A Meta-Model and Framework for User Mobility in Mobile Networks

Illya Stepanov*, Jörg Hähner+, Christian Becker, Jing Tian•, and Kurt Rothermel

University of Stuttgart
Institute of Parallel and Distributed Systems (IPVS)
Universitätsstr. 38
70569 Stuttgart, Germany
{stepanov, haehner, becker, tian, rothermel}@informatik.uni-stuttgart.de

Abstract -- **Mobility patterns play an important role for performance evaluations of mobile networks. To simulate user movement, existing simulation tools provide only a few simple mobility models (e.g., random movement) suitable for particular scenarios. To evaluate a new scenario, an appropriate model needs to be created, but this requires extra work that distracts the researcher from his/her main task. In general, three key elements determine the mobility of users: the spatial environment, the user trip sequences, and the user movement dynamics (e.g., speed). In this paper, we introduce a meta-model that integrates these three elements in an easy-to-use framework, allowing a flexible modeling of user mobility in custom scenarios. The framework is available for download as a stand-alone trace generator and may be used together with any simulation or emulation tool for mobile networks to evaluate a specific scenario.**

Index Terms -- **simulation, mobility modeling, user movement**

I. Introduction And Motivation

Simulation is typically used to provide performance analysis for dynamic systems, such as mobile networks, where real-life measurements are hard or even impossible to achieve.

The mobility of users depends significantly on the given scenario. For example, mobile nodes in a military mission may move randomly in the corresponding area. Pedestrians in a city will follow the streets and pathways, hence being more restricted in their movement than nodes in a rescue mission. Since a variety of scenarios is possible with different node mobility models, it is desirable to provide means for flexible descriptions and integration of mobility models into simulation tools.

Current simulation tools offer support to model scenarios, where nodes move arbitrarily within a simulation area, e.g., rescue and military operations. Although it is commonly known that the mobility model impacts simulation results [4, 5, 32], many of the recent publications [7, 17, 20] still use such random mobility models primarily due to their simplicity and availability.

The existing models are limited in evaluations of more sophisticated scenarios. For example, to simulate car traffic in a city, it is required to reflect at least spatial constraints, because cars move on roads. The preparation of appropriate mobility models for evaluations requires additional work and may distract from the given research problem.

In this paper we provide a flexible framework for mobility modeling, which simplifies the creation of mobility models for custom scenarios and is easy to use. The framework is not bound to a particular simulation or emulation tool. We show the feasibility and usefulness of our framework by modeling user mobility in concrete scenarios.

The remainder of the paper is structured as follows. First, we discuss the related work in the area of mobility modeling. Then, in Section 3, we derive requirements on mobility models and describe our new meta-model and the supporting framework. In Section 4, we demonstrate examples of using the framework to model user mobility in concrete scenarios. Finally, we conclude the paper and give an outlook for future work.

II. Related Work

Mobile networks are evaluated in many different scenarios, such as the simulation of communication in an open area between mobile users (a so-called battlefield scenario, which reflects military or rescue operations, pedestrians in a park, etc.). In these scenarios, the mobility of users is simulated as random movement within the simulation area.

The *Brownian Walk Model* [8, 22] simulates the movement of users as part of Brownian motion. The movement of a single user is defined by a motion vector $\vec{V} = (V, \Theta)$, where V is the movement speed, and Θ the movement direction. The vector's coordinates continuously vary between $[V_{\min}, V_{\max}]$ and $[\Theta_{\min}, \Theta_{\max}]$ thus producing random motion.

To reflect the dynamics of transport vehicles, the model may be improved by adding a correlation to previous values, which

* Illya Stepanov is funded by the Landesgraduiertenförderung of the state of Baden-Württemberg (graduate funding for PhD studies)
+ Jörg Hähner is funded by the Gottlieb Daimler and Karl Benz Foundation
• Jing Tian is funded by the European Project CarTALK 2000, contract number IST-2000-28185

avoids sudden changes in speed ($\frac{\partial}{\partial t}V(t) \to \infty$) and direction (large $\frac{\partial}{\partial t}\varphi(t)$). In the *Smooth Mobility Model* [1], speed and direction are changed incrementally in several time units until the target values are reached. To make the speed behavior more realistic, the model relies on typical values (for example, typical speed in a city is 50-60 km/h, outside the city it is 100-120 km/h).

In the *Random Waypoint Mobility Model* [3, 6], mobile users move with constant speed between randomly chosen points inside the simulation area, thus performing certain trip sequences.

