On Scenarios to Evaluate Mobile Ad Hoc Networking Routing Protocols

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Abstract: A mobile ad hoc network (*MANET*) is a mobile, wireless network, that does not require any preexisting infrastructure and thus needs to establish a distributed routing infrastructure in a self-organized way. A lot of routing protocols for MANETs have been proposed, and also some evaluating work has been done. A key characteristic of evaluations is the scenario in which the protocol used. Scenarios used in evaluations have a great impact on the results, so it is very important to choose these scenarios carefully, such that results are usable for further development and possible real deployments of such networks. This report discusses how scenarios are used so far to evaluate *MANET*s, and further suggests how to improve scenarios, to get more realistic and more applicable results.

1 Introduction

Mobile Ad Hoc Networking is a way of communication, which does not rely on any existing infrastructure, such as dedicated routers, transceiver base stations or even cables (of any kind)[Per01]. Clearly wireless channels are used as a communication medium (but without fixed stations as in cellular networks) and each node needs typically to act also as a router to relay packets to nodes more far away. Such multi-hop routing in a wireless environment with mobile nodes is a much more complex task than routing in conventional (static) networks. The solution requires to take care of all the characteristics of this task, which are determined mainly by the characteristics of the media, the behavior of nodes and the data and traffic pattern communicated.

Mobile Ad Hoc Networks can be applied to a large variety of use cases, where conventional networking cannot be applied, because of difficult terrain,

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lacking cost-effectiveness or other reasons. Examples to such situations are: A disaster area, where any possible infrastructure has been destroyed; a large business fair, where people are moving around a lot, or a conference with changing speakers and audience. Other possible uses are so called *sensor networks*, where intelligent sensors are deployed in an unaccessible area, that transmit their data in an ad hoc manner. Of course a very important field of application is the military battlefield. Military organizations do fund a large fraction of ad hoc networking research. And last not least, there is the vision, that any mobile device, people are carrying in their everyday life anyway (cell phone, organizer, notebook), could be MANET enabled, thus allowing personal communication without the need of a communication carrier.

The research topic of mobile ad hoc networks is currently experiencing a lot of research effort. Although being just a recent field of research[1], but it has challenged many excellent scientists and Internet pioneers, like Anthony Ephremides, Charles E. Perkins, and Mario Gerla, just to name a few.

The result of just a few years of research is a large amount of papers and studies ranging from very general to very concrete issues, covering any network layer from physical media characteristics to security protocols and service location.

One of the most discussed areas is routing, as this is a very crucial topic. This part of the problem has produced also a large amount of suggested solutions, i.e. routing protocols. As there are so many aspects that routing can be based on, and many constraints that can be focused on, nearly 30 different routing protocols have been designed and presented, each focusing on some characteristic of the network and trying to improve things in a certain direction. The nature of the problem implies contradictory goals, so it is clear that there is no general solution.

As each proposed strategy has to be justified, simulations are commonly used to show the advantages and attributes of those suggestions. It goes without saying, that simulations that are part of a proposal of a certain algorithm, are often in favor of that algorithm.

As mentioned above, the environment of an ad hoc network has a severe impact on the required characteristics and strategies. This is valid for a real use of an ad hoc network, as well as for a simulation to evaluate a routing strategy. Since evaluations are crucial for further research and development and for a real use, special care must be taken to model the environment for

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[1] Around 1994 the first papers appeared about this modern type of ad hoc networking, of course related efforts have been done much earlier, like the Packet Radio Network (PRnet) project of the US army.

evaluations to match the intended use case as close as possible.

The environment consists of many aspects like physical characteristics of the medium and interfaces, type and characteristics of traffic to be transported in the ad hoc network, and also movement and behavior of nodes (communication devices) and characteristics of the area, in which the nodes move. These aspects are subject of this paper: We will examine the node behavior, movement patterns and characteristics of the observed area (we will call these aspects together a *scenario*), as used in previous evaluations. We will evaluate them and propose a way, how to craft scenarios to be used in future simulations.

The rest of the paper is organized as follows: The next section will define and describe terms and notions used in the paper. Then we will describe criteria that we use to judge scenarios. Commonly used scenarios in previous evaluations will be described and we will point out their advantages and drawbacks. In section 6.3.1 we suggest, what properties a scenario should contain, and how to specify and generate such a scenario for simulations. Finally a summary and a perspective for future work will be given.

2 Definitions

This section will define commonly used terms and phrases throughout the paper.

node A node is MANET enabled device, attached to an object that can move and act individually. Examples for *nodes* are:

- A person, that carries a cellular phone, a notebook computer or an organizer with MANET capable communications hardware.
- Such persons, but using a bicycle or public transport.
- A car fitted with MANET capable communications hardware.
- A tank or other military vehicle (possibly unmanned) fitted with MANET capable communications hardware.

Also aircraft, helicopters and ships could generally be regarded as *nodes*, but this paper does not take these types of nodes into account.

node density The node density in the observed area, as commonly defined:

$$\frac{\text{number of nodes}}{\text{amount of space, that contains all those nodes}}$$

area, observed area The observed area of the evaluation (simulation, testbed or real installation). The shape of the *area* is usually a rectangle, but doesn't necessarily need to be.

region or subarea This is a usually smaller (but not larger) part of the →*observed area*. It can have special properties that affect node movement and communications.

border The border of the →*observed area*.

border behavior The behavior of →*nodes*, if they approach the →*border*. This is an important characteristic of a →*mobility model*. Possible border behavior is described more detailed in section 5.8.5.

mobility model The *mobility model* is defined as the set of rules, that determine the movement of the →*nodes*.

mobility metric A metric to measure the *degree of mobility*. Examples for a simple mobility metric could be: average speed of the nodes or average →*pause time*. Much more complex mobility metrics are possible and discussed in sections 5.3.1 and 5.8.2.

