Paper

A survey on mobility models for performance analysis in tactical mobile networks

Nils Aschenbruck, Elmar Gerhards-Padilla, and Peter Martini

Abstract—In scenarios of military operations and catastrophes – even when there is no infrastructure available or left – there is a need for communication. Due to the specific context the communication systems used in these tactical scenarios need to be as reliable as possible. Thus, the performance of these systems has to be evaluated. Beside field-tests, computer simulations are an interesting alternative concerning costs, scalability, etc. Results of simulative performance evaluation strongly depend on the models used. Since tactical networks consist of, or, at least, contain mobile devices, the mobility model used has a decisive impact. However, in common performance evaluations mainly simple random-based models are used. In the paper we will provide classification and survey of existing mobility models. Furthermore, we will review these models concerning the requirements for tactical scenarios.

Keywords— mobility models, performance analysis, wireless networks, mobile networks, tactical networks.

1. Introduction

Military operations as well as catastrophes, be it natural ones (like hurricanes or tornados), man-made ones (like explosions or fires), or technical ones (like material-fatigue), cause an area of destruction. Buildings, bridges, as well as the infrastructure of the private and public systems for mobile communication might be destroyed. Hence, units working in these disaster areas need reliable communication which is independent of any infrastructure.

As the communication systems used in these tactical or disaster area scenarios need to be as reliable as possible, the performance of these systems has to be evaluated. Field-tests in manoeuvres may be the preferred evaluation method. However, they are expensive, as sufficient hardware is needed. Furthermore, the results concerning some characteristics (e.g., scalability) are limited – who can perform field-tests with several hundreds of devices? Thus, especially for the evaluation of algorithms and protocols, simulation is an alternative.

Naturally, the results of simulative performance evaluation strongly depend on the models used. Since tactical networks consist of, or, at least, contain mobile devices, the mobility model used has a decisive impact. However, in common performance evaluations mainly simple random-based models are used.

In the paper our aim will be to give a survey on mobility models used for performance evaluation in tactical mobile networks. As tactical networks may also be networks without infrastructure, the individual nodes and there movement characteristics need to be modeled. In this paper we will focus on models that realize the movement of individual nodes (microscopic models). In the literature there are already some surveys on mobility models [2, 4, 11]. However, these surveys are quite old or miss a lot of specific models. Furthermore, there is no review concerning the requirements for tactical scenarios. Thus, in this paper we will give a survey on existing mobility models and classify and review these models concerning the requirements of tactical communication systems.

The remaining part of this paper is structured as follows: Section 2 points out requirements for tactical communication. Next, we will introduce the way the existing models are classified (Section 3). After that, we will give a survey on existing models and review to which extent these models meet the requirements of tactical scenarios (Sections 4–8). Finally, we will conclude the paper (Section 9).

2. Requirements

The users of tactical communication systems are military or civil (e.g., civil protection) forces. These forces are strictly structured (e.g., platoons, groups, etc.) and their actions are strictly organized. The units do not walk around randomly. There is one leader or a group of leaders which tells everybody where and how to move or in which area to work. In general, the movements are driven by tactical reasons. Due to this, the units normally use the optimal path to a destination.

The destinations depend on the working site which is based on tactical issues. The tactics as well as the scene are usually hierarchically organized. Typically, the site is divided into different tactical areas. Each unit belongs to one of these areas. For example, in a disaster area scenario a firefighter belongs to an *incident site* and a paramedic will work at one place in the *casualties treatment area*. The units sent to a specific location once will typically stay close to this location. Some of them may have special tasks that make them move from one area to another (e.g., transport units). However, the major part of the units does not leave the area. Thus, the area in which a unit moves depends on tactical issues but is restricted to one specific area.

Furthermore, as tactical scenarios take place in areas of destruction, obstacles might be encountered. Smaller ones may be ignored, because they only have little impact on the movement. However, larger ones (walls, houses, etc.) will have a certain impact on movements.

In tactical networks, units and troops often move in tactical formation. Even if the detailed position may only have little impact, this fact implies group mobility. Moreover, there are units of different types. The units typically differ in their equipment. Some of them possess vehicles and use them resulting in faster movement. Others are pedestrians and move slower. Thus, there is heterogeneous velocity based on the type of node.

Finally, especially in tactical communication systems, it is quite common that units leave the scenario, while others join later on. In military scenarios there may be fatalities, and in civil protection scenarios there may be units that take patients to hospital. When some units leave the scenario, typically others are requisitioned.

