using the Random Waypoint Mobility Model

The flooding with self pruning protocol is very similar to the behavior of the simple flooding in both the delivery ratio and the message ratio. The impact of the saved messages is too small to give a significant better message ratio.

Concluding by considering the efficiency of the protocols you can observe big fluctuations for the probabilistic protocols. Often there is only one protocol which has a good delivery ratio and a passable message ratio. In contrast the adaptive probabilistic protocols are very efficient and nearly independent of the network density. Altogether using well adjusted parameters the probabilistic and the adaptive probabilistic protocols achieve maintainable performance using the Random Waypoint Mobility Model.

5.3 Experiments with the Area Graph-based Mobility Model

In this subsection we describe two scenarios of our experiments using the Area Graph-based Mobility Model and show their results. Although the Area Graph-

Table 3: Density of the sub-scenarios of scenario 1

| Area size | Waiting time | Ø no. of neighbors | | |
|-----------|--------------|--------------------|---------|-------|
| | | path | cluster | total |
| 200×200 m | 300-700 s | 20.9 | 32.7 | 29.0 |
| 200×200 m | 1000-1400 s | 11.7 | 30.3 | 27.1 |
| 300×300 m | 300-700 s | 20.2 | 24.1 | 22.9 |
| 300×300 m | 1000-1400 s | 11.2 | 18.6 | 17.4 |

based Mobility Model can be used to describe scenarios very detailed, here our goal is to extract general information about the behavior of protocols in heterogenous scenarios. So we do not use a special graph like in Fig. 1.

The first scenario shows the behavior of the protocols in a fictive, but realistic setting. The second scenario we choose to show the characteristics (like the influence of heterogeneity) of the Area Graph-based Mobility Model more clearly.

5.3.1 Scenario 1 - Circle

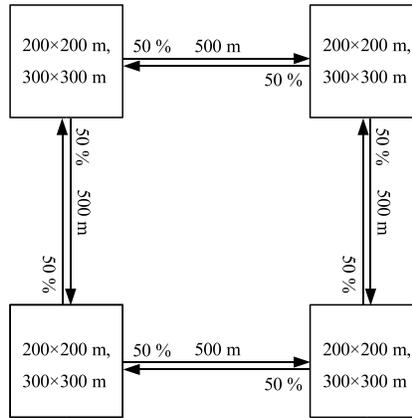
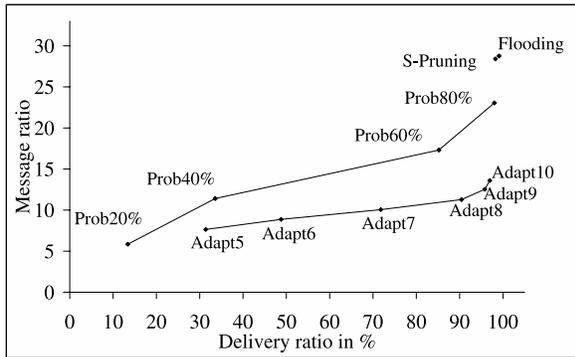


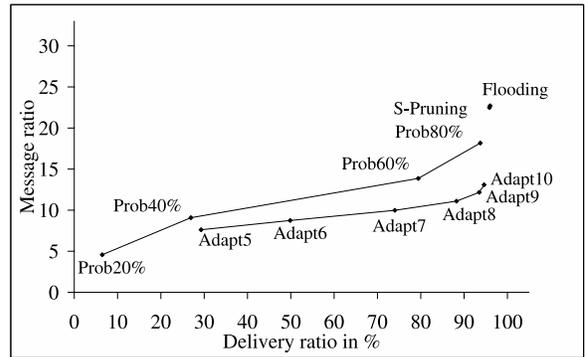
Figure 3: Circular area graph

For these experiments we use a scenario with 4 clusters and 4 connections which is shown in Fig. 3. The clusters and the connections are arranged in a circular way. The connections have a length of 500 m and the weights of the edges are labeled with 50%. That means that both connected clusters are chosen with the same probability if the current cluster is left by a node.