movement strategy The *movement strategy* is an important part of the *mobility model*. We define the *movement strategy* as the set of rules, that determine the intended target of movement of each node, and also the intended movement speed. The real movement speed and direction will also be influenced by other parameters (like maximum speed in a certain *region*), which are not part of the *movement strategy*.

group A *group* is a set of *nodes*, which share some common characteristics. Usually a group has a common *movement strategy*, but does not need to. The actual characteristics may vary and are defined by the group specification.

group mobility *Group mobility* or a *group mobility model* is part the general *mobility model*. It is defined as the set of rules that allow nodes to form *groups* and determine the movement decisions of *nodes* as group members.

scenario The *scenario* in our context, is the union of the *observed area* some *subareas* and the *mobility model* plus some additional characteristics as described in section 4. We do not mean a *specific* scenario, which is one single strictly determined way, how nodes behave. Of course a specific scenario, is the kind of scenario that is ultimately used in a simulation, but an evaluation needs to make more simulations (cf. [Mit97]) with the same parameters to rule out statistical anomalities. Thus we focus only on *scenarios* in the sense described above, and their possible parameters.

pause time This term was used first in the introduction of the first *random waypoint* mobility model in [JM96]. The *pause time* is a fixed time, that a node waits between movements. The *random waypoint* is described more detailed in section 5.2.1.

performance Since the goal of simulations and evaluations is to determine, which routing strategy *performs* best, under which conditions, the term *performance* is used very often. Since there is not a single performance criteria, we define performance in the sense of an overall performance which takes the following measures into account, which are commonly used throughout the evaluations: **end-to-end delay of a packet**, **average and maximum throughput and goodput**, **initial connection setup latency**, **routing overhead**, **path length** and **overhead due to suboptimal paths**. There can be even different uses of these values in the various works, like **throughput** and **overhead** can be measured in terms of *Bytes* or *Packets*. For our use of *performance*, we do not prefer one or the other possible definition, since that is up to the evaluations itself. With *performance*, we mean the performance of a routing protocol qualitative under the various aspects mentioned here.

3 Related Work

Despite the huge amount of research in mobile ad hoc networking, the simulation environment did not get much attention, so far. [Bet01] addresses some of the physical and [SSH01] also aims a lot for realism even providing a tool. Just recently before this work was finished, a technical report was published, which is closely related to this one: [TCD02]. It also discusses commonly used mobility models, border behavior and puts some weight on group mobility.

4 Characteristics and Quality of a Scenario

In this section we present the key characteristics of a scenario and its parameters in detail. Then we discuss these characteristics and their importance for the quality of a scenario. Also we describe, what is important in our opinion for a scenario of a good quality.

The main goals for our understanding of good quality scenarios is **realism** together with **applicability** for the intended use cases of the scenario.

Observed Area As defined in section 2, this is one fundamental characteristic. It is a mandatory characteristic, and no scenario based simulation[2] or evaluation can be done without it. Its two main parameters are **shape** and **size**. The **shape** used in any scenario for the evaluation of ad hoc network routing protocols is a *rectangle*. There are good reasons for that: A rectangle is easily specified, most simulation software just supports rectangles and other shapes do not offer any obvious advantage. The **size** does vary much more and is indeed a parameter that affects the real world situation to be modeled very much. Sizes vary from a small room (3m × 6m) to an area that could cover several towns (10000m × 10000m).

Good quality scenarios can be of any size, but the size should reflect the intended use case as close as possible. Usually this is not a problem.

Types of nodes As described in section 2, nodes can be of different types, which will behave differently (pedestrians will move different, than cars). Each node type will have certain characteristics itself, which will affect the level of detail for the model and thus the degree of realism.

The node type determines the following parameters, which may or may not be present in the various models:

- Likelihood of moving at a certain time
- Capabilities in terms of
  - *acceleration*
  - *deceleration*
  - *maximum speed*
  - *change of direction*
- Interaction with certain subareas (e.g. *cars* can only move on *streets*)
- Moving strategy (as explained in Section 6.2)
- Time intervals of operation (the node may be an active part in the network only during certain time intervals).

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[2] Of course, complexity analysis or other analytical work does not need a scenario at all.

Number of Nodes This is also a very basic parameter of a scenario. Both the overall number of nodes, as well as the number of nodes of each different type are important. However, in our opinion the overall number of nodes will have a larger impact on the simulation results, as it determines also the *node density*.

Radio Model and Radio Range The radio model should reflect the kind of radio hardware used for communication. Often this choice determines also the link layer. A large variety of hardware is available, but not too much can be used for mobile ad hoc networking. Parameters that depend on the radio model are (among others) **channel bandwidth** and the **radio range**. In combination with *node density*, the *radio range* will highly affect the results of the simulation because it affects connectivity and channel competition, two effects of contradictory benefit.

Radio Propagation and Obstacles (for signal propagation) In a real world scenario, the observed area will consist of a flat, free space only in very rare cases. Obstacles of some kind are the general case. There are different ways, to model this. One way is with a general radio propagation model, that statistically restricts the propagation and therefore the range of the radio signals. Another method would be, to explicitly allow the placement of obstacles in the area, that specifically reduce the range of the radio signals. This can be done, by allowing the placement of *subareas* (see section 2), with a certain characteristic, that affects the propagation of a signal through this area.

Restricted Areas and Obstacles (for movement) Obstacles can not only obstruct radio signals, but also of course movement of nodes. This can also be reflected in the scenario by the placement of *subareas* which have certain restrictions for node movement. E.g. nodes cannot move through a building, or nodes of type "car" can only move on subareas of type "street". So the scenario could allow the definition of types of subareas with certain characteristics, that will affect node movement. In our opinion this can be a very important part for some scenarios to model a real world situation close enough.