As a conclusion, the analysis yields the following main requirements:

- heterogeneous velocity,
- tactical areas,
- optimal paths,
- obstacles,
- units join and leave the scenario,
- group movement.

The following sections present existing mobility models and examine which models meet these requirements.

3. Classification

In general, the mobility models can be classified according to the different kind of dependencies and restrictions that are considered.

- **Random based**. There are neither dependencies nor any other restriction modeled.
- **Temporal dependencies**. The actual movement of a node is influenced by the movement of the past.
- **Spatial dependencies**. The movement of a node is influenced by the nodes around it (e.g., group mobility).
- **Geographic restrictions**. The area in which the node is allowed to move is restricted.
- **Hybrid characteristics**. A combination of temporal dependencies, spatial dependencies, and geographic restrictions is realized.

4. Random based movement

The mobility model often used in the last years (especially in performance evaluation of ad hoc networks) is the *random-waypoint* model. The random-waypoint model is a simple stochastic model in which a node perpetually chooses destinations (waypoints) and moves towards them. In the original model [21] the nodes are distributed randomly over the simulation area. After waiting for a constant pause time, each node chooses a waypoint and moves towards it with a speed chosen from an interval $[\upsilon_{\min}; \upsilon_{\max}]$. After arriving at the waypoint, the node again waits for a constant pause time and chooses the next waypoint. In [30] it is proposed to also choose the pause time from an interval $[p_{\min}; p_{\max}]$. The different random variates are mostly chosen uniformly distributed.

In the last years, there were several studies that analyze the random-waypoint model with respect to implicit (unwanted) assumptions and characteristics. As the nodes are initially distributed randomly, it takes some time until the nodes reach a stationary distribution (cf. [28]). Thus, a long enough initial period should be discarded. In [36] it is shown that the average velocity is decreasing over simulation time if $v_{\min} = 0$. Thus, $v_{\min} > 0$ and $p_{\max} < \infty$ should be chosen. Furthermore, in several publications it was shown that the nodes cumulate in the middle of the simulation area (cf. [6, 7, 10]). For a square simulation area a density as shown in Fig. 1 results.

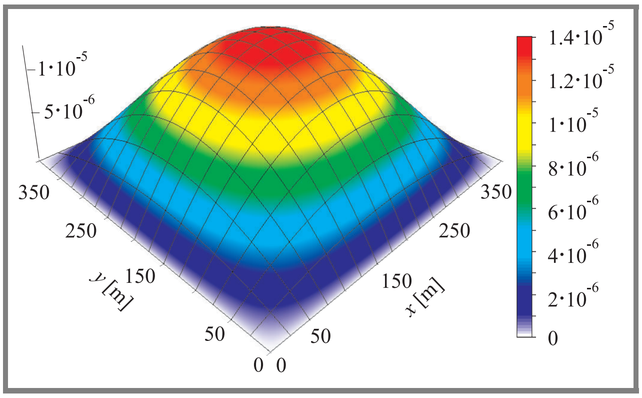

Fig. 1. Density for the random-waypoint model.

A distribution and movement of the nodes across the entire simulation area does not fit to the characteristics of most realistic movements. There are extensions (e.g., [7]) which add attraction points to this model in order to generate more realistic non-equally distributed mobility. The probability that a node selects an attraction point or a point in an attraction area as next waypoint is larger than the choice of other points. The nodes visit some points more frequently than others. Hence, they still move across the complete simulation area. The *clustered-mobility* model [24] is motivated by disaster areas and uses a similar approach. The difference is that the attraction of a point depends on the amount of nodes nearby. This implies that the areas of higher density variate concerning the intensity and position. Further approaches like the *random-direction* model [31], *random-border* model [7], and the *modified-random-direction* model [31] also result in fully random movement with different node density distributions.

All random-based models result in random movement across the complete simulation area. The models are quite simple to implement, but the only characteristics of an tactical scenario that is realized are the optimal paths. However, at least heterogeneous velocity may be integrated quite easily.

5. Temporal dependencies

Using one of the models of the previous section, the nodes suddenly may change speed or direction. This is quite unrealistic considering aspects like acceleration and deceleration. The models presented in this section realize such aspects by using temporal dependencies.

In the *Gauss-Markov* model [23] velocity and direction of the future (time interval $t+1$) depend on the current values (time interval t). Initially for each node position, velocity, and direction are chosen uniformly distributed. The movement of each node is variated after an interval δt. The new values are chosen based on a first-order autoregressive process. Further details can be found in [23].

