Graph-Based Mobility Model for Mobile Ad Hoc Network Simulation

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Abstract

Imagine a world where people constantly try to pass through walls and cars suddenly leave the roads and drive into rivers. Although this is unrealistic, most simulations for mobile ad hoc networks so far are based on the so called "random walk" of mobile objects, which are not constrained by their surrounding spatial environments. In this paper we propose a novel graph-based mobility model, which provides a more realistic movement than the random walk model by reflecting the spatial constraints in the real world. We analyzed three commonly used ad hoc network routing protocols, DSDV, DSR and AODV with both a random walk-based and our graph-based mobility model. Our simulation results show that the spatial constraints have a strong impact on the performance of ad hoc routing protocols.

1. Introduction

A mobile ad hoc network (MANET) [8] is an autonomous system of mobile nodes that does not rely on an existing infrastructure. Mobile nodes use wireless transceivers to communicate with each other. Communication between two nodes is only possible when they are within their radio communication range. To overcome this constraint, intermediate nodes, so called relays, are chosen to forward the packets from sender to receiver. Therefore, mobile nodes in such ad hoc networks act as both routers and hosts. Furthermore, the mobility of these nodes can frequently change the network topology and invalidate existing routes, which makes routing in MANET different from traditional wired networks.

Conventional scenarios in MANET simulation use random mobility models, in which mobile nodes move randomly in an area. However, mobile nodes in the real world, such as human beings or vehicles, do not move randomly. For example, the movement of pedestrians is bound to roads. In this paper, we introduce a novel graph-based mobility model that reflects the spatial constraints of the real world better than random mobility models do. The significance of our model is shown by comparing the performance of three commonly used ad-hoc routing protocols both using our graph-based model and the random walk model. Besides the 250 m transmission range used in many evaluations [1,4,5,7] we also used lower transmission ranges from 10 m to 150 m. The results show significant differences between our graph-based model and the random walk model, especially for low transmission ranges.

The remainder of the paper is organized as follows. Section 2 introduces a graph-based mobility model reflecting spatial constraints on the movement pattern of mobile nodes. A brief description of the investigated routing protocols is given in Section 3. In Section 4 we describe the simulation methodology and the simulation results based on both random walk and graph walk. Related work is introduced in Section 5. Finally, Section 6 closes the paper with conclusions and an outlook to further work.

2. Graph-Based Mobility Model

We use a graph to model the movement constraints imposed by the infrastructure. The *vertices* of the graph represents locations that the users might visit and the *edges* model the connections between these locations, e.g. streets or train connections. We assume that the graph is connected, i.e. there is a path form any vertex to any other vertices in the graph.

Each mobile node is initialized at a random vertex in the graph and moves towards another vertex, which is selected randomly as its destination. The node moves to the destination always on the shortest possible path. After the node reaches its destination, it makes a short pause for a randomly selected period and then picks out another destination from other vertices randomly for the next movement. Although a certain grade of randomness still exists in this model, we believe that this model provides a realistic balance between completely deterministic and completely random mobility models. An example graph modelling a city center is shown in Figure 1.

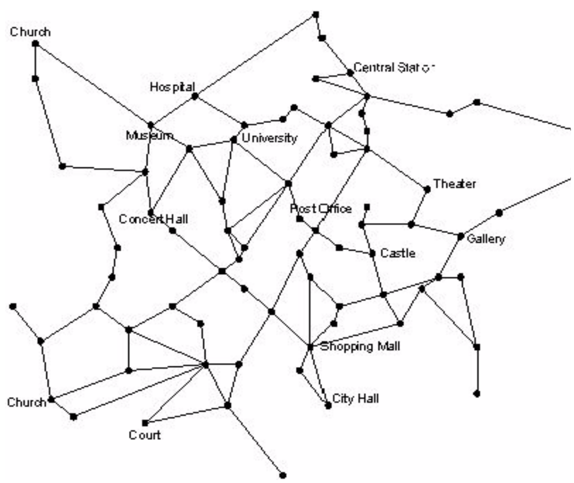


Figure 1: Example of a graph modelling a city center.

We define the smallest possible rectangle that includes all vertices as the *gross area* of the graph. The length and the width of the *gross area* are defined as the *gross length* and *gross width* of the graph.