Border Behavior This is also an important aspect of the scenario. [Bet01] and [TCD02] have shown, that the border behavior has an important impact on the user distribution over the area, which affects local density and therefore the simulation results. The way, how nodes will behave on approaching a border will certainly affect the realism and the applicability of a scenario. See also section 5.8.5.

Introduction and Removal of Nodes This characteristic is related to the *border behavior*. In a real world scenario it will happen, that nodes enter the observed area, while others leave it. Further nodes within the area can be switched off and thus cease to be part of the network and of course also switched on and just start to participate in the ad hoc network. We also regard the possibility to reflect such behavior in certain scenarios as an important contribution towards realism and applicability.

Group Mobility The possibility to form groups (as defined in Section 2) of nodes and the flexibility of group criteria, and the quality[3] of the *group mobility model* to also contribute to our quality measure of scenarios.

Observing Time This is the duration of the scenario, which usually corresponds to the simulation time (although, it would be possible to simulate several steps of a scenario separately. We consider this not a real part of the scenario, but more a simulation parameter, so it has only a minor role in this work. We mention it anyway for sake of completeness and because it affects the runtime of a simulation. Also very short observation times may be subject to initialization effects. Very long observation times may be a hint to a less detailed modeling of other simulation aspects (like no modeling of the physical properties of the wireless interface).

Further, it is important to derive more parameters from the given characteristics (just like *node density*, that can be used as a measure of mobility or a *mobility metric* (cf. section 2). For the comparison of routing protocols in terms of performance (cf. section 2), it is important to determine a *degree of mobility.*

The impact of *mobility* (like in terms of average speed, pausing periods, direction changes, etc.) is expected to be significant for the performance of certain routing protocols. It is expected, that some algorithms perform much better under a *"high mobility"* than others, while with *"low mobility"*, there may be no difference.

These characteristics introduced above, will be used during the examination of existing comparisons and evaluations, to identify the scenarios used, and also to categorize and rate them in terms of quality.

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[3] again in terms of realism and applicability

5 Scenarios used so far

This section will summarize the scenarios used in previous papers, categorize them and finally tries to evaluate these scenarios with respect to our definition of quality.

5.1 Common observations

Area: All applied scenarios have used a rectangular area. This seems a sensible choice, as other geometries don't offer any particular advantages.

Role of Nodes: All nodes are assumed to be devices, carried by persons or in vehicles controlled by persons. They only move on ground-level in two dimensions.

5.2 Simple Scenarios

With *Simple Scenarios* we define scenarios with the following characteristics:

- The observed area is a flat empty space. There are no subareas, obstacles or other movement restrictions. Nodes can move arbitrarily on the area.
- Nodes cannot leave the area, new nodes cannot be introduced, and nodes are always active.
- Nodes move according to a *simple* strategy (cf. section 2), like *Random Waypoint* or *Random Direction*.
- Nodes can only move at a constant speed.
- Nodes don't change direction during a single move. All direction changes are *sharp*, there is no smooth turning or curves.

Scenarios like this have been used in many simulations, with some minor differences. We will now roughly describe what variants have been used.

5.2.1 Basic Random Waypoint Scenarios

This type is used frequently. The *Random Waypoint* movement model implies, that each node chooses a random destination within the given area, moves to that destination at constant speed on a direct path and then waits for a fixed *pause time* (cf. section 2), before choosing the next destination. This scenario has been used in [BMJ+98], [DPR00], [HV99], [Ö00] and others.

In these works, further characteristics are:

Area size:	1500 × 300m and 2200 × 600m (in [DPR00])
Radio Range:	250 m
Number of nodes:	10, 20, 30, 40, 50 and 100 (once)
Speed of nodes:	[0..1] m/s and [0..20] m/s
Pause times:	30 - 900 seconds, globally fixed for all nodes
Simulation time:	500 and 900 seconds

The authors of [JM96] also use a related scenario, and their work is the first paper, that introduced the *Random Waypoint* mobility model. However, it is one of the earliest papers on the subject and the scenario itself differs a lot from the ones in the other papers[4], so that we mention it here, but it does not really belong to this (or any other) class of scenarios.

A similar situation exists with [GLAS01], where a scenario is used with an area of 5000 × 7000m, pause times from 30 to 90 seconds and only 20 nodes.

Mobility Metric Although not explicitly mentioned, these scenarios use either the *pause time* or the *mean speed* as a mobility metric.

These parameters are varied in the simulations, to reflect different degrees of mobility. It is widely expected, that more *mobility* will make it more difficult for the routing protocol to perform well.

Although such a simple mobility metric can not reflect all aspects of mobility, for these simple mobility models, it appears sufficient. More complex mobility metrics will be discussed in sections 5.3.1 and 5.8.2.

Border Behavior From the movement strategy it is obvious, that there is no border behavior required. The nodes always choose a destination within the area, so a border is never crossed (although it may be reached). Nodes cannot accelerate or decelerate. Their direction is determined by the current destination point, and the likelihood of moving is determined by the pause time (i.e. always moving, except during pause phase).

Area Size and Shape The odd area size of 1500 × 300m (which is used widely) is argued to stress the routing protocol more than like a 1000 × 1000m scenario. It allows a high node density but together with long paths,

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[4] The ranges are much more limited, i.e. the area is a 9 × 9m room, radio range of 3m, simulation for 4000 seconds with 6 to 24nodes.

without the need for much more nodes (which will lead to problems with the simulation due to the extended runtime).

5.2.2 Modified Random Waypoint Scenarios

A modified version appears in [JLH+99] where the model was extended such that the *pause time* is not globally fixed, but can be chosen at each individual movement. The area used was 1000×1000m but the simulation ran only for 250 seconds. In this paper more sophisticated scenarios have been used, as well; we will discuss them later.