The *smooth-random* model [4, 5] is a more detailed approach. The nodes are classified concerning their maximum velocity, preferred velocity, maximum acceleration, and deceleration. New velocities and directions are calculated based on these parameters and the current ones. Velocity and direction may also be chosen in correlation to each other. By doing so, more realistic movements like deceleration before a change of direction may be realized.

By using one of these models and realizing the temporal dependencies the movements of the nodes become smoother concerning direction and velocity. However, typical characteristics of tactical scenarios are not realized in this approach.

6. Spatial dependencies

Beside temporal dependencies there are also spatial ones. Nodes may move together in groups. Thus, the movement of one node may influence the movement of others around him.

One approach to realizing spatial dependence is the use of reference points. The *reference-point-group-mobility* model (RPGM) [15] models the movement of groups of nodes. The movement of the groups is modeled according to an arbitrary mobility model. The movement of the nodes inside a group is realized using a reference point for each node. The actual position of a node is a random movement vector added to the position of his reference point. The absolute positions of the reference points do change according to the arbitrary mobility model, but the relative positions of the reference points inside a group do not change. Hence, the spatial dependence is realized using the reference points.

In [9] a variance of the model called *structured-group-mobility* model is proposed. In this model there is no random movement vector. The nodes of a group move in a fixed non-changing formation. The formations are motivated by firefighter, police, and tanks. However, even if there is a formation of tanks, there may be some variances due to obstacles. In literature there are also found several other variances of the RPGM model, e.g., *column* model, *pursue* model, *nomadic-community* model (cf. [11, 34]).

Another approach to realize spatial dependence is to found on social networks. The *social-network-founded* mobility model [26] bases on interaction indicators for all pairs of nodes – the larger an interaction indicator, the larger the probability of a social relationship, the smaller the geographic distance. Initially the nodes are grouped in clouds according to their interaction indicator. The clouds as well as the nodes inside the clouds move according to a random-waypoint model, where the waypoints are chosen according to the interaction indicators as well. In [27] this approach is reinvented as *community-based* mobility model. Different more realistic algorithms are used for the classification of the nodes into groups and the movement inside the clouds. Furthermore, the interaction indicators are modified over time.

For realizing group mobility in tactical scenarios, the RPGM model seems to be the better approach, as with an appropriate choice of parameters relative positions of nodes inside the groups can be modeled explicitly. Using the RPGM model, beside the characteristic of group movement, other characteristics may be realized by using an appropriate model for the reference points.

7. Geographic restrictions

Beside considering temporal and spatial dependencies, for many scenarios it is unrealistic to assume that the nodes are allowed to move across the entire simulation area. There are very different approaches to restrict the nodes movement to certain parts of the simulation area. The following sections will describe several approaches realizing the different kind of geographic restrictions.

7.1. Graph-based approaches

A quite intuitive approach is to manage the allowed paths in a movement graph. The *graph-based* mobility model [35] realizes a graph whose vertices are the possible destinations and whose edges are the allowed paths. Based on this graph a random waypoint approach is used. The nodes initially start at a random position on the graph, choose a destination (vertex), move there at random velocity, and choose the next destination and velocity.

Another approach that is using graphs is the *weighted-waypoint* mobility model [16]. The vertices of the graph are specific areas (e.g., classroom, cafe, etc.). The nodes choose destinations inside these areas. The directed edges of the graph contain probabilities of choosing a destination in the directed area depending on the current area. Having chosen a waypoint, the nodes move there on the direct way similar to the random-waypoint model. Compared to the graph-based model, the movement is not restricted to distinct paths.

7.2. Voronoi-based approaches

One possibility of modeling simulation areas with obstacles is to determine the movement paths or areas using Voronoi-diagrams. This approach was first introduced with the *obstacle* mobility model [18, 19]. In this model, the edges of the buildings (e.g., of a campus) are used as an input to calculate a Voronoi-diagram. The movement graph consists of the Voronoi-diagram and additional vertices. These vertices are the intersection of the edges of the Voronoi-diagram and the edges of the obstacles. They model entrances to obstacles (e.g., buildings). The movement on the graph is realized similarly to the graph-based model. By using Voronoi-diagrams, the paths are modeled equidistant from all obstacles. Considering the requirements of tactical networks, these are not necessarily the optimal paths. Furthermore, even for a campus network it is a strong assumption that all streets are built equidistant from all buildings and all nodes move in the middle of the street. In [37] the approach is extended to realize buildings and streets more realistically. In the Voronoi mobility model movement, paths are refined to movement areas. The nodes choose their destinations inside these areas. The movement using this model is more realistic, as streets and buildings are realized more precisely. However, there is still no movement on optimal paths.