In the graph walk pattern, the *gross area* is not completely covered. Depending on the graph and the radio range of the nodes some sub-areas will never be covered with radio signals, no matter how the nodes move along the graph. Under the assumption, that all the mobile nodes have the same radio range *R*, we define the *maximum radio coverage of graph-walk,* or $CMax_g$ as

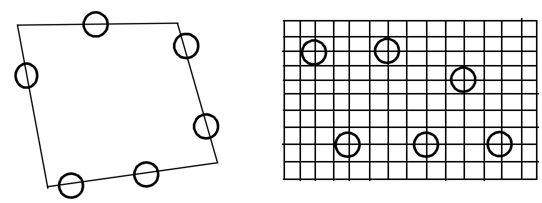
$$CMax_g = \sum_{e \in E} l(e) \times 2R$$

where *E* is the set of edges in the graph and *l(e)* is the length of the edge *e*. The value of $CMax_g$ equals the sum of all edge's lengths multiplied with the diameter of radio range. Note that $CMax_g$ is an approximation, to get the real radio coverage the overlappings should be removed. Depending on the ratio between radio range and the graph size, this approximation may hold well or not. Since this approximation suits well for short radio ranges, which are the focus in this paper, we choose to use this formula for simplicity.

In contrast to the graph walk model, we introduce the *maximum radio coverage of random-walk,* or $CMax_r$, for the random walk model, defined as

$$CMax_r = A_r = l \times w$$

where A_r is the *gross area* of the graph, *l* the *gross length*, and *w* the *gross width* of the area. We assume that the radio coverage of mobile nodes does not exceed the *gross area*. Since in random walk the nodes can move to anywhere in the *gross area*, the maximum radio coverage equals the whole *gross area*.



a) rect graph ***b) grid graph***

Figure 2: Two possible scenarios, where the circles indicate the radio range of mobile nodes.

Moreover, we observed that the $CMax_g$ defined above does not only depend on the radio range of nodes, but also the distinct graph structures. Consider for example two scenarios shown in Figure 2. Although the number of nodes and the radio range are identical, the $CMax_g$ is less than $CMax_r$ in scenario *a*, whereas in scenario *b* the value of $CMax_g$ is significantly greater than $CMax_r$. However, if we remove the overlappings from the $CMax_g$ in scenario *b*, the value of $CMax_g$ equals $CMax_r$.

Table 1 shows the total edge lengths of the three graphs described above.

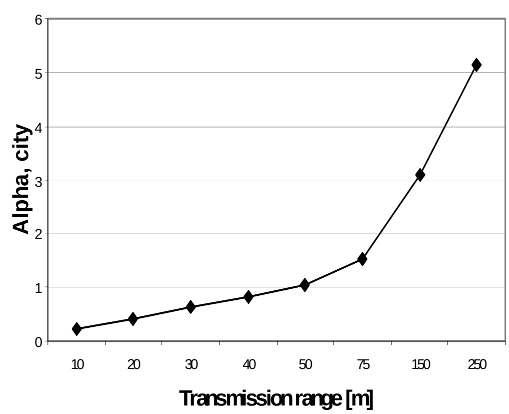
Table 1: Length of sample graphs, for *gross area* 1250x900.

Graph	$\sum_{e \in E} l(e)$
city	11560 m
rect	4100 m
grid	40000 m

The density of nodes is another important metric of mobile ad hoc networks and have a big impact on the performance of routing protocols. Taking into account of the varied radio ranges we define the *radio coverage density D* as the total radio coverage of *n* nodes divided by the maximum radio coverage defined above.

For graph walk, D_g equals $\frac{\pi R^2 n}{CMax_g}$, while for random walk, D_r equals $\frac{\pi R^2 n}{CMax_r}$.

To compare the graph walk and random walk, we define the ratio between the radio coverage density of random walk and graph walk as α. With the same number of nodes and same radio range, we get



$$\alpha = \frac{D_r}{D_g} = \frac{CMax_g}{CMax_r} = \frac{2R \times \sum_{e \in E} l(e)}{l \times w}$$

Figure 3: α values in sample city graph for different transmission range.