In [BGB00] there is also a modified version called *Restricted Random Waypoint*. As the modification introduces some special regions, we will categorize this as a more advanced model in section 5.3.2.

5.2.3 Random Direction Scenarios

This scenario was described in [PR01]. Nodes move in a direction from $[0..2\pi]$ with a speed from [0..10] m/s until they hit the border. Then they wait a certain time, before choosing a new direction from $[0..\pi]$ relative to the "wall" (nodes are reflected from the borders). Thus, the border behavior plays an important part of the movement model itself, and is therefore defined in precise way. In this case, a contact with the border is even the only reason for a node to stop. It's characteristics are:

Area size:	1000×1000m, 1500×1500m, 2400×2400m and 3450×3450m
Radio Range:	250m
Number of nodes:	50 and 500
Speed of nodes:	[0..10] m/s
Direction:	$[0..\pi]$ relative to the "wall"
Pause times:	on each border hit, but duration not specified
Simulation time:	300 seconds

The authors of [HP01] is using a similar model, also with nodes being reflected from the border on contact, but not pausing. The are is 1000×1000m with 200 nodes and the radio range is 105m.

Both scenarios seem rather artificial and appear to provide the least realistic movement patterns for nodes like pedestrians, cars, bicycles, etc. Such a mobility model would be more appropriate for billiard balls.

5.2.4 Other Simple Scenarios

In [DCYS98] a much different approach was chosen. Each movement is specified by a triple of *direction*, *speed* and *distance*, which have been chosen at each step as follows:

Area size:	1000×1000m
Radio Range:	350m
Number of nodes:	30 and 60
Direction:	chosen from $[-\pi/8.. + \pi/8]$ relative to the previous direction.
Speed:	chosen from [0.4..0.6]m/s and [3.5..4.5]m/s
Distance:	exponentially distributed over a mean of 5m.
Simulation time:	10000 seconds

5.3 Advanced Scenarios

The following scenarios are more advanced:

Some introduce obstacles (hindering both node-movement and radio propagation). There are different types of nodes with different properties possible. Even certain regions within the area (subareas) are used, that impose certain restrictions to nodes in that subarea.

5.3.1 Johansson Scenarios

[JLH$^+$99] describes three scenarios, which are very different from the simple ones, and which appear far more realistic in terms of node behavior than the simple scenarios.

They allow the use of obstacles that absorb any communication, such that no link can go through an obstacle. Alas, the movement strategy is not described in the paper.

Mobility Metric This paper provides a much more complex mobility metric. The approach is general enough to be used as a basis for other scenarios. The following sketches the idea of the mobility metric:

$|v(x, y, t)|$ (with v being defined as the relative velocity of nodes x and y at time t) is averaged over time and then averaged over all node pairs. We don't repeat the exact definitions here, but refer to [JLH$^+$99].

Conference Room A conference room is modeled with a *speaker node*, several (rather static) listeners and a few people moving around. This is a rather static scenario. Only 10% of the nodes move, with a maximum speed of 1m/s. Most nodes are assigned to specific locations, but are still able to move, but it is not specified, how they move. Nodes can be blocked by obstacles. There are different types of nodes: a speaker, several curious bypassers and the remaining lot are attending listeners. Other known parameters are:

Area size:	150 × 90m
Radio Range:	25m
Number of nodes:	50
Speed:	< 1m/s
Simulation time:	900 seconds

Event Coverage & Disaster Area The *Event Coverage* scenario should model a large event, like a trade fair, with several groups and individuals moving on a large area. As in the *Conference* scenario, the nodes move with 1m/s but at least 50% of the nodes are moving. There are obstacles as well, and there is some chance that up to 10 nodes may form a group. The cause and implications of such a group forming are not stated clearly, but it is likely, that they move together. Also, the movement strategy is not described at all.

The *Disaster Area* (which obviously should resemble a site of a large accident) scenario differs only in the way of the node movement. There are three distinct areas, which nodes cannot leave and which are too far away for a direct communication. Nodes move randomly within each area. Two dedicated nodes (which should model helicopters) move between these areas with a much higher speed of 20m/s.

Parameters for both scenarios are:

Area size:	1500 × 900m
Radio Range:	250m
Number of nodes:	50
Speed:	< 1m/s and 20m/s for 2 nodes in Disaster Area
Simulation time:	900 seconds

5.3.2 Restricted Random Waypoint

The *Restricted Random Waypoint* scenario used in [BGB00] introduces *town* and *highway* regions. Within a *town* region, the usual *Random Waypoint* model (cf. section 5.2.1) is used. After a certain amount of moves, a node chooses a destination in another town. Additionally, there are *commuter* nodes, that move between the towns with a higher speed and a pause at each town for 1 second. Areas of 3500 × 2500m and 4500 × 3500m have been simulated with three *towns*. Each town is a square of 600m side length. The following parameters have been used:

Area size:	3500 × 2500m and 4500 × 3500m
Town size:	600 × 600m
Radio Range:	250m
Number of nodes:	400 (100 regular, 300 commuters) and 600 (with 500 commuters)
Speed:	$<$ 10m/s (regular nodes) and [10..20]m/s (commuters)
Pause time:	[0..200] seconds in steps of 50 (regular nodes) and 1 second for commuters
Steps in town:	20
Simulation time:	not specified

It is not clear, why this scenario is called *restricted.* It is possible, that the movement of the nodes can be regarded as more restricted than in the usual *Random Waypoint* model, since most nodes cannot leave a town area until a certain amount of moves, but are then forced to move to another town. Their freedom of choice is more limited in that sense.