7.3. Division-based approaches

Another approach is to divide the simulation area in subareas and to use in them arbitrary mobility models.

The *area-graph-based* mobility model [8] tries to realize clusters (sub-areas) with higher node density and paths in between with lower node density. The clusters are regarded as vertices of the area graph while the paths are regarded as edges. A weight (probability) is assigned to each edge. A node moves inside the cluster for a randomly chosen time according to the random-waypoint model. After this time, he chooses one path according to probabilities at the edges. Next, the node moves on the path to the next area.

A similar approach is used in *CosMos* [14]. The simulation area is subdivided into non-overlapping zones. In each zone the nodes move according to an arbitrary mobility model. The transition between the zones is realized similarly to the area graph based mobility model using transition probabilities. If a node is chosen to change the zone, he moves to a handover area and switches to the other mobility model.

Considering tactical scenarios, both models contain interesting aspects as it is possible to realize tactical areas. However, neither of the model realizes all requirements of tactical scenarios.

7.4. Map-based approaches

A further approach to restrict the movement area geographically is to use information from road maps.

In the context of the UMTS standardization, the so-called *Manhattan-grid* model was specified [13]. The simulation area is divided into squared blocks. Nodes are modeled as pedestrians moving on the vertices of the squares (streets). Initially the nodes are randomly distributed on the streets. Each node chooses a direction and a velocity. If a node reaches a corner, the node changes direction with a certain probability. The velocity is changed over time.

The *random-waypoint-city* model [22] realizes vehicular traffic in urban environments. Therefore, road maps including speed informations and crossroads are retrieved. A node chooses a destination on the streets similar to the random-waypoint model and chooses a route after an arbitrary metric (e.g., smallest travel time). At the crossroads delays are modeled according to the amount of roads. Furthermore, an equal distribution of the nodes throughout the simulation area is realized.

In [25] two further models are described which realize mobility models (e.g., random-waypoint) on graphs based on road maps.

In respect to the requirements of tactical scenarios these models seem to be not applicable. On the one hand, the requirements are not realized, on the other, the streets on which the maps base may be destroyed.

8. Hybrid characteristics

In the previous sections several models were described that could quite clearly be assigned to one class of dependencies. However, there are also some models that realize hybrid dependencies and restrictions.

8.1. Complex vehicular traffic models

The *freeway* mobility model [3] realizes temporal and spatial dependencies as well as geographic restrictions. The nodes variate their velocity in dependence to their current velocity (temporal dependencies). Furthermore, the velocity is influenced by the velocity of a vehicle on the same line inside a certain radius (spatial dependence). The overall movement is restricted to a freeway (geographic restrictions).

The *street-random-waypoint* model (STRAW) [12] uses information from maps similar to the random-waypoint-city model. However, the actual movement of the vehicles is realized according to vehicular congestion and simplified traffic control mechanisms. The model realizes temporary dependencies (acceleration), spatial dependencies (to other vehicles) and geographic restrictions (streets).

Both models are specific for vehicular road-traffic and do not fit to a tactical scenario.

8.2. User-oriented meta-model

A general approach to modeling complex scenarios is described in [32] as *user-oriented mobility meta-model*. The model consists of three components:

1. Modeling the simulation area containing restrictions concerning the movements as well as attraction points.
2. Sequences of movement made by a user, e.g., a sequence of attraction points.
3. Temporal and spatial dependencies concerning the movements of a user.

Using this model, typical movements of node during a day may be modeled (cf. [33]). This abstract meta-model is generic and can be seen as general description of many other models. The requirements of tactical scenarios may be realized using this abstract meta-model. However, the concrete realization of the requirements is not specified in the meta-model.

8.3. Models for tactical scenarios

Apart from a lot of generic models, there are also some approaches to realize specific scenarios. In [20] three scenarios are considered. Beside a conference and a concert scenario there is also a *catastrophe scenario*. In the scenarios, obstacles, group movements, and tactical areas are considered. As one example for a military scenario in [17] a *hostage rescue scenario* was specified. The scenario is divided into periods (e.g., march, pull, fallback). The movement is modeled with regard to the specific phases. Another scenario [29] models the movement of a platoon in a city area. All these scenarios – the catastrophe, the hostage rescue as well as the platoon scenario – realize several requirements of tactical scenarios. However, they are only specific scenarios that are restricted concerning scalability, e.g., the amount of nodes and the size of the simulation area.