In the reality the radio coverage of a graph cannot exceed the radio coverage of its *gross area*, so the value of α can not exceed 1. This means that the radio coverage density D_g is always greater than or equal to D_r. The smaller the α is, the greater is the radio coverage density D_g comparing to D_r. However, since the formula above does not remove the overlappings from $CMax_g$, the redundancy of overlappings can make the value of α greater than 1. Although we use this formula in the context of this paper for simplicity and consistency, we suggest to take into account of the overlappings if the α value is evidently greater than 1. The α values in the city graph with varied radio ranges are listed in Figure 3.

3. Description of Routing Protocols

A variety of routing protocols for ad hoc networks have been proposed in the literature. Three routing protocols are studied in this work, namely Destination Sequenced Distance Vector (DSDV) [6], Dynamic Source Routing (DSR) [2] and Ad hoc On Demand Distance Vector (AODV) [3]. These protocols are chosen for their broad usage and representative characteristics: DSDV is a proactive protocol while DSR and AODV are reactive protocols. DSR is a source routing protocol and AODV is based on traditional distance vector method. Furthermore, these three protocols were often selected for random walk simulations, such as in [1,4,5,7]. Therefore, it is interesting to compare and evaluate them with our graph walk mobility model. The remainder of this section gives a short description of these three ad hoc routing protocols.

3.1. Destination-Sequenced Distance-Vector

DSDV [6] is a proactive routing protocol based on traditional distance vector method. Each node maintains a routing table that contains routing information of all the reachable destination nodes, such as the number of hops and the next-hop to the destination. To keep the routing table up to date, nodes in the network periodically broadcast routing table updates. In addition, DSDV uses triggered route updates when the topology changes. The transmission of updates is delayed to avoid update storms if the topology is changing rapidly. The key advantage of DSDV over traditional distance vector protocols is that it uses sequence numbers to guarantee the protocol to be loop-free by indicating the freshness of a route. The parameter values used for DSDV in the simulations are given in the Table 2.

Table 2: DSDV Simulation Parameters.

Periodic route update interval	15s
Periodic updates missed before link declared broken	3
Initial triggered update weighted setting time	6s
Route advertisement aggregation time	1s
Maximum packets buffered per node per destination	5

3.2. Dynamic Source Routing (DSR)

DSR [2] is a reactive routing protocol which uses source routing to deliver data packets. The DSR protocol consists of two mechanisms: *Route Discovery* and *Route Maintenance*. If a node wants to find a route to another node, it uses the route discovery mechanism to flood a *Route Request (RREQ)* packet through the network. If a route to the destination is found, a *Route Reply (RREP)* packet will be sent back to the source node by unicast. Each intermediate node that forwards the RREP message also learns this route by caching it in its routing table. The source node then sends data packets to the destination node, which contain the complete route in the packet's header. Since the packets themselves carry the route, all the intermediate nodes do not need to maintain the up-to-date routing information. If a source route to the destination is broken, the Route Maintenance mechanism will notify the source node to use any alternative routes or invoke a new Route Discovery process. Table 3 lists the parameters of DSR protocol in the simulation.

Table 3: DSR Simulation Parameters.

Time between retransmitted Route Requests	500 ms
Size of source route header carrying n addresses	$4n + 4$ bytes
Time-out for nonpropagating search	30 ms
Time to hold packets awaiting routes	30 s
Maximum rate for sending replies for a route	1/s

3.3. Ad Hoc on Demand Distance Vector

AODV [3] is a reactive routing protocol based on the conventional distance vector method. It combines the on-demand route discovery from DSR and the hop-by-hop routing with sequence numbers from DSDV. Whenever a node needs to find a route to another node, it broadcasts a *Route Request (RREQ)* packet to all its neighbors. The *RREQ* message is flooded through the network until it reaches the destination or a node with a fresh route to the destination. A *Route Reply (RREP)* packet is then sent back to the source node by unicast. Route entries for the destination will be created in intermediate nodes. Each node detects its neighbors by periodic HELLO messages. Table 4 shows the parameters used for the AODV simulation.

Table 4: AODV Simulation Parameters.