5.4 Real installations: CMU Testbed

[MBJ99] describes a testbed with a real installation of DSR [JM96]. The scenario consisted of 5 cars with laptops equipped with standard WaveLAN cards, as well as two fixed nodes, 750 m apart. The cars move constantly in a loop around the fixed nodes, but there is real traffic on the roads. Until now, this was the only published testbed installation so far.

On March 25th and 26th, a successful test of real AODV implementation using both IPv4 and IPv6 was done at the UCSB. A report about that event is not yet available, at the writing of this text.

5.5 Modeling Turning and Acceleration: Smooth is Better than Sharp

C. Bettstetter proposed a *smooth* mobility model in [Bet01]. This is not a scenario description, as proposed in most other papers, but a fine grained movement model, that focuses on the kinetical characteristics of a move of each single node. It introduces acceleration and deceleration of nodes, as well as speed-correlated direction changes. To complete the model with some movement strategy, a Poisson process is assumed: It generates *speed change* and *direction change* events during the simulation time. The events are generated according to an exponential distribution, using $\lambda = p_{v^*}/\Delta t$, with p_{v^*} being the probability of a change event at each time step Δt.

So, unlike the other scenarios, the model does not assume individual discrete movements, but is driven by these speed change and direction change events.

This shows, that this model was not designed with the prerequisite, to work with simulation software packages, that just accept constant speed movement descriptions. The common simulation tools NS-2 [A^+] and GloMoSim [UW] have these limitations. However it is still possible to derive such movements from the model, by discretizing an accelerated movement into small steps of increasing (or decreasing) constant speed. The same is possible for the turns. The accuracy then depends on the time resolution, but a high resolution will result in an increasing amount of discrete constant-speed-movements, for a single move, on each speed change or direction change event.

5.6 Scenario Generators and CADHOC

There is a small set of scenario generators available, but most of them are only capable of generating scenarios already described above, i.e. *simple scenarios*, with some minor enhancements like group mobility (e.g. scengen[Qim]).

The only notable exception is CADHOC[SSH01]. CADHOC is a Java based scenario generator, that is capable of creating more "realistic" scenarios than other tools. The main advantage in terms of realism is, that it is possible to define regions where the nodes can move and where not. So one could create a building with rooms and halls for pedestrians, a street pattern for cars, etc. The initial location of each node can be specified, as well as movement patterns from a restricted set of strategies including a *Brownian movement* and a *pursuit model.*

CAHOC is also capable of generate data traffic between the nodes. However, this tool is very awkward to be used efficiently, as it is primarily GUI driven and requires a lot of resources to run. After the specification, it took a very long time to actually create the scenario. Although this was a very promising concept, it is unusable, if you want to create many different patterns from a single scenario specification, or worse if you want to specify many different scenarios and create even more unique scenarios[5] from each specification.

5.7 Why have these Scenarios been used

Although, there are a lot of advanced scenarios, they have been used rarely.

One could expect much more different or more sophisticated scenarios. So, why are these simple models chosen so often, instead? Two main reasons seem to be the cause:

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[5] In this context, a unique scenario is the set of exact movement and traffic instructions for each node at any time step.

Comparativeness: The random waypoint scenario with 1500×300m area was used in very early evaluations, like [BMJ$^+$98]. Subsequent developments and evaluations need to be comparative to the earlier results, such that a statement about the performance of the developed algorithm (or routing protocol) could be made. So even independent studies[6], that compared a whole set of routing protocols, used these scenarios (like [JLH$^+$99]).

Simulation Constraints: This may be the reason, why such a scenario was chosen in the first place. There are two simulation software packages, that are very commonly used in evaluating ad hoc networks. These are: NS-2[A$^+$] from the VINT project, Berkeley and GloMoSim[Uni99] a Parsec based simulation package developed at UCLA.

Sophisticated simulation software like NS-2 and GloMoSim (they model each network layer) results in complex calculations. The computing time and memory requirements does not scale with increasing node numbers. This makes it difficult to simulate more sophisticated scenarios. Especially NS-2 consumes a huge amount of resources for more than 50 nodes, and also produces huge amount of data. Simulations with more nodes and for a longer simulation time, are nearly impossible with NS-2, even on very powerful machines. GloMoSim seems to perform better, but still consumes a lot of memory.

5.7.1 Why the 1500×300m area?

Section 5.2.1 already covers some possible reasons. The dimensions are chosen relative to the transmitter range, which is commonly around 250m, so that in one direction multi-hop links are needed to be established. As mentioned before, a higher node density in combination with the need for multi-hop paths is achieved with a lower number of nodes. Another argument was, that the area is kept narrow to force movements primarily in the "extended" direction, thus causing link breaks and stressing the protocol.

5.7.2 Why random waypoint/random direction ?

The *random waypoint* model maps very good to the input data, NS-2 and GloMoSim require. So it is very easy to use the data of such a model with these two simulators. Also the model itself is simple and therefore simple

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[6] independent in the sense, that the author of the study is not also the author of a routing protocol

to implement. *Random direction* is equally simple and easy to map to the simulation software.

5.8 Critique of proposed scenarios

5.8.1 Node Behavior

The scenarios with most questionable behavior are clearly the *simple* scenarios. There is reasonable doubt, whether devices attached to people, or people operated vehicles, would move in a way as suggested by the *Random Waypoint* or *Random Direction* model. It has been found out in [TCD02], that the *Random Waypoint* model is vulnerable to some initialization problems, which lead to a very unstable neighbor set in the first $600 - 1000$ seconds of a simulation. Also a clear area with no obstacles or restrictions will only occur in rare cases in a real deployment. Further the observed time intervals are rather short, although this may be acceptable for such simple scenarios, since there would not change much over time.