8.4. Disaster-area model

In [1] a model which realistically represents the movements in a disaster area scenario is provided. This model supports heterogeneous area-based movement on optimal paths avoiding obstacles with joining/leaving of nodes as well as group mobility.

To realize area-based movement, the simulation area is divided into polygonal tactical areas. The tactical areas are classified according to the civil-protection concept *separation of room* (cf. Fig. 2). Each node is assigned to one of these tactical areas. For some areas there are both stationary nodes, which stay in the distinct area moving according to a random based mobility model, as well as transport nodes that carry the patients to the next area following a movement cycle. Different areas and classes allow heterogeneous speeds. The area and the class (stationary or transport) the node belongs to define the movement of the node as well as the minimal and maximal speed distinguishing pedestrians from vehicles.

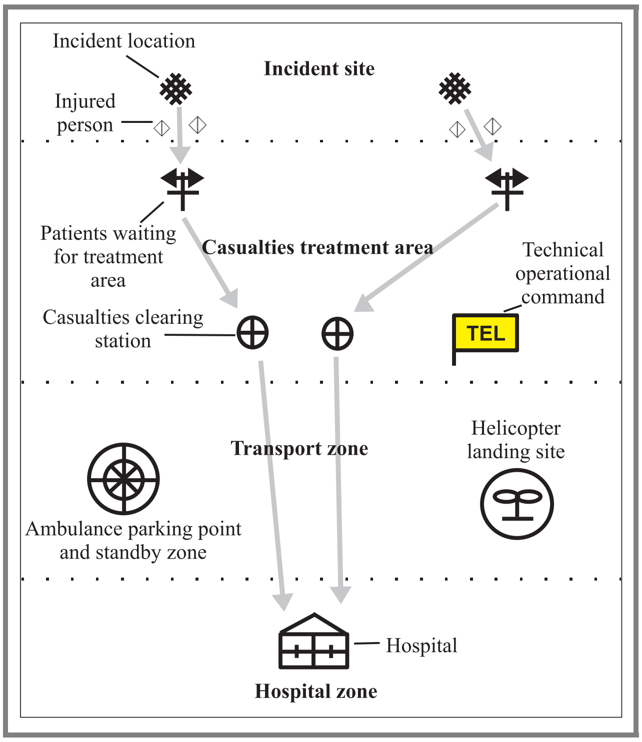

Fig. 2. Separation of the room in civil protection.

The optimal path for the movement of the transport units between the different areas is determined by methods of robot motion planning. For finding the shortest paths and avoiding obstacles between the tactical areas, visibility graphs are used. A visibility graph is a graph where its vertices are the vertices of the polygons. There is an edge between two vertices, if the vertices can "see" each other – meaning the edge does not intersect the interior of any other obstacle. The shortest path between two points consists of an appropriate subset of the edges of the visibility graph. Thus, after having calculated the visibility graph containing all possible shortest paths between the areas avoiding obstacles, the direct path between two areas for each transport unit can be calculated.

Vehicular transport units (e.g., ambulances) typically leave the disaster area to carry patients to hospital. Thus, joining and leaving nodes are realized using specific entry and exit points (registration areas).

Group mobility is realized as an optional characteristic for disaster areas, as in civil protection there may only be one device for each group. Nevertheless, it is realized similar to RPGM [15] using reference points. The units of each area are grouped. The size of the group depends on the type of the area and the group. Similar to RPGM the nodes follow their reference point. The movement of each node in a group is calculated in relation to the movement of the reference point.