HELLO interval	1s
Active route time-out	50 s
Route reply lifetime	60 s
Allowed HELLO loss	3
Request retries	3
Time before broken link is deleted from routing table	3s
Time to hold packets awaiting routes	30 s
MAC layer breakage detection	yes

4. Simulation

In this section we will first introduce our simulation environment, and then analyze the simulation results of both graph walk model and random walk model. In the end of this section we give a brief summary of the simulation.

4.1. Simulation Environment

The scenario chosen for the simulations is based on the city scenario introduced in Section 2. To describe the movement of persons carrying their handheld devices, the city center was modeled as a graph [10] (Figure 1). The graph used for the simulations contains 115 vertices describing significant locations within the city and 150 edges interconnecting them, covering an area of approximately 1250 m by 900 m.

For the simulation each node moves from one randomly chosen location to the next on a shortest path. After reaching a destination a pause time between $t_{staymin}$ and $t_{staymax}$ was chosen before moving towards the next destination.

The simulations were done using the Network Simulator (ns2) [11] with the CMU extension [12]. Since ns2 does not support our graph movement pattern, a movement program was developed to simulate the city center scenario. This program generates movement input files for ns2, describing every movement of n different nodes over a simulation period of t_{sim}. Every node has a minimum and maximum speed (v_{min}, v_{max})

for its movement. A new speed is chosen with every new destination.

The speed chosen was between v_{min}=2 km/h and v_{max}=5 km/h to represent a typical pedestrian walking. The total simulation time t_{sim} was set to one hour. The intermediated stay at each destination was between $t_{staymin}$=120 s and $t_{staymax}$=600 s to represent people stopping at a shop or a train station.

The physical radio characteristics of mobile nodes are based on the IEEE 802.11 standard with direct sequence spread spectrum radio. The IEEE 802.11 distributed coordination function (DCF) media access control protocol is based on the implementation by CMU. It uses a RTS/CTS/DATA/ACK pattern for all unicast packets and simply sends out DATA for all broadcast packets. Across simulations, the transmission range was varied with a special focus on lower ranges between 10 m and 75 m, which are typical ranges to satisfy the need of mobile consumer devices considering energy consumption and cost.

Since the deployment of such handheld devices which are capable of relaying messages is currently still quite low, we choose a relative small number of mobile nodes to simulate a sparse network which could be heavily partitioned. All simulations included 50 nodes, 26 of which were part of 40 CBR (Constant Bit Rate) connections. Each connection transmits 5 packets of size 64 Bytes per second at 2Mbps.

Table 5 summarizes the general simulation parameters.

Table 5: Simulation parameters.

Parameter	Value
Total simulation time	3600 s
Total number of nodes	50
Size of simulation area	1250 m by 900 m
Transmission range	10-250 m
Movement speed	0.56 -1.39 m/s
Intermediate stay	120-600 s
Traffic type	CBR
Packet rate	5 packets/s
Packet size	64 byte
Number of connections	40

4.2. Simulation Results

In this section we compare simulation results of the three routing protocols mentioned above. We will compare the performance of protocols in terms of the average end-to-end delay, packet delivery rate and routing protocol packet overhead. All protocols were tested on random walk as well as graph walk, and also with a variety of radio ranges.

4.2.1.Average End-to-End Delay. The results for the three protocols are shown in Figure 4. The average packet delay of DSDV in the graph walk model is greater than in random walk model. The explanation is that the spatial constraint of graph forced more hops to be used on detours along the graph than in random walk. Surprisingly, in contrast, DSR and AODV both achieve lower delay in graph walk than in random walk even with more hops needed. This is because of the different major factors impacting the delay time: while the delay of AODV and DSR is mainly caused by the buffering of undeliverable packets, the number of hops plays a critical role in DSDV. When the value of α is significantly less than 1, also the $CMax_r$ much greater than $CMax_g$, which indicates a higher *radio coverage density* of nodes in graph walk than in random walk with the same number of nodes and radio range. The higher density of nodes increases the probability of finding relay nodes to forward the packets, which reduces the buffering time of undeliverable nodes in DSR and AODV. We also observed, however, when the α value is much greater than 1, which means that the radio coverage density in graph walk is very close to random walk, the average packet delay in all the three protocols does not show a significant difference between both models.