From the more complex scenarios, the Johansson scenarios[JLH$^+$99] are a far step into the right direction. The scenarios have been modeled after certain real-life situations, there are obstacles, certain restricted movements and group mobility. More investigations regarding this work would have been very interesting. Johansson et al. did announce in their paper that more work was in progress, but it seems that it was never published. The simulation itself is questionable, as it seems that for each scenario only a single simulation was performed. From a statistical point of view, this is certainly not adequate. This major drawback was already pointed out in [CH01]. But since this problem is not related to the scenarios themselves, we consider them one of the more appropriate scenarios.

Apart from this work, and the possible usage of CADHOC[SSH01], there are no restricted regions, that could induce some kind of “channeling” of the nodes or force some other kind of correlated behavior. Different kinds of nodes and group mobility are only used in rare cases, although [Qim] would support both. Accelerated movement is not used at all.

5.8.2 Mobility Metric

The need to define a mobility metric parameter (as described in section 4) is not commonly seen. The parameters used (if at all) are very simplistic and do not reflect all aspects of mobility. A high speed of certain nodes does not necessarily mean a likely break of links (e.g. if all the nodes move together with that high speed in the same direction). The only exception is again [JLH$^+$99] which defines and uses a more sophisticated and reasonable mobility metric already described in section 5.3.1.

5.8.3 Number of Nodes

In most scenarios the number of nodes is relatively low. Many scenarios just simulate up to 50 nodes, a few cases did simulate up to 400 nodes. In my opinion a low number of nodes may be justified for certain kinds of scenarios, but it is certainly important to make more simulations with a higher number of nodes, possibly up to 10000.

Node density has been taken into account, on choosing the used scenarios and it is widely agreed, that node density is a crucial parameter of a scenario[7]. Strangely enough there have been no studies about the impact of node density over a variety of routing protocols.

5.8.4 Modeling of Physical Properties

The *Smooth is Better than Sharp* mobility model is a first attempt to add physical constraints to the movement of nodes, i.e. direction changes cannot occur all of a sudden, they must be made in terms of turns. Further, the current speed an impact on the turn radius. Speed changes are performed by acceleration and deceleration, and a direction change may also require a speed change first.

This is certainly important for more realistic scenarios. However, this model as proposed in [Bet01] has never been used in simulations of ad hoc networks so far.

The question is, if such realistic modeling of physical movement constraints will have a noticeable impact on simulation results. We suspect, that this will not be the case, since such mode realistic movements will not affect the density distribution within the area or will lead to a different number of link breaks.

The design of the *Smooth is Better than Sharp* model prevents a direct adaption in one of the common simulators, but it would be possible to modify it accordingly. So, it is very valuable as a reminder, to optionally add these physical constraints to future scenario generators. As NS-2 and GloMoSim do not support accelerated movement, and all discrete moves are straight, a turn and acceleration (and deceleration) must be emulated with intermediate steps. This will result in a tradeoff between accuracy and increased simulation time, due to the amount of intermediate steps.

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[7] The author has got this impression, from the various discussions on the MANET mailing-list, on which many scientist in this area participate.

5.8.5 Border Behavior

The use of the *Smooth is better than Sharp* model requires an explicit dealing with the crossing of a border. This is different to most scenarios which deal indirectly with the border (by not selecting “target” points beyond the area) or in a simple way (e.g. nodes are reflected).

Obviously, the problem of *border behavior* was not handled in a proper and thorough manner, yet. Either the problem is avoided or solved in a very simple way. It cannot be ignored, though, since [Bet01] and [TCD02] have also shown, that the border behavior has an important impact on the node distribution over the area, which affects density and therefore the simulation results.

A realistic approach would be to remove nodes crossing the area border, and of course it would be required to eventually introduce new nodes, that enter the area from a border. Other possibilities include a “wraparound” border, that instantly transports the node to an opposite position, from where it will resume its movement[8](cf. [TCD02]), or some kind of reflection method, as used in the *random direction* model.

Unfortunately, this aspect of the simulation depends very much on the capabilities of the simulation software. Especially the removal and introduction of nodes during the simulated period is not yet supported in the commonly used simulation software packages.

6 Requirements of Scenarios

Now, that we have pointed out some problems with the scenarios used so far, the question remains how to make things better.

First of all we take a look at the perspective from where to look at a routing protocol and what to focus on.

6.1 Other Views of Scenarios

As described, current scenarios observe a particular region of a given geometry and size, populated with a specific amount of nodes over a given time period. We will call this view an *area based model.*

If one observes a fixed area, with certain characteristics that resemble a particular location in the real world, like an office building, a popular town square or a battlefield, the movement pattern of nodes is not static, but

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[8] This would result in an area shaped as a torus.

varies over time. A typical time period that shows regular changes could be 24 hours.

Many people arrive at the office in the morning, then do their work, more or less distributed over the area, go for lunch around noon, leave the building in the evening with just a few people remaining there at night.

This example shows, that the environment in which the routing has to take place, may change a great deal over time. Parameters like node density can reach extremes during a certain period of a day, so this needs to be taken into account for a decision what routing protocol may be best suited to use (probably not a single one).

Depending on the time frame, such changes need to be considered in an *area based model*.

Depending on the problem, other possible views may be better suited. An obvious alternative would be a *node based model*: On observing nodes, some nodes will not be present in an particular area over the observed period. Nodes may move out of this area and into other ones.

So one could argue, the *area based model* is not correct, since the office building does not run any routing protocol at all, but the nodes do it. Thus it may be considered to choose a a scenario, that is not fixed on a certain location, but on a certain node, and describes it's environment (in terms of other nodes, density, obstacles, etc) over a certain period of time. Maybe a circle of a given radius around a fixed node, with his environment reflecting the various situations it is confronted with, could be an appropriate way.

On a first glance, such a model would be much more difficult to implement (mainly because fixed obstacles would change their location, from a single nodes view).