The *Random Waypoint Mobility Model with obstacle avoidance* has been introduced in [18]. The model is similar to the Random Waypoint Model but users avoid predefined obstructions of the movement area.

The *Restricted Random Waypoint Mobility Model* is used in [2]. The simulation scenario consists of three large movement areas ("towns") and three highway connections in between. Within a town, mobile users move according to the Random Waypoint Mobility Model, but, with a certain probability, they move on a highway to another town.

In [32], it is proposed to model movement constraints imposed by an infrastructure with a graph (*Graph Walk Mobility Model*). The vertices of the graph represent places that users might visit (points of interest: restaurants, museums, etc.) and the edges model interconnections between the places (streets or road connections). The users move between randomly chosen vertices of the graph on edges thus respecting spatial constraints of the simulation area.

Some evaluation scenarios include regular travel behavior of mobile users. For example, in [24] the mobility model is built as a two-level hierarchy: *Global Mobility Model* (GMM) and *Local Mobility Model* (LMM). The simulation area is divided into cells. The GMM is used to create intercell movements and the LMM is used to create intracell movements. The Global Model describes the regular movement behavior of a mobile user and contains a list of cells to be visited. The Local Model simulates movement within a cell and has three parameters: current position, speed, and direction.

In [23], the authors proposed to model the regular movement with circle-like patterns (closed circuits). Each circle corresponds to a state and identifies a location to be visited by the user.

The Integrated Mobility Model (IMM) used in [25] consists of three levels: City Area (set of zones connected via high-capacity routes), Area Zone (set of streets and building blocks), and Street Unit (highways, streets with traffic-light(s)-controlled flow, high and low-priority streets, etc.). The integration of the three components provides a possibility to model the mobility of different classes of mobile users (e.g., pedestrians, drivers) in a city.

To sum up, different models are used to simulate the mobility of users. Each of the models satisfies only a specific set of scenarios. To evaluate new scenarios, proper mobility models need to be created. To minimize the model creation overhead, we propose a meta-model suitable for different scenarios, which is integrated into a framework and is easy to use.

III. Concept Of A User-Oriented Mobility Meta-Model

An important question is to determine which components the meta-model must include.

First, the movement of mobile users in many scenarios is constrained by the spatial environment (roads, streets, etc.). For example, normally, people do not go through walls and cars do not leave the roads. One way of reflecting such real-world constraints is to include a *spatial environment* into the mobility model.

Second, mobile users move with a certain purpose. According to the Activity-Based Travel Demand Modeling Approach, "Travel is a demand that arises through people's needs and desires to participate in activities" [28]. People move because they want to do something in a certain place. For example, they go shopping, to restaurants, to work, sightseeing, etc. People move between elements of the spatial environment, e.g., shops, restaurants, monuments, etc. The elements of the spatial environment get a meaning from the perspective of trip modeling – *points of interest*. The mobility model must reflect *activity sequences* that mobile users follow during an observation.

Third, a mobility model must reflect *dynamics* of mobile users. For example, pedestrians are likely to move with a low speed and frequent interruptions; cars influence the movement of neighboring vehicles, so when a car ahead slows down, the succeeding cars will also decrease speed.

The following components are integrated into the meta-model:

- the model of the simulation area with spatial constraints and points of interest (*Spatial Model*);
- the trip sequences made by mobile users (*User Trip Model*);
- the movement dynamics of mobile users (*Movement Dynamics Model*).

The integration of the three components form a *Meta-Model*, which allows to create user trips in accordance with their profile, constraints of the spatial environment and user movement dynamics. The model is *oriented* towards a particular mobile user or a group of users, therefore, we call it *User-Oriented Mobility Meta-Model* (Fig. 1).

The model is *generic*, since the reviewed mobility models can be created as its instances. For example, the Random Waypoint Mobility Model can be instantiated using a rectangular-bounded area in the Spatial Model, the constant-speed motion in the Movement Dynamics Model and random trip sequences between points of the area in the User Trip Model. Instantiation of the Graph Walk Mobility Model is similar to the Random

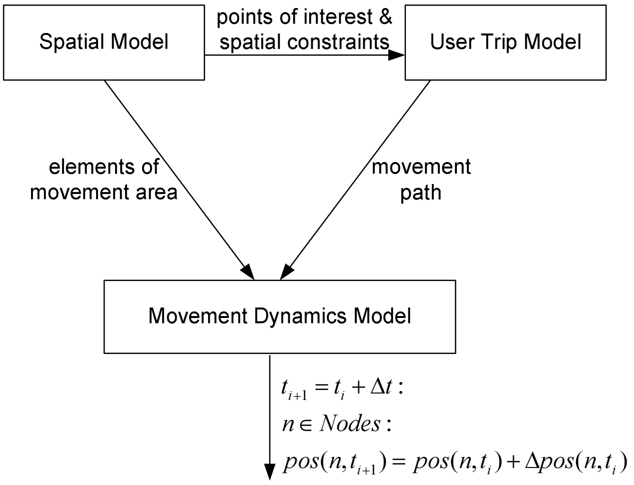

Fig. 1. Structure of the User-Oriented Mobility Meta-Model.