4.2.2.Packet Delivery Rate. The results for the three protocols are shown in Figure 5. For all three candidates the packet delivery rate grows exponentially for the transmission ranges up to 75 m. All protocols deliver more packets in the graph walk than in random walk: since $CMax_r$ in the random walk scenario is greater than $CMax_g$ for the corresponding graph scenario, the radio coverage density in graph is higher, which reduces the possibility of partitions in the network.

AODV and DSR have higher delivery rates compared to DSDV, because more undeliverable packets are buffered. The lowest delivery rates are observed in the random walk scenario of DSDV, because of the lower radio coverage density of nodes combined with the fact that more undeliverable packets are dropped. Both DSR and AODV in the graph scenario achieve highest delivery rate, because of the combination of more buffering and higher radio coverage density. Moreover, we also observed that when the α value is significantly greater than 1, especially at 250 m radio range, the packet delivery rates for all three protocols do not have evident difference in the graph walk mod-

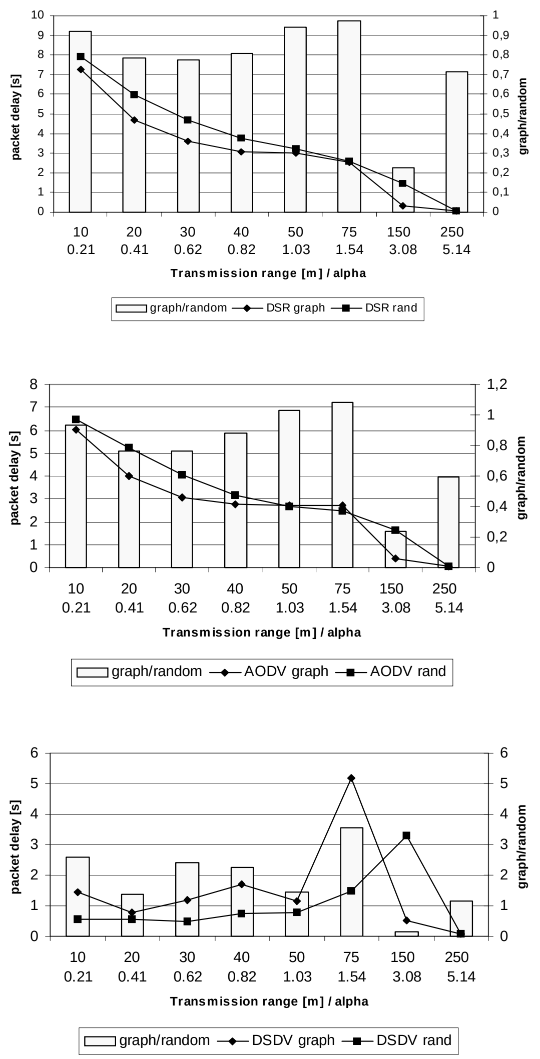


Figure 4: Average end-to-end delay for the three different routing protocols.

el comparing to the random walk model.

4.2.3.Routing Protocol Packet Overhead. The results for the three protocols are shown in Figure 6. None of the three protocols show large differences in routing protocol packet overhead between graph walk and random walk models. The DSDV protocol has an approximately constant overhead for transmission ranges up to 75 m and increases slightly for higher ranges. This is because that the routing tables are larger for higher ranges to contain more neighbors. Additionally, more tables have to be exchanged among those neighbors, which also leads to an increase of the routing packet overhead.

AODV shows an approximately linear increase of the protocol overhead in short ranges for both graph and random walk. The explanation for this is the increasing number of HELLO messages sent for neighborhood detection. The number of neighbors increases with the radio range. Within the lower radio ranges the graph walk has a higher overhead than the random walk, because $CMax_g$ is smaller than $CMax_r$, resulting in more neighbors on average in graph walk model and therefore more HELLO messages. For higher radio ranges both random and graph walk behave similarly because the number of neighbors are about the same for both cases. The routing packet overhead decreases in both DSR and AODV with high radio ranges. The explanation is that high radio ranges result in less numbers of hops in routes.