Table 1
Survey on an requirement analysis of existing mobility models

Model		Dependencies			Requirements for tactical scenarios					
		Temporary	Spatial	Geographical	Heterogeneous velocity	Tactical areas	Optimal paths	Obstacles	Units leave the scenario	Group movement
Random-waypoint	[21]				(√)	(√)	√			
Random-waypoint with attraction points	[7]				(√)	(√)	√			
Clustered-mobility	[24]		(√)		(√)	(√)	√			
Random-direction	[31]				(√)	(√)	√			
Random-border-model	[7]				(√)	(√)	√			
Modified random-direction	[31]				(√)	(√)				
Random-walk	[11]				(√)	(√)				
Gauss-Markov	[23]	√			(√)	(√)				
Smooth-random	[5]	√			√	(√)	√			
Reference-point-group	[15]	(√)	√	(√)	(√)	(√)	(√)	(√)	(√)	√
Structured-group	[9]		√		(√)	(√)				√
Social-network-founded	[26]		√		(√)	(√)				√
Community-based	[27]		√		(√)		√			√
Graph-based	[35]			√	(√)		√	(√)		
Weighted-waypoint	[16]			√	(√)		√			
Obstacle	[18]			√	(√)			√		
Voronoi	[37]			√	(√)			√		
Area-graph-based	[8]			√	(√)	√	(√)	(√)		
CosMos	[14]			√	(√)	√	(√)			
Manhattan-grid	[13]			√	(√)					
Ramdom-waypoint-city	[22]			√	(√)					
Graph-random-waypoint	[25]			√	(√)					
Graph-random-walk	[25]			√	(√)					
Freeway	[3]	√	√	√	(√)					
Street-random-waypoint	[12]	√	√	√	√					
User-oriented-meta-model	[32]	√	√	√	√		√	√		√
Catastrophe-scenario	[20]		√	√	√	√		√		
Hostage-rescue	[17]		√	√	√					
Platoon	[29]		√	√	√					√
Disaster-area-model	[1]		√	√	√	√	√	√	√	√

9. Conclusion

Finally, we want to discuss which requirements are realized and which approaches model tactical scenarios. Table 1 sums up the survey and requirements analysis that was provided in the paper. In the table for each model the dependencies considered as well as the requirements modeled are shown. A "√" means "explicitly modeled", while a "(√)" means "not modeled but can be easily extended". For example *heterogeneous velocity* is not considered in all models. However, it is quite easy to extend the models supporting heterogeneous velocities for different classes of nodes. *Tactical areas* are explicitly realized in some models. Others may be easily extended using an approach like the area-graph-based model. *Group movement* may be easily integrated in other models using the reference point approach. The other requirements *optimal paths*, *obstacles*, and *units join and leave the scenario* are considered in some specific models. However, beside the disaster area model there is no model that considers combinations of all of them.

The disaster-area model is a model that realizes mobility for one tactical scenario in detail, considering all the requirements. This scenario may also be used for the performance evaluation of communication systems for military usage. However, with respect to a military usage of a communication system, medical or humanitarian scenarios similar to civil protection are not the only ones to be considered. There may be totally different characteristics in other specific military scenarios that may have a certain impact on the performance of the communication systems. There are valuable first realizations of specific scenarios, e.g., the hostage rescue and the platoon scenario. However, in the future new scalable models for military scenarios should be invented. Furthermore, the characteristics of these, and, within this, the impact on existing performance evaluation results should be examined.

References

[1] N. Aschenbruck, E. Gerhards-Padilla, M. Gerharz, M. Frank, and P. Martini, "Modelling mobility in disaster area scenarios", in *Proc. 10th ACM IEEE Int. Symp. Model. Anal. Simul. Wirel. Mob. Syst. MSWIM*, Chania, Greece, 2007.

[2] F. Bai and A. Helmy, "Wireless ad hoc and sensor networks", Chapter 1: "A survey of mobility models", 2004, http://nile.usc.edu/ helmy/important/Modified-Chapter1-5-30-04.pdf

[3] F. Bai, N. Sadagopan, and A. Helmy, "IMPORTANT: a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks", in *Proc. IEEE INFOCOM*, San Francisco, USA, 2003, pp. 825–835.

[4] C. Bettstetter, "Mobility modeling in wireless networks: categorization, smooth movement, and border effects", *ACM SIGMOBILE Mob. Comp. Commun. Rev.*, vol. 5, no. 3, pp. 55–66, 2001.

[5] C. Bettstetter, "Smooth is better than sharp: a random mobility model for simulation of wireless networks", in *Proc. 4th Int. Symp. Model. Anal. Simul. Wirel. Mob. Syst. MSWIM*, Rome, Italy, 2001, pp. 19–27.

[6] C. Bettstetter, G. Resta, and P. Santi, "The node distribution of the random waypoint mobility model for wireless ad hoc networks", *IEEE Trans. Mob. Comp.*, vol. 2, no. 3, pp. 257–269, 2003.

[7] C. Bettstetter and C. Wagner, "The spatial node distribution of the random waypoint mobility model", in *Proc. 1st German Worksh. Mob. Ad-Hoc Netw. WMAN'02*, Ulm, Germany, 2002, pp. 41–58.