Waypoint Mobility Model but the model uses a graph representing the spatial environment in the Spatial Model. More sophisticated mobility models (e.g., IMM) rely on digital maps in the Spatial Model and appropriate User Trip and Movement Dynamics models.

The design of the meta-model components will be discussed in the next subsections.

A. Spatial Model

The mobility model relies on the Spatial Model to reflect spatial constraints of user movement imposed by the environment. The model provides a map of the area containing its topological elements. To offer a standard interface for data access and to reuse existing data sources, the Spatial Model is built on top of existing standards for describing environments in digital form.

Two widely accepted standards for describing spatial environments in digital form are Geographic Data Files (GDF) [13] and Geography Markup Language (GML) [14].

Both describe an environment in a common way:

- A spatial environment is specified as the collection of topological elements (roads, museums, hotels, restaurants, cinemas, etc.).
- The topological elements represent the environment at different presentation levels (from general to partial specialization).
- The geometry of elements is specified with common geometrical primitives (Point, Line, Polygon, etc.).
- The elements contain additional, feature-specific attributes (opening time of museum, speed limit of the road, etc.).
- Relations between the elements are specified (“belongs to”, “prohibited maneuver”, etc.).

In contrast to GML, which standardizes only basic rules to define the elements, GDF explicitly specifies a variety of elements, e.g., roads, restaurants, hotels, museums, their attributes and relations. Therefore, GDF was chosen as the primary specification for the Spatial Model used in the framework.

In GDF, every topological element is identified with its ‘theme code’ identifier that specifies the class to which the element belongs (“Road and Ferries”, “Railways”, “Public Transport”, “Road Furniture”, etc.). The element’s attributes and relations are stored using key/value pairs (Fig. 2).

To reuse existing data sources, we implemented a GDF parser and included it into the framework. Converters from other formats to GDF, e.g., GML to GDF, are available, e.g., in [11].

B. User Trip Model

The necessity of the User Trip Model is motivated by the fact that, in real life, people with a goal neither move to make a certain number of steps in different directions nor move between randomly chosen points of the area. The movement of persons often has a distinct repeatability, e.g., commuting to work on weekdays. In order to reflect this, individual trip planning decisions need to be included into the mobility model. The Activity-Based Travel Demand Modeling approach [21, 27, 28] is widely used to model travel decisions.

1) Activity-Based Travel Demand Modeling Approach

The approach defines travel as the demand to participate in activities: “No one would think about how many trips to make when developing a plan for a day; rather, one would think about what she wants to or needs to do, where the activities can or need be engaged, and, only then, would think about how to visit these places. Importantly, how many trips will be made depends on how the visits to different places are sequenced and combined into trip chains” [21].

The movement is defined as a trip chain (Fig. 3). The chain

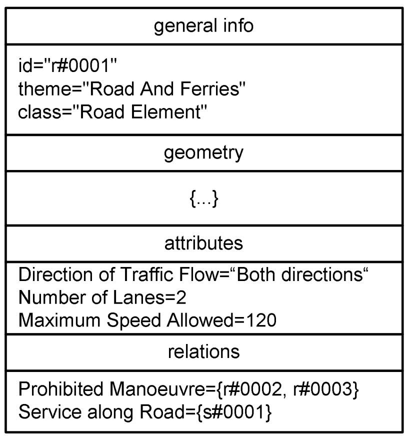

Fig. 2. Example of a Road Element in GDF.