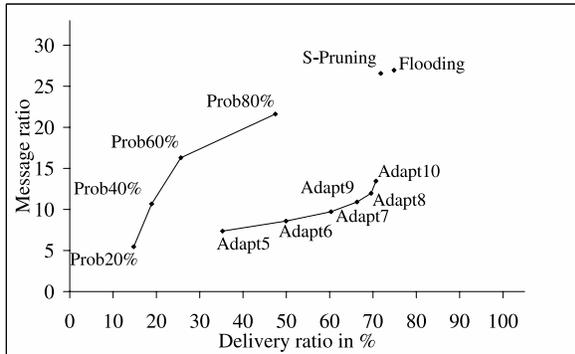
Altogether we are testing four different sub-scenarios (cluster sizes 200×200 m and 300×300 m, waiting time 300 - 700 s and 1000 - 1400 s). The parameters for the Random Waypoint Mobility Model inside the clusters are the same as in



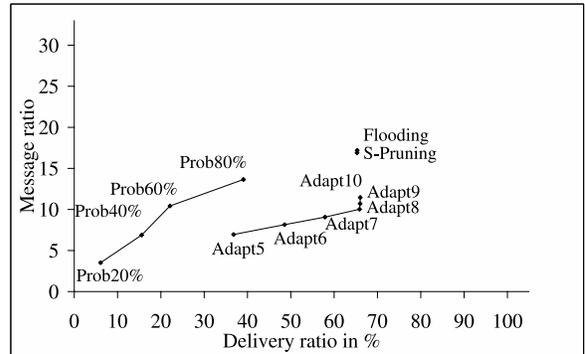
(a) 200x200 m, short waiting time



(b) 300x300 m, short waiting time



(c) 200x200 m, long waiting time



(d) 300x300 m, long waiting time

Figure 4: Results using the circular area graph

the first scenario in Sect. 5.2 (speed of the nodes $1 - 4 \frac{\text{m}}{\text{s}}$ and no waiting time). The parameters of the scenarios have been chosen to align to the characteristics (total area, density) of the first scenario to make them more comparable. The measured densities of the four sub-scenarios are given in Table 3. The difference between the clusters and the connections according to the network density ranges from 16% to 61% less neighbors on the connections compared to the neighbors in the clusters.

The main difference to the scenario using the Random Waypoint Mobility Model is the heterogeneity of this scenario. Every sub-scenario includes several areas with different topologies (plane, line) and densities. The results of the experiments are shown in Fig. 4.

Looking at the delivery ratios you can observe that in the two sub-scenarios with a low density on the paths (Fig. 4(c), Fig. 4(d)) at least 25% - 30% of the nodes have not been reached. In the sub-scenarios with a high density (Fig. 4(a), Fig. 4(b)) on the paths only one of the probabilistic protocols ($p = 80\%$) is having a delivery ratio similar to flooding (2 - 3% less). In the sub-scenarios with a low density no probabilistic protocol has an acceptable delivery ratio. Thus none of the probabilistic protocols has an acceptable delivery ratio in all sub-scenarios. Flooding has a good delivery ratio but its message ratio is much higher (factor 1.5 to 2.5) than the message ratio of adaptive probabilistic protocols having a similar delivery ratio.

The adaptive probabilistic protocols with the threshold values x of 9 and 10 are having delivery ratios similar (maximal 7% and 5% less respectively) to flooding. All other adaptive probabilistic protocols have lower delivery ratios. In comparison to the scenario using the Random Waypoint Mobility Model you can see that the threshold value for an efficient adaptive protocol has increased from 5 - 6 to 9 - 10 in this scenario. The reason for that is the topology of the paths and the transition areas. The transition areas (between the paths and the clusters) need more messages to ensure a good dissemination. As in Sect. 5.2 the self pruning protocol shows no significant difference to simple flooding.

Altogether the results of this scenario show that the adaptive probabilistic protocols with threshold values x of 9 and 10 are the only protocols being efficient. All other protocols are either having a low delivery ratio or a high message ratio. This is a strong contrast to the results obtained using the homogeneous Random Waypoint Mobility Model.

5.3.2 Scenario 2 - Line

Like in the experiments in Scenario 1 we use a setting with 4 clusters, now arranged in a line. We choose this setting to show the influence of the heterogeneity on the broadcast protocols more clearly. The scenario is shown in Fig. 5. Again the connections have a length of 500 m. In the inner clusters there are two possibilities to leave a cluster. If nodes are located at the outer clusters they can only follow 1 connection.