Thus it makes sense to think of a way to use the easier and well understood properties of an *area based model*, together with the more realistic changing environment of the *node based model*. A possible solution would be the following *phase based model*:

It appears possible to break down the changing environment of the *node based model* into a set of situations, like *driving through town to work*, *entering office building*, *work at workplace*, *attend meetings*, *go to lunch*, *have lunch*, *leave office building*, *drive home from work*, *spend remaining time at home.*

Such a sequence of more static scenarios which could be bound to specific areas, may reflect the changing environment (as in the *node based model*) well enough.

Although this is certainly not the ideal case, yet, it is certainly worth to be pointed out.

6.2 Movement Properties

How are nodes supposed to move then if not as described in the scenarios already used. We assume that each node is attached to a person or a vehicle, that is controlled by a person[9].

If we look at an individual node, it's movement can be described by two key properties.

Kinetical State We use this term to describe the triple of *current direction*, *current speed* and *current acceleration*.

Strategy The reason why a node has a certain *kinetical state*.

To explain this further, we look again at our existing scenarios and models. *Smooth is Better Than Sharp* is obviously dealing with the *kinetical state* properties in the first place. It controls speed and direction changes. However, there is also a *strategy* defined, which controls how such speed or direction changing events can occur.

In the simple scenarios, there is not much control of the *kinetical state*. Speed is chosen from a fixed interval with a predefined distribution. Direction is directly imposed by the *strategy*. There is no correlating rule between these properties. Acceleration is not taken into account at all. In *Random Waypoint* the *strategy* mainly works by choosing certain destination coordinates by random, and deciding not to move for a certain time, after the destination is reached. It is obvious, that the *strategy* of the simple scenarios is a random strategy.

For a good mobility model, both parts must be combined in a sensible way, although the *strategy* is the more important part, since the *kinetical state* is largely determined by the *strategy*. A more detailed *kinetical state* model (as in [Bet01]), will probably have not as much impact on performance results from simulations, as a more realistic *strategy* (cf. section 5.5).

6.3 Good Strategies

A key element, that is missing in most used *strategies* (which act more or less just random), is that nodes do not act just for themselves in the majority, but interact. Typically nodes interact with each other, but also interact with the environment, in a matter that affects often more than one node at a certain time in a certain region. The way, how nodes interact with each other and

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[9] A military drone, that is controlled by a computer, would not fall in this category. However we argue, that for the implications of our assumption it will not matter.

the environment is highly dependent on the role a node assumes. Cars move different than pedestrians and they are much different from paratroopers.

The formation of groups, which is already considered in some mobility models, is a good example for node interaction. Other examples (focused on people in an urban area) include:

- People want to meet each other
- People want to visit a certain location (office building, shop, cinema, conference room).
- Cars form lanes and keep a certain distance to other cars (and other obstacles).
- Traffic lights cause a set of nodes to stop in a relatively small area for a certain time interval.
- Pedestrians will stay on the sidewalk if possible.
- Cars will always stay on the road.
- ...

All these interactions cause a certain concentration of nodes at certain locations. These locations can be considered as hot-spots, since nodes tend to appear in groups at these locations and thus will increase the node density.

Since node density is a factor of important influence (increased node density results in increased competition about the physical channel) on the performance of many Ad Hoc routing protocols, it can be deduced, that this interactive behavior of nodes should be part of the investigation. A pattern mainly consisting of random movements, may show useless results, if the modeled scenarios never appear in the real world (or in very rare cases).

Group mobility is an aspect of such behavior that is already part of some existing models.

6.3.1 Crafting of Good Mobility Models

So: how to craft a good mobility model, that takes the arguments in section 6.3 into account?

A very good thing to start with would be empirical data. To collect a representative set of such data from possibly thousands of people at various places over a long period of time seems impossible.

In an experiment I have tried to track my location over a long time with a GPS receiver. Alas, this was very unfruitful, although it consumed a lot of time and effort, and I was just tracking a single person.

However, it is likely that telecommunication carriers for mobile phone networks did collect such data on a large scale, since such tracking data of mobile phone users is crucial for the layout and structure of communication cells. Also it is easy to track mobile phone users, since the transceiver base stations can act as reference points with a known location[10].

Unfortunately, phone companies do not seem to give away such data to the public and not even to the research community. Our attempts to get hold of such tracking data have been unsuccessful. Thus this helpful start is unfortunately not available.

I shall propose a way, how to formally describe a scenario, that can take many of the interacting properties into account, although it cannot be comprehensive. The following model will focus on the *strategy*, and has the option to include a detailed *kinetical state* model, too, but this is not required.

6.4 The Interactive Mobility Model

We will introduce a mobility model based upon several components that can be described through various parameters. An implementation needs to take these parameters into account and create movement instructions for the nodes according to these specified rules.

6.4.1 Basic Components and Types

Nodes are the basic components of the simulation and they are also basic components of the scenario description. As a scenario likely includes various different types of nodes, we allow to define these types.

A node type definition should at least include the following characteristics:

- maximum speed
- maximum acceleration
- maximum deceleration
- turning factor[11]

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[10] The ability to locate the user of a mobile phone, is also required by law in some countries for the future, to enable rescue services finding someone, who calls in an emergency, or for law enforcement to get hold of criminals.

[11] This determines, how fast the node is able turn at a certain velocity.

Nodes may further be combined into groups, that will show some common movement behavior. It will be likely, that only nodes of the same type may form a group. The group will act as a large blurred node with typical node characteristics as described above. Also the group will have characteristics like:

- maximum diameter
- node movement strategy within the group
- node density within group
- number and types of group member nodes
- probability of nodes joining or leaving the group

Then we need to define certain types of **regions** within the area. The regions itself are described by geometric properties, but we also need several types of regions, to reflect their characteristics.