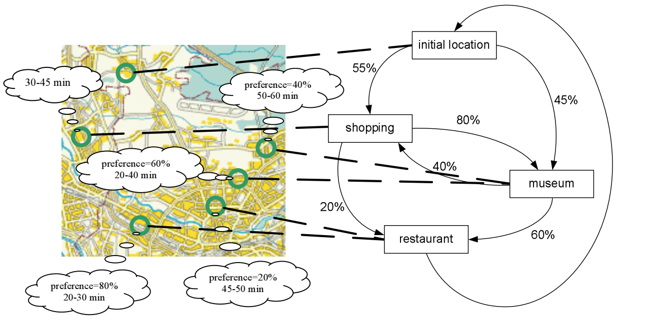

Fig. 3. Example of a Trip Chain and Integration of the User Trip Model with the Spatial Model using geographic coordinates.

is a sequence of actions to be executed. Each action contains a set of places where this action may be performed with a preference of one place over another and duration of the activity's execution at a particular location. After finishing the current activity, the next one is chosen from the set of alternatives with a certain probability and the movement continues. The movement takes place due to the switching of activities.

The User Trip Model matches the activities with the places of their execution from the Spatial Model using geographic coordinates. Another possibility of interaction between the models is to use the semantic of topological elements. For example, the shopping activity might be executed at the topological elements that belong to the "Services" group and have "Shopping Center" class code, or the specific name (e.g., supermarket's name). Referring to semantic meta-data of the Spatial Model, e.g. sights, allows an easy modeling of complex trips. In the future, a graphical user interface can further ease the trip model construction.

To express such trip chains in the model, we use *non-deterministic finite automata of activity sequences*.

2) Automaton of Activity Sequences

A non-deterministic finite automaton (Fig. 4) [16] is composed of a finite set of states Q and transitions between the states. The transitions occur on input symbols α_i from a finite input alphabet Σ according to the transition function δ. The automaton is non-deterministic, therefore, it has to perform zero, one or more transitions out of the state on the same input symbol. The automaton starts in the initial state q_0 and stops in one of the final states $q_i \in F$ ($q_0 \in Q$, $F \subseteq Q$).

The trip chain might be described by the non-deterministic finite automaton. That is, the set of activities to be executed can be matched one-to-one with the automaton's states. Therefore, each state denotes one activity and contains a set of places where this action may be performed with a preference of one place over another and a duration of the activity's execution at a particular location (or a function which calculates the duration

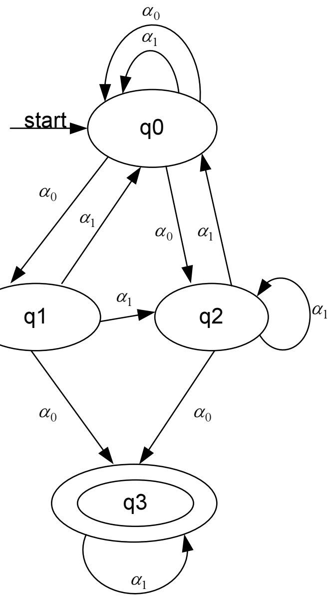

Fig. 4. Non-deterministic Finite Automaton.

for a particular case, for example, taking into account the time of the day) (Fig. 5).

The activity from which the user starts the movement is denoted as the automaton's initial state, the final activities correspond to final states. The initial activity is associated with the user's initial position.

The automaton switches non-deterministically between the states thus realizing the heterogeneity upon switching between the activities. Internally, the switching is performed by the transition function in accordance with transition probabilities. The input value serves as a signal to the automaton to perform a transition; the input alphabet contains a single value $\Sigma = \{\alpha\}$.

Describing trip sequences with the finite automaton ideally fits the simulation model and allows describing various trip sequences. The automaton's states match the activities executed by a mobile user and contain additional data concerning loca-

$$q_i \rightarrow \begin{Bmatrix} loc_1 & p(loc_1) & d(loc_1) \\ loc_2 & p(loc_2) & d(loc_2) \\ \ldots & & \\ loc_n & p(loc_n) & d(loc_n) \end{Bmatrix} \qquad \sum_{k=1}^{n} p(loc_k) = 1$$

$$\text{restaurant} \rightarrow \begin{Bmatrix} \text{12 AlbSt.} & 80\% & 20-30 \text{ min} \\ \text{7 MaySt.} & 20\% & 45-50 \text{ min} \end{Bmatrix}$$

Fig. 5. Data Associated with an Activity: Locations, Location Attractiveness, and Activity Execution Duration.

tions for activity execution, probability that a location will be chosen, and duration of execution. Random transitions between the activities in a trip chain correspond to the non-deterministic switching between the states in an automaton. The transition probabilities of the trip chain are reflected by the automaton's transition function.