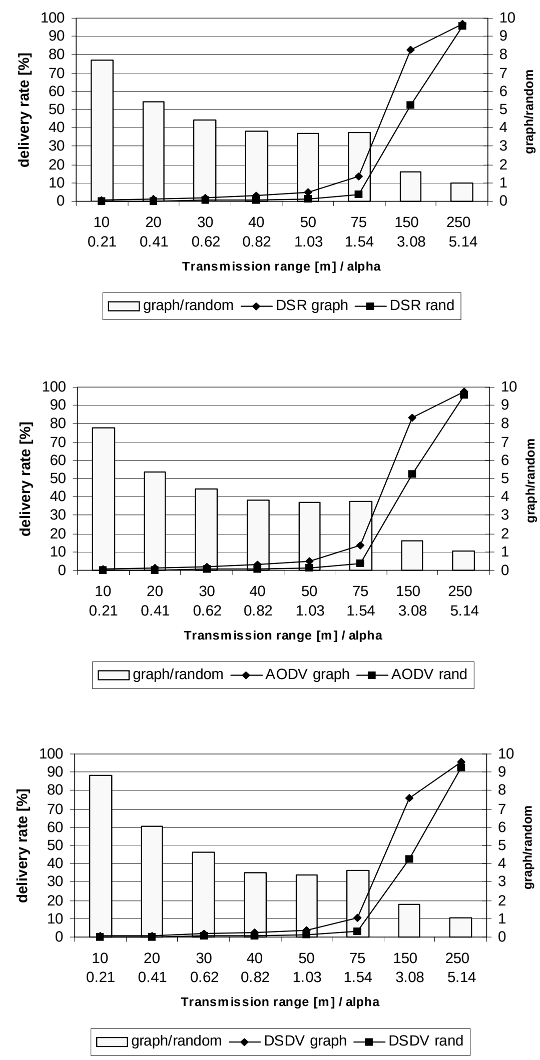


Figure 5: Packet delivery rates for the three different routing protocols.

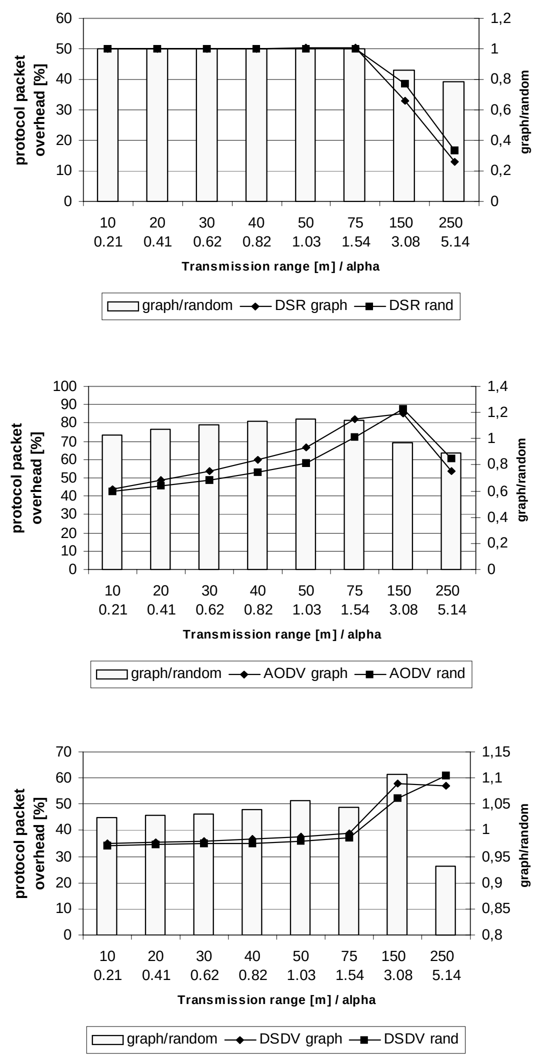


Figure 6: Routing protocol packet overhead for the three different routing protocols.

4.3. Simulation Summary

We simulated all the three protocols using both the graph walk model and the random walk model with a variety of radio ranges. The results of the simulations show very different performance of these routing protocols between the two models.