[8] S. Bittner, W.-U. Raffel, and M. Scholz, "The area graph-based mobility model and its impact on data dissemination", in *Proc. IEEE PerCom*, Kuaai Island, Hawaii, USA, 2005, pp. 268–272.

[9] K. Blakely and B. Lowekamp, "A structured group mobility model for the simulation of mobile ad hoc networks", in *Int. Conf. Mob. Comp. Netw., Proc. 2nd Int. Worksh. Mob. Manag. Wirel. Acc. Protoc.*, Philadelphia, USA, 2004, pp. 111–118.

[10] D. M. Blough, G. Resta, and P. Santi, "A statistical analysis of the long-run node spatial distribution in mobile ad hoc networks", *Wirel. Netw.*, vol. 10, pp. 543–554, 2004.

[11] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research", *Wirel. Commun. Mob. Comp.*, vol. 2 no. 5, pp. 483–502, 2002.

[12] D. R. Choffnes and F. E. Bustamante, "An integrated mobility and traffic model for vehicular wireless networks", in *Int. Conf. Mob. Comp. Netw., Proc. 2nd ACM Int. Worksh. Veh. Ad Hoc Netw.*, Cologne, Germany, 2005, pp. 69–78.

[13] "Universal Mobile Telecommunicatios System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS (UMTS 30.03 version 3.2.0)", ETSI TR 101 112 V3.2.0 (1998-04).

[14] M. Günes and J. Siekermann, "CosMos – communication scenario and mobility scenario generator for mobile ad-hoc networks", in *Proc. 2nd Int. Worksh. MANETs Interoper. Iss. MANETII'05*, Las Vegas, USA, 2005.

[15] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang, "A group mobility model for ad hoc wireless networks", in *Proc. Int. Symp. Model. Simul. Wirel. Mob. Syst. MSWiM*, Seattle, USA, 1999, pp. 53–60.

[16] W.-J. Hsu, K. Merchant, H.-W. Shu, C.-H. Hsu, and A. Helmy, "Weighted waypoint mobility model and its impact on ad hoc networks", *ACM SIGMOBILE Mob. Comp. Commun. Rev.*, vol. 9, no. 1, pp. 59–63, 2005.

[17] M. Jahnke, J. Tölle, A. Finkenbrink, and A. Wenzel, "Dokumentation zum Forschungsvorhaben E/IB1S/6A661/2F005 – 1. Zwischenbericht", Tech. Rep., FGAN-FKIE im Auftrage des IT-AmtBw, 2006 (in German).

[18] A. Jardosh, E. M. Belding-Royer, K. C. Almeroth, and S. Suri, "Towards realistic mobility models for mobile ad hoc networks", in *Proc. IEEE MobiCom*, San Diego, USA, 2003, pp. 217–229.

[19] A. P. Jardosh, E. M. Belding-Royer, A. K. C., and S. Suri, "Real-world environment models for mobile network evaluation", *IEEE J. Selec. Areas Commun.*, vol. 23, no. 3, pp. 622–632, 2005.

[20] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark, "Scenario-based performance analysis of routing protocols for mobile ad-hoc networks", in *Proc. IEEE MobiCom*, Seattle, USA, 1999, pp. 195–206.

[21] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks", in *Mobile Computing*, T. Imielinski and H. Korth, Eds. Norwell: Kluwer, 1996, vol. 353, pp. 153–181.

[22] J. Kraaier and U. Killat, "The random waypoint city model – user distribution in a street-based mobility model for wireless network simulations", in *Proc. 3rd ACM Int. Worksh. Wirel. Mob. Appl. Serv. WLAN Hotsp.*, Cologne, Germany, 2005, pp. 100–103.

[23] B. Liang and Z. J. Haas, "Predictive distance-based mobility management for multidimensional PCS networks", *IEEE/ACM Trans. Netw.*, vol. 11, no. 5, pp. 718–732, 2003.

[24] S. Lim, C. Yu, and C. R. Da, "Clustered mobility model for scale-free wireless networks", in *Proc. IEEE Conf. Loc. Comput. Netw. LCN 2006*, Tampa, USA, 2006, pp. 231–238.

[25] P. S. Mogre, M. Hollick, N. d'Heureuse, H. W. Heckel, T. Krop, and R. Steinmetz, "A graph-based simple mobility model", in *Proc. WMAN'07, Proc. Conf. KiVS'07*, Bern, Switzerland, 2007, pp. 421–432.