3) Trip Construction

The movement destination point is chosen from the places for the current activity execution taking into account the points' attractiveness for the user. A path between the current point and the destination point is calculated in accordance with the underlying movement area from the Spatial Model. To calculate this path, we create a graph of the movement area. The vertices of the graph represent points of the Spatial Model (e.g., points of interest, road crossings, etc.) and the edges model interconnections between the locations (e.g., road elements). If necessary, attributes of movement area elements are considered upon path calculation, e.g., traffic flow directions for cars, etc. Currently, we assume that mobile users move on the shortest path between the points, therefore, we use Dijkstra's algorithm [9] to calculate it. In the future, we plan to use more sophisticated algorithms for path construction, e.g., as used in the urban travel modeling [27].

C. Movement Dynamics Model

The Movement Dynamics Model defines user speed and direction changes during the movement along the trip path. In contrast to Spatial and User Trip models, the model is a highly dynamic model possibly reflecting the movement of nearby nodes. The choice of a particular Movement Dynamics Model is implied by the user's nature. For example, the dynamics of pedestrians might be characterized with the low-speed motion and frequent stop-and-go behavior. There are several models to define the dynamics of cars (vehicular traffic), such as the Fluid Traffic Model [31] (based on the dependency between the traffic speed and volume), Intelligent Driver Model [33] (based on the dependency between the movements of neighboring vehicles), Smooth Random Mobility Model [1] (based on correlating the speed and direction to previous values). The Boids Model [29, 30] simulates movements of different mobile users collaborating atomic steering behaviors. Any of these dynamics models might be used in the User-Oriented Mobility Meta-Model to simulate the dynamics of mobile user.

Attributes of movement area elements may be taken into account upon simulating the movement dynamics of specific classes of mobile users, e.g., speed limit for the vehicular traffic.

D. Integration of the Mobility Model into the Framework

The User-Oriented Mobility Meta-Model is integrated into a framework for mobility modeling (Fig. 6). The framework is implemented on top of a discrete JAVA-based simulation environment. The framework produces user mobility traces for a given simulation scenario. The scenario is described in the popular eXtensible Markup Language (XML) format [10]. The resulting traces are converted to a trace format used by a concrete simulation tool. Therefore, the framework is not bound to a particular simulation tool and a particular platform. Since the framework exists as a stand-alone application, it does not influence the simulation tool's performance. The framework integrates a GDF parser and thus allows simulating user mobility in real environments, which are commonly defined in GDF or can be converted into it.

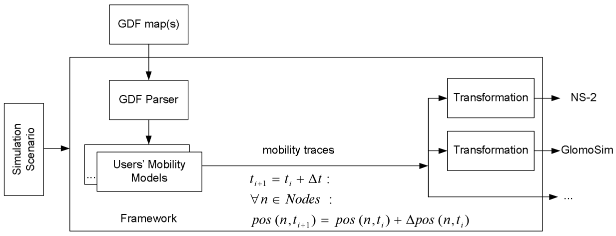

Fig. 6. Structure of the Framework for User Mobility Modeling.

In the framework, movements of every mobile user are simulated with a separate instance of the mobility model. This allows flexible modeling of movements made by different classes of mobile users, in that we may use several Spatial, User Trip or Movement Dynamics models in one simulation. The framework supports the mobility modeling for classes of users. Users belonging to the same class share similar Spatial, Trip or Dynamics models thus accomplishing the similarity of their movements. Defining a mobility model for a group of users requires the same overhead as defining a model for an individual user. Therefore, we can simulate the mobility of different classes of mobile objects (cars, pedestrians, tourists, etc.) in a single scenario as well as the mobility of individual mobile users.

To ease the preparation of a particular scenario, we implemented and included a number of User Trip models (Random Trip Model and Activity-Based Trip Model), and Movement Dynamics models (Constant-Speed Motion for pedestrians, Fluid Traffic Model, Smooth Mobility Model, Intelligent Driver Model for cars).

Furthermore, the framework is extensible. It is based on the concept of plug-ins (extension modules), so the new modules may be easily added, e.g., new User Trip or Movement Dynamics models, simulation tools support.

The framework source code is available for download and may be used by other researches for modeling the user mobility in custom scenarios.

IV. Examples Of The Framework Usage

In this part, we demonstrate the flexibility and the usefulness of the framework by describing several simulation scenarios.