A possible set of characteristics of a type of a region is:

- attractive to nodes of types [..] by degree $d \in [0..1]$
- forbidden for node types [..]
- restricted to node types [..]
- maximum speed in this area
- nodes in this area are forced to stop at certain intervals[12]

A value greater than 0.5 for the *degree of attraction* d, is considered attractive, a value below is repelling, exact 0.5 would be neutral. This property can also be included into the nodes, such that nodes of certain type are attractive or repellent to each other (e.g. cars like to avoid other nodes to prevent an accident, so they would be repellent to any other node to a certain degree).

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[12] This can be used to model traffic lights at an intersection.

6.4.2 Scenario Specification

Now from the defined types we can build the specification, which needs to contain:

- Number of nodes of Type n
- Region of type r, at coordinates $(x1, y1, x2, y2, \ldots)$
- Node-groups

These specifications define a scenario with individual movement strategies for nodes and region and node dependent constrains. This allows to derive a concrete scenario with exactly determined node movements, suitable to feed into a simulator. The specification leave enough degrees of freedom for sensible random behavior in terms of probability functions, without letting the nodes just behave arbitrary.

6.4.3 Implementation Aspects

For an implementation, the scenario specification described needs to be formulate in a language. We suggest to use XML for this purpose, since parsers and validators are widely available, and XML is flexible enough to allow specification of all aspects in a simple and intuitive way. Other specification languages, e.g. C-style are of course also possible.

7 Conclusion and Outlook

We have developed certain criteria, how to categorize scenarios for simulation of mobile ad hoc networks. We have inspected and classified scenarios used in previous evaluating simulations. Further we have illustrated the drawbacks and problems with the scenarios used. Requirements for more realistic scenarios have been proposed and we have suggested a way, how to specify more adequate (in terms of reality) scenarios.

An implementation of a scenario-generator, that is based on this work, is currently in progress. We hope to present results in Fall 2002.

Scientists using such a scenario specification for simulations still need to define the scenario characteristics. A lot of effort may e required to find specifications that will match a real world situation close enough to derive really applicable results from the simulation. A meta tool, that can generate sensible scenarios of a set of predefined types would be helpful, but this problem is not further discussed in this work.

A Examples

A.1 Type Definitions

A.1.1 Nodes and Node-groups

```
<NODETYPE>
  <NAME>Car</NAME>
  <MAXSPEED>40</MAXSPEED>
  <MAXACCEL>6</MAXACCEL>
  <MAXDECEL>12</MAXDECEL>
  <TURNING>...</TURNING>
  <ATTRACTION type="node" degree="0.2">Car</ATTRACTION>
  <ATTRACTION type="node" degree="0.2">Pedestrian</ATTRACTION>
  <RESTRICTION>Road, Crossing, ZebraCrossing</RESTRICTION>
  <FORBIDDEN>Building</FORBIDDEN>
</NODETYPE>

<NODETYPE>
  <NAME>Pedestrian</NAME>
  <MAXSPEED>2</MAXSPEED>
  <MAXACCEL>2</MAXACCEL>
  <MAXDECEL>2</MAXDECEL>
  <TURNING>...</TURNING>
  <ATTRACTION type="node" degree="0.2">Car</ATTRACTION>
  <ATTRACTION type="node" degree="0.6">Pedestrian</ATTRACTION>
  <ATTRACTION type="region" degree="0.2">Road</ATTRACTION>
  <ATTRACTION type="region" degree="0.7">Sidewalk</ATTRACTION>
  <ATTRACTION type="region" degree="0.8">ShopEntrance</ATTRACTION>
  <FORBIDDEN>Building</FORBIDDEN>
</NODETYPE>

<NODEGROUPTYPE>
  <NAME>Projectteam1</NAME>
  <NODES>Pedestrians</NODES>
  <MAXDISTANCE>25</MAXDISTANCE>
</NODEGROUPTYPE>
```

A.1.2 Regions

```
<REGIONTYPE>
```

```
  <NAME>Road</NAME>
  <CONSTRAINT type="maxspeed">20</CONSTRAINT>
</REGIONTYPE>

<REGIONTYPE>
  <NAME>Crossing</NAME>
  <SPECIAL type="stop-on-enter" value="60">Car</SPECIAL>
  <SPECIAL type="stop-on-enter" value="60">Pedestrian</SPECIAL>
</REGIONTYPE>

<REGIONTYPE>
  <NAME>ZebraCrossing</NAME>
  <SPECIAL type="stop-on-enter" value="60">Car</SPECIAL>
  <SPECIAL type="stop-on-enter" value="2">Pedestrian</SPECIAL>
</REGIONTYPE>

<REGIONTYPE>
  <NAME>Sidewalk</NAME>
</REGIONTYPE>

<REGIONTYPE>
  <NAME>ShopEntrance</NAME>
  <SPECIAL type="stop-on-enter" value="600">Pedestrian</SPECIAL>
</REGIONTYPE>

<REGIONTYPE>
  <NAME>Building</NAME>
</REGIONTYPE>
```

A.2 Scenario Specification

```
<SCENARIO>
  <NAME>Stachus</NAME>
  <AREA>2000,3000</AREA>
  <NODES type="Car">0,20</NODES>
  <NODES type="Pedestrian">21,30</NODES>
  <NODES type="Pedestrian">31,50</NODES>
  <NODEGROUP type="Projectteam1">21,27</NODEGROUP>
  <REGION type="Road" shape="rectangle">0,200,300,200,0,220,300,220</REGION>
```

```
  <REGION type="Crossing" shape="rectangle">300,200,320,200,300,220,320,220</REGIO
  <REGION type="Road" shape="rectangle">320,200,600,200,320,220,600,220</REGION>
  ...
</SCENARIO>
```

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