[26] M. Musolesi, S. Hailes, and C. Mascolo, "An ad hoc mobility model founded on social network theory", in *Proc. 7th ACM Int. Symp. Model. Anal. Simul. Wirel. Mob. Syst.*, Venice, Italy, 2004, pp. 20–24.

[27] M. Musolesi and C. Mascolo, "A community based mobility model for ad hoc network research", in *Proc. 2nd ACM/SIGMOBILE Int. Worksh. Multi-hop Ad Hoc Netw. Theory Real. REALMAN'06, Colocated with MobiHoc2006*, Florence, Italy, 2006, pp. 31–38.

[28] W. Navidi and T. Camp, "Stationary distributions for the random waypoint mobility model", *IEEE Trans. Mob. Comp.*, vol. 3, no. 1, pp. 99–108, 2004.

[29] S. Reidt and S. D. Wolthusen, "An evaluation of cluster head TA distribution mechanisms in tactical MANET environments", in *Proc. Conf. ACITA*, College Park, USA, 2007.

[30] G. Resta and P. Santi, "An analysis of the node spatial distribution of the random waypoint model for ad hoc networks", in *Proc. ACM Worksh. Princip. Mob. Comp. POMC*, Toulouse, France, 2002, pp. 44–50.

[31] E. M. Royer, P. M. Melliar-Smith, and L. E. Moser, "An analysis of the optimum node density for ad hoc mobile networks", in *Proc. IEEE Int. Conf. Commun.*, Helsinki, Finland, 2001, vol. 3, pp. 857–861.

[32] I. Stepanov, J. Hähner, C. Becker, J. Tian, and K. Rothermel, "A meta-model and framework for user mobility in mobile networks", in *Proc. 11th Int. Conf. Netw. ICON 2003*, Sydney, Australia, 2003, pp. 231–238.

[33] I. Stepanov, P. J. Marron, and K. Rothermel, "Mobility modeling of outdoor scenarios for manets", in *Proc. 38th Ann. Simul. Symp. ANSS'38*, San Diego, USA, 2005, pp. 312–322.

[34] M. Sánchez and P. Manzoni, "ANEJOS: a Java based simulator for ad hoc networks", *Fut. Gener. Comput. Syst.*, vol. 17, no. 5, pp. 573–583, 2001.

[35] J. Tian, J. Hähner, C. Becker, I. Stepanov, and K. Rothermel, "Graph-based mobility model for mobile ad hoc network simulation", in *Proc. 35th Ann. Simul. Symp.*, San Diego, USA, 2002, pp. 337–344.

[36] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful", in *Proc. IEEE INFOCOM*, San Francisco, USA, 2003, pp. 1312–1321.

[37] H.-M. Zimmermann and I. Gruber. "A Voronoi-based mobility model for urban environments", in *Eur. Wirel. 2005 Conf.*, Zypern, Greece, 2005.

Nils Aschenbruck received his Diploma in computer science (Dipl.-Inform.) from the University of Bonn, Germany, in 2003. Currently he is a Ph.D. candidate and research Assistant in the communication systems group at the University of Bonn. His research interests include mobile and wireless networks, especially mobility and traffic modeling as well as security.

e-mail: aschenbruck@cs.uni-bonn.de
Institute of Computer Science IV
University of Bonn
Roemerstr. 164
53117 Bonn, Germany

Elmar Gerhards-Padilla received his Diploma in computer science (Dipl.-Inform.) from the University of Bonn, Germany, in 2005. Currently he is a Ph.D. candidate and research Assistant in the communication systems group at the University of Bonn. His research interests include mobile and wireless networks, especially security in tactical mobile ad hoc networks and honeynets.

e-mail: padilla@cs.uni-bonn.de
Institute of Computer Science IV
University of Bonn
Roemerstr. 164
53117 Bonn, Germany

Peter Martini received his Diploma and Ph.D. degrees from the Aachen University of Technology, Germany, in 1986 and 1987, respectively. From 1986 to 1990 he was with the Institute of Computer Science IV at the Aachen University of Technology. From 1990 to 1996 he was Professor of operating systems and computer networks at the University of Paderborn, Germany. Since 1996, Professor Martini heads the Institute of Computer Science IV at the University of Bonn. His current research interests include IT security and security assistance systems, mobile communication systems and mobile devices, high speed networks, and performance engineering.

e-mail: martini@cs.uni-bonn.de
Institute of Computer Science IV
University of Bonn
Roemerstr. 164
53117 Bonn, Germany