A. Scenario 1 – Users in a Rescue Mission

In *Scenario 1*, we simulate the movement of users in a rescue operation similar to the Random Waypoint Mobility Model. The content of the simulation scenario file is depicted in Fig. 7. At the beginning, we define the dimensions of the simulation area (1000m x 1000m, *dimx* and *dimy* tags). Then we plug in the module to convert the mobility traces to NS-2 format [26], the module to stop the simulation after 3600s of simulation time and the Spatial Model Module. Since the nodes perform random movement, we plug in two additional modules to make random initial placement of mobile users and generate trips between randomly chosen points of the simulation area. Stay duration between two successive trips is randomly chosen between 120 and 600s and is a parameter of the Random Trip Generation Module. We simulate the movement of 50 mobile nodes (defined in *nodegroup* tag). The user movement dynamics is set to the Constant Speed Motion with speed values randomly chosen between 0.56 – 1.39m/s.

B. Scenario 2 – Car Traffic in a City Center

In *Scenario 2*, we simulate the vehicular traffic in a city center similar to the Graph Walk Mobility Model [32]. The content of the simulation scenario file is shown in Fig. 8. The mobility traces are produced for the GloMoSim simulation environment [15], so we plug in the module to convert the traces to the GloMoSim format. To initialize the spatial environment, we use the GDF Reader Module and configure the module to process the city central part only (defining the clipping window coordinates *min_x*, *max_x*, *min_y*, *max_y*). Similar to the previous scenario, trips are produced by the Random Initial Position Generator and Random Trip Generation modules, but since the Spatial Model is initialized from the map, the modules reflect constraints of the movement area. Since we are interested in trip modeling between particular points of the spatial environment, we have extracted the coordinates of required points to a text file and used the file contents in our trip generation modules (*points* tag) to generate trips between the given points (the framework includes a module to process and extract a subset of points of the Spatial Model). The user movement dynamics are set to the Fluid Traffic Model.

```
<?xml version="1.0"?>
<!-- Users in a Rescue Mission -->
<universe>
  <dimx>1000.0</dimx>
  <dimy>1000.0</dimy>
  <extension class="sim.extensions.NSOutput"/>
  <extension class="sim.simulations.TimeSimulation" param="3600.0"/>
  <extension class="spatialmodel.core.SpatialModel"/>
  <extension name="PosGen" class="tripmodel.generators.RandomInitialPositionGenerator"/>
  <extension name="TripGen" class="tripmodel.generators.RandomTripGenerator">
   <minstay>120.0</minstay> <maxstay>600.0</maxstay>
  </extension>
  <nodegroup n="50">
   <extension class="uomm.ConstantSpeedMotion" initposgenerator="PosGen" tripgenera-
tor="TripGen">
     <minspeed>0.56</minspeed> <maxspeed>1.39</maxspeed>
   </extension>
  </nodegroup>
</universe>
```

Fig. 7. Description of Scenario 1.

```
<?xml version="1.0"?>
<!-- Car Traffic in a City Center -->
<universe>
  <extension class="sim.extensions.GlomosimOutput"/>
  <extension class="sim.simulations.TimeSimulation" param="3600.0"/>
  <extension class="spatialmodel.core.SpatialModel"/>
  <extension class="gdfreader.GDFReader" source="Boston.gdf" min_x="4000" max_x="6000"
min_y="3000" max_y="4000"/>
  <extension name="PosGen" class="tripmodel.generators.RandomInitialPositionGenerator">
   <points>points.txt</points>
  </extension>
  <extension name="TripGen" class="tripmodel.generators.RandomTripGenerator">
   <points>points.txt</points>
   <minstay>120.0</minstay> <maxstay>600.0</maxstay>
  </extension>
  <nodegroup n="100">
   <extension class="uomm.FluidTrafficModel" initposgenerator="PosGen" tripgenera-
tor="TripGen">
     <!—Fluid Traffic Generator Parameters -->
   </extension>
  </nodegroup>
</universe>
```

Fig. 8. Description of Scenario 2.

```
<?xml version="1.0"?>
<!-- Tourists in a City Center -->
<universe>
  <extension class="canumobisim.extensions.NSOutput"/>
  <extension class="canumobisim.simulations.TimeSimulation" param="14400.0"/>
  <extension class="spatialmodel.core.SpatialModel"/>
  <extension class="gdfreader.GDFReader" source="Boston.gdf" min_x="4000" max_x="6000"
min_y="3000" max_y="4000"/>
  <extension name="Gen" class="tripmodel.generators.ActivityBasedTripGenerator">
   <activity id="initial">
     <points>initial.txt</points>
     <minstay>0.0</minstay> <maxstay>0.0</maxstay>
   </activity>
   <activity id="shopping">
     <points>shopping.txt</points>
     <minstay>900.0</minstay> <maxstay>1800.0</maxstay>
   </activity>
   <!—More activities …  -->
   <transition>
     <src>initial</src> <dest>shopping</dest> <p>0.55</p>
   </transition>
   <transition>
     <src>initial</src> <dest>museum</dest> <p>0.45</p>
   </transition>
   <!—More transitions …  -->
  </extension>
 <nodegroup n="100">
   <extension class="uomm.ConstantSpeedMotion" initposgenerator="Gen" tripgenerator="Gen">
     <minspeed>0.56</minspeed> <maxspeed>1.39</maxspeed>
   </extension>
  </nodegroup>
</universe>
```