The setting contains four different sub-scenarios with varying parameters (cluster size 200×200 m and 300×300 m, waiting time from 300 - 700 s up

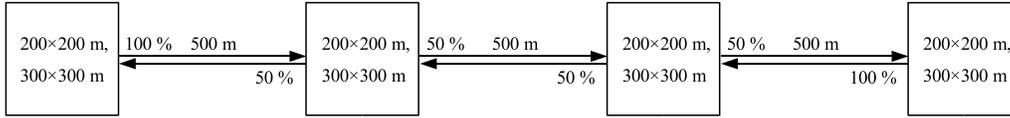


Figure 5: Linear area graph

Table 4: Density of the sub-scenarios of scenario 2

| Area size | Waiting time (inner, outer clusters) | Ø no. of neighbors | | |
|-----------|---|--------------------|--------|-------|
| | | path | clust. | total |
| 200×200 m | 300-700, 850-1250 s | 22.5 | 32.3 | 29.8 |
| 200×200 m | 1100-1500, 2400-2800 s | 11.5 | 28.8 | 26.6 |
| 300×300 m | 400-800, 950-1350 s | 20.0 | 24.3 | 23.3 |
| 300×300 m | 1000-1400, 2200-2600 s | 11.8 | 17.5 | 16.8 |

to 2400 - 2800 s). The dissemination always starts with the leftmost network node (in the leftmost cluster). So there is only one way for the messages to

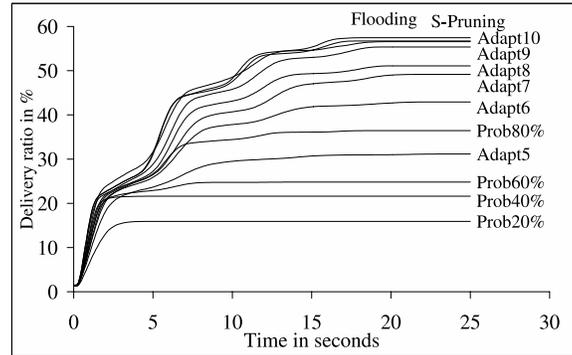
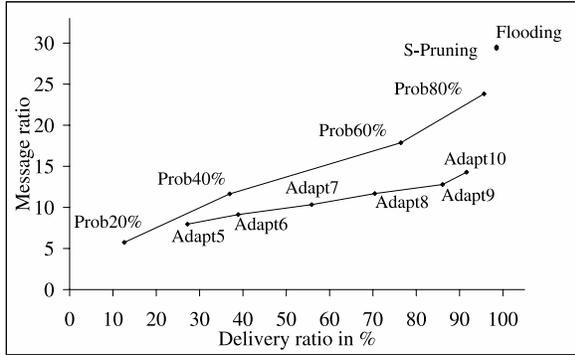


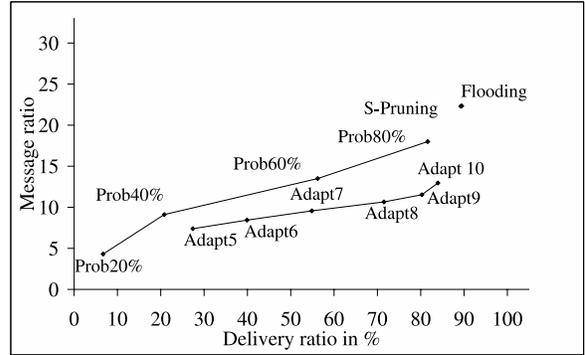
Figure 6: Delivery ratio using the linear area graph

disseminate in the network. The measured densities of the four sub-scenarios are given in Table 4. The differences between the clusters and the connections are nearly the same as in the last scenario and range they 18% to 60% less neighbors on the connections compared to the clusters.