The reactive protocols DSR and AODV achieved lower average end-to-end delay in the graph walk model than in the random work model. In contrast, the proactive protocol DSDV showed more delay in the graph walk model. This indicates that the spatial constraints may have different impact on different types of routing protocols concerning the distinct network metrics. Moreover, the reactive protocols show significantly more delay than the proactive protocol in both models with short radio ranges. This means that the route acquisition time can be a big performance constraint of reactive routing protocols in such a scenario.

All three protocols delivered significant more packets in the graph walk model than in the random walk model in short radio ranges. The value of α is much less than 1 in these ranges, which indicates D_g much greater than D_r . This also proves that the radio coverage density plays a critical role for routing protocol performance. However, in the large radio ranges the $CMax_g$ is very close or equal to $CMax_r$, so the delivery rate of all protocols do not show evident difference between the graph walk model and the random walk model.

The source routing protocol DSR showed nearly the same routing packet overhead in both models with short radio ranges. However, with large radio ranges the overhead of DSR in the graph walk model is less than the random walk model. This shows that the radio coverage density does not have obvious impact on the routing packet overhead for source routing protocol. In contrast the distance vector protocols DSDV and AODV achieved slightly more routing packet overhead in the graph walk model than in the random walk model within short radio ranges. Moreover, the reactive protocols DSR and AODV achieved less overhead with increasing radio range whereas the proactive protocol DSDV got more overhead.

Based on the simulation results we observed that if the α value is significantly less than 1, i.e. the radio coverage density of the graph walk model is much greater than in the random walk model, the routing protocols show very different performance between the two models. Another interesting point is that the graph walk model has very different impact for different routing strategies.

5. Related Work

Several papers have compared the performance of existing ad hoc routing protocols on simulated mobile ad hoc networks, for instance [1,4,5,7]. However, most of assessments and comparisons were based on random movement model, in which mobile nodes move arbitrarily in the whole area. For instance, they all use the “random waypoint” model as movement model. In this model, each node moves from a random location straight to a random destination with a randomly chosen speed. Once the destination is reached, the node chooses another random destination after a pause. In our graph walk model, each node chooses its destination only out of the vertices on the graph. Moreover, most of simulations so far only used the standard Wireless LAN radio range of 250 meter. Considering the simulation area and number of nodes used in those simulations it is clear that the networks were well connected. In contrast, we also considered a variety of small radio ranges in our simulation, because such short radio ranges will very likely be used due to the energy constraint of normal handheld devices.

Johnasson *et al.* [1] introduced three additional scenarios: Conference, Event Coverage, Disaster Area. These scenarios were examined to get an understanding on how the protocols behave in an realistic environment. They have used an obstacle-approach by adding some obstacles in the scenario to prevent radio propagation. If the straight line between any two nodes is crossed by an obstacle, a link between these nodes is considered broken until the nodes move out of the shadowed area of obstacle. Although this *obstacle-approach* has made the radio propagation more realistic, its focus was not to improve the modelling of the movement of mobile nodes. As a result, most of nodes still move randomly except if their movement is prevented by an obstacle.

In contrast to the obstacle-approach above, we use a *graph-approach* in our simulation to model the movement of mobile nodes. In each scenario, a graph is used to specify the spatial constraints of the scenario, and all the mobile nodes in the network are moving along the edges of the graph.

6. Conclusion

In this paper, we introduced a graph-based mobility model that reflects the constraints of movement given by the spatial environment in the real world. In this model, the nodes do not move randomly, but always along the edges of a graph that models the given infrastrucuture.

The result of our simulation proves that the spatial constraints have a big impact on the performance of mobile ad hoc routing. We extracted a graph from external spatial data to represent the realistic movement constraints of pedestrians walking in the city. As the result showed, routing protocols performed quite differently in this graph walk model from the random walk model. Moreover, we have also made comprehensive simulations with short radio ranges considering the energy constraint of handheld devices.

For the near future we plan to extend our graph model by including obstacles in the model to prevent the radio propagation. We also plan to include movement profiles of distinct nodes in our model. Although we have only evaluated the routing protocols that do not use location information, our also plan to evaluate the location aware routing protocols like LAR [9] and GPSR [13] with our graph walk model in the future. Another topic of our future research will be the study of additional scenarios.

7. Acknowledgements

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