Fig. 9. Description of Scenario 3.

C. Scenario 3 – Tourists in a City Center

In *Scenario 3*, we model the movement of tourists in a city center. The content of the simulation scenario file is shown in Fig. 9. In contrast to the previous scenarios, the mobile users have a distinct set of activities to execute, therefore, we use the Activity Based Trip Generator to produce the trips. The automaton of activity sequences is depicted in Fig. 3. Similar to Scenario 2, the locations for activity execution have been extracted to text files (a separate text file for each activity). Within a particular activity, every location may be chosen with equal probability.

V. CONCLUSION

Mobile networks are used in many different scenarios. Since the mobility of users is a key element of such networks, it has to be reflected in the simulations. Because the mobility of users depends significantly on the given scenario, it is desirable to provide means for flexible creation of new mobility models for distinct scenarios. We proposed a generic meta-model integrated into a framework for user mobility modeling that relies on three key elements defining the movement: reflection of spatial constraints, execution of user trip sequences, and movement dynamics. Therefore, the meta-model integrates:

- the model of a simulation area with spatial constraints and points of interest (*Spatial Model*);
- the trip sequences made by the user (*User Trip Model*);
- the movement dynamics of a user (*Movement Dynamics Model*).

The framework for mobility modeling is implemented on top of a standalone JAVA-based simulation environment. The resulting mobility traces can be used with nearly any available simulation or emulation tool for mobile networks [12, 15, 19, 26, 34, 35]. Since the framework is based on the concept of extension modules, it may be easily extended with new User Trip or Movement Dynamics modules, or support additional simulation tools.

The framework includes a parser for GDF data sources and thus allows simulating user mobility in real environments, which are defined in GDF format or can be converted into it.

In the future, we plan to integrate more User Trip and Movement Dynamic models into the framework (e.g., taken from the urban travel modeling) to improve its capabilities.

The limitation of the framework is that the spatial constraints impact communication (e.g., tunnels, etc.), which cannot be covered by an external mobility generator. In future work, we plan to integrate the Spatial Model into NS-2 to simulate radio propagation more accurately.

The proposed framework for user mobility modeling can be downloaded from:

http://canu.informatik.uni-stuttgart.de/mobisim

ACKNOWLEDGMENT

We want to thank Martin Bauer, Dominique Dudkowski, Pedro José Marrón, and Christoph Ruffner for reading the draft of the paper and their valuable suggestions. Special thanks to Frank Dürr for help with geographic data files and to Gregor Schiele for writing the initial version of the simulation environment.

Illya Stepanov is a PhD student at both the University of Stuttgart and the Donetsk National Technical University, Ukraine. We thank Prof. Svyatnyj from the Donetsk National Technical University, Ukraine for the cooperation.

REFERENCES

[1] C. Bettstetter, "Smooth is Better than Sharp: A Random Mobility Model for Simulation of Wireless Networks", Proceedings of the 4th ACM International Workshop on Modeling, Analysis, and Simulation of Wireless and Mobile Systems (MSWiM'01), Rome, Italy, July 2001.

[2] L. Blazevic, S. Giordano, J. Y. Le Boudec, "Self Organized Terminode Routing", Technical Report No. DSC/2000/040, Swiss Federal Institute of Technology, Lausanne, December 2000.

[3] J. Broch, D.A. Maltz, D.B. Johnson, Y. -C. Hu, and Jorjeta Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols", Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking, ACM, Dallas, TX, October 1998.

[4] T. Camp, J. Boleng, V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research", Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, vol. 2, no. 5, pp. 483-502, 2002.

[5] D. Cavin, Y. Sasson, A. Schiper, "On the accuracy of MANET simulators", Proceedings of the second ACM international workshop on Principles of mobile computing, Toulouse, France, 2002.