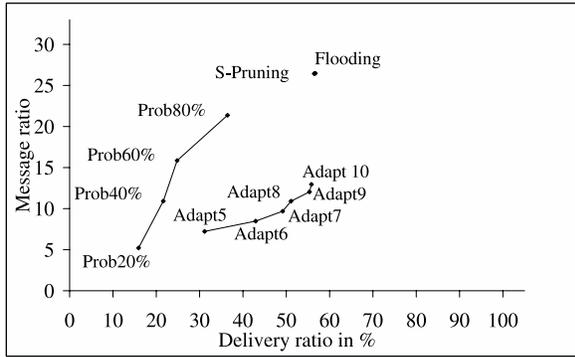
In Fig. 6 we show the development of the delivery ratio over time of one sub-scenario for the first 25 seconds. You can observe all curves having a step like form, which is clearly caused by the linear arranged clusters. So in the clusters the data disseminates very fast and on the paths the dissemination is slower. You can also see that adaptive probabilistic protocols have a better delivery ratio than probabilistic protocols. Altogether you can say that although the protocols reach a different number of clusters (and nodes), there are no



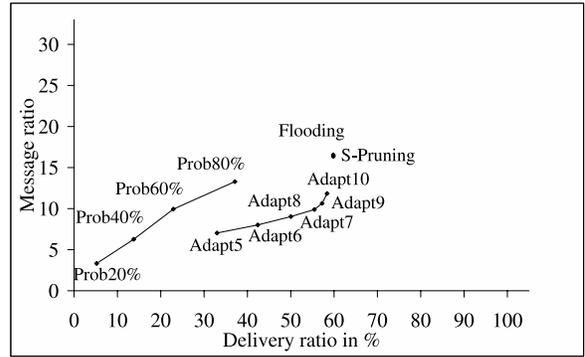
(a) 200x200 m, short waiting time



(b) 300x300 m, short waiting time



(c) 200x200 m, long waiting time



(d) 300x300 m, long waiting time

Figure 7: Results using the linear area graph

significant differences between the development of their delivery ratios over time.

The results of the delivery ratios and the message ratios shown in Fig. 7 are quite similar to the results of our first scenario using the Area Graph-based Mobility Model. Again the sub-scenarios with a low density on the paths (Fig. 7(c), Fig. 7(d)) only have maximum delivery ratios which are significantly below (67% - 72%) the optimum rate of 100%. This is the result of network partitions occurring in these cases. Apart from that you can observe that in this experiment a threshold value x of 9 is not sufficient for the adaptive probabilistic protocols anymore. Only the protocol with a threshold value x of 10 has a delivery ratio similar to flooding (maximal 8% less) but much lower message ratio. The need of a higher threshold value is because there is only one way of dissemination in this scenario. Thus you can observe that like in the other scenarios the adaptive probabilistic protocols are disseminating the data most efficiently. The only difference is the necessity of a slightly higher threshold value x . The probabilistic protocols have no acceptable delivery ratios if using this linear setting

(especially in the cases of low densities on the paths).

Concluding our experiments the mobility model used in simulations has a strong impact on the efficiency of broadcast protocols. Only the adaptive probabilistic protocols have been efficient in both homogeneous and heterogeneous scenarios.

6 Conclusions and Future Work

In this paper we introduced our new Area Graph-based Mobility Model which uses a graph-like structure of connected areas to build up scenarios which maintain the major aspects of real settings. To obtain general results we avoided modeling specific scenarios in detail, as it is done by other mobility models. To show the characteristics of our new model we examined data dissemination by making several experiments with common broadcast protocols. In these experiments we especially focused on the heterogeneity of realistic scenarios and therefore used the Area Graph-based Mobility Model. For a comparison to previous works we also made the same experiments with the Random Waypoint Mobility Model.

The experiments showed that the performance of the examined protocols strongly depends on the underlying mobility model. There are protocols performing well using the homogeneous Random Waypoint Mobility Model but being not efficient when using the heterogeneous Area Graph-based Mobility Model. The main reason is that in contrast to the Random Waypoint Mobility Model the Area Graph-based Mobility Model consists of areas with differing topologies and densities.

Furthermore we showed that it is necessary to use adaptive broadcast protocols when using heterogeneous mobility models like the Area Graph-based Mobility Model, because an efficient broadcast is not possible without an adaptation to the local network density. But there is still need for enhancement of the adaptive protocols because in different scenarios different threshold values produce optimal results. The adaptation of the threshold value could be a possible solution for that problem.

For a further examination of the Area Graph-based Mobility Model we are planning more experiments in the future. In these experiments we will examine both new scenarios and more protocols. The focus will be on more sophisticated protocols with neighbor knowledge [17] and on area-based protocols [3].

In these experiments we will also examine scenarios with more complex area graphs with more clusters and paths. Other experiments will focus on scenarios with very low densities resulting in more frequent network partitions.

In parallel we will try to develop a theoretical model for our Area Graph-based Mobility Model to predict the behavior of the dissemination. We will focus on ideas from probabilistic and percolation theory [18] because they seem to be quite promising for developing this theoretical model.

References

- [1] D. B. Johnson and D. A. Maltz, “Dynamic Source Routing in Ad Hoc Wireless Networks,” in *Mobile Computing*. Kluwer Academic Publishers, 1996, vol. 353, pp. 153–181.
- [2] C. E. Perkins and E. M. Royer, “Ad-hoc On-Demand Distance Vector Routing,” in *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications (WMCSA '99)*, New Orleans, USA, February 25–26 1999, pp. 90–100.
- [3] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu, “The Broadcast Storm Problem in a Mobile Ad Hoc Network,” in *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM '99)*, Seattle, USA, August 15–19 1999, pp. 151–162.
- [4] B. Williams and T. Camp, “Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks,” in *Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing (MOBIHOC '02)*, Lausanne, Switzerland, June 9–11 2002, pp. 194–205.
- [5] T. Camp, J. Boleng, and V. Davies, “A Survey of Mobility Models for Ad hoc Network Research,” *Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, vol. 2, no. 5, pp. 483–502, 2002.
- [6] C. Bettstetter, “Smooth is Better Than Sharp: A Random Mobility Model for Simulation of Wireless Networks,” in *Proceedings of the 4th ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2001)*, Rome, Italy, July 21 2001, pp. 19–27.
- [7] A. Jardosh, E. M. Belding-Royer, K. C. Almeroth, and S. Suri, “Towards Realistic Mobility Models for Mobile Ad hoc Networks,” in *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking (MobiCom 2003)*, San Diego, USA, September 14–19 2003, pp. 217–229.
- [8] E. M. Royer, P. M. Melliar-Smith, and L. E. Moser, “An Analysis of the Optimum Node Density for Ad hoc Mobile Networks,” in *Proceedings of the IEEE International Conference on Communications (ICC '2001)*, Helsinki, Finland, June 11–15 2001, pp. 857–861.
- [9] Z. Haas, “A New Routing Protocol for Reconfigurable Wireless Networks,” in *Proceedings of the IEEE International Conference on Universal Personal Communications (ICUPC '97)*, San Diego, USA, October 12–16 1997, pp. 562–565.

- [10] J. Tian, J. Haehner, C. Becker, I. Stepanov, and K. Rothermel, "Graph-Based Mobility Model for Mobile Ad Hoc Network Simulation," in *Proceedings of the 35th Annual Simulation Symposium (SS '02)*, San Diego, USA, April 14–18 2002, pp. 337–344.
- [11] X. Hong, M. Gerla, R. Bagrodia, and G. Pei, "Group Mobility Model for Ad hoc Wireless Networks," in *Proceedings of the 2nd ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, Seattle, USA, September 19 1999, pp. 53–60.
- [12] X. Hong, T. Kwon, M. Gerla, D. Gu, and G. Pei, "A Mobility Framework for Ad hoc Wireless Networks," in *Proceedings of the 2nd International Conference on Mobile Data Management (MDM '2001)*, Hong Kong, January 8–10 2001, pp. 185–196.
- [13] C. Ho, K. Obraczka, G. Tsudik, and K. Viswanath, "Flooding for Reliable Multicast in Multi-hop Ad Hoc Networks," in *Proceedings of the 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIAL-M 1999)*, Seattle, USA, August 20 1999, pp. 64–71.
- [14] H. Lim and C. Kim, "Multicast Tree Construction and Flooding in Wireless Ad Hoc Networks," in *Proceedings of the ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM)*, 2000.
- [15] A. Varga, "The OMNeT++ Discrete Event Simulation System," in *Proceedings of the 15th European Simulation Multiconference (ESM '2001)*, Prague, Czech Republic, June 6–9 2001.
- [16] I. S. Committee, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," in *IEEE 802.11 Standard*. IEEE, New York, 1997.
- [17] W. Peng and X.-C. Lu, "On the Reduction of Broadcast Redundancy in Mobile Ad Hoc Networks," in *Proceedings of the 1st ACM International Symposium on Mobile Ad Hoc Networking & Computing (MOBIHOC '00)*, Boston, USA, August 11 2000, pp. 129–130.
- [18] G. Grimmett, *Percolation*. New York: Springer-Verlag, 1989.