[6] B. Chen, K. Jamieson, H. Balakrishnan, R. Morris, "Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks", Proceedings of the 7th ACM International Conference on Mobile Computing and Networking, pages 85-96, Rome, Italy, July, 2001.

[7] S.K. Das, B.S. Manoj, C. Siva Ram Murthy, "A Dynamic Core Based Multicast Routing Protocol for Ad hoc Wireless Networks", Proceedings of the third ACM international symposium on Mobile ad hoc networking & computing (MobiHoc 2002), Lausanne, Switzerland, 2002.

[8] S.R. Das, R. Castaneda, J. Yan, and R. Sengupta, "Comparative performance evaluation of routing protocols for mobile ad hoc networks", Proceedings of the 7th International Conference on Computer Communications and Networks (IC3N), pages 153-161, October 1998.

[9] E.W. Dijkstra, "A note on two problems in connection with graphs", Numerische Mathematik, 1, pp.269-271 (1959).

[10] Extensible Markup Language (XML) 1.0 Specification, W3C Recommendation, 6 October 2000. Available at: http://www.w3.org/TR/REC-xml

[11] Feature Manipulation Engine (FME). Available at http://www.safe.com/products/fme/index.htm

[12] J. Flynn, H. Tewari and D. O'Mahony, "A Real-Time Emulation System for Ad Hoc Networks", Proceedings of the Communication Networks and Distributed Systems Modeling and Simulation Conference (CNDS 2002), San Antonio, Texas, January 27-31, 2002, pp 115-120.

[13] Geographic Data Files (GDF) Home Page. Available at http://www.ertico.com/links/gdf/gdf.htm

[14] Geography Markup Language (GML) 2.0, OpenGIS® Implementation Specification, OGC Document Number: 01-029. Available at http://www.opengis.net/gml/01-029/GML2.html

[15] GloMoSim: Global Mobile Information Systems Simulation Library. Available at http://pcl.cs.ucla.edu/projects/glomosim/

[16] J.E. Hopcroft, J.D. Ullman, "Introduction to Automata Theory, Languages, and Computation", Addison-Wesley, 1979.

[17] Y.-C. Hu, A. Perrig, D.B. Johnson, "Ariadne: A secure On-Demand Routing Protocol for Ad hoc Networks", Proceedings of MobiCom 2002, Atlanta, Georgia, USA, September 23-28, 2002.

[18] P. Johanson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark, "Scenario-based Performance Analysis of Routing Protocols for Mobile Ad-hoc Networks", Proceedings of ACM/IEEE MOBICOM'99, Seattle, WA, August 1999, pp. 195-206.

[19] Q. Ke, David Maltz, David B. Johnson, "Emulation of Multi-Hop Wireless Ad Hoc Networks", Proceedings of the 7th International Workshop on Mobile Multimedia Communications (MoMuC2000), October, 2000.

[20] A. Khelil, C. Becker, J. Tian, K. Rothermel, "An epidemic model for information diffusion in MANETs", Proceedings of the 5th ACM international workshop on Modeling analysis and simulation of wireless and mobile systems, Atlanta, Georgia, USA, 2002.

[21] R. Kitamura, “Applications of Models of Activity Behavior for Activity Based Demand Forecasting”, Proceedings of Activity-Based Travel Forecasting Conference, June 2-5, 1996.

[22] Y.-B. Ko and N. H. Vaidya, “Location-aided routing (LAR) in mobile ad hoc networks”, Proceedings of ACM/IEEE Int. Conf. on Mobile Computing and Networking (MobiCom'98), October 1998.

[23] G. Liu and G. Maguire, “Efficient Mobility Management Support for Wireless Data Services”, Proceedings of 45th IEEE Vehicular Technology Conference (VTC'95), Chicago, Illinois, USA, July 26-28, 1995.

[24] T. Liu, P. Bahl, “Mobility Modeling, Location Tracking, and Trajectory Prediction in Wireless ATM Networks”, IEEE Journal on Special Areas in Communications, Special Issue on Wireless Access Broadband Networks, Vol. 16, No. 6, (August 1998): 922-936.

[25] J.G. Markoulidakis, G.L. Lyberopoulos, D.F. Tsirkas, E.D. Sykas, “Mobility Modeling in Third-Generation Mobile Telecommunications Systems”, IEEE Personal Communications, pp. 41-56, August 1997.

[26] Network Simulator - NS-2. Available at http://www.isi.edu/nsnam/ns/

[27] N. Oppenheim, “Urban Travel Demand Modeling: From Individual Choices to General Equilibrium”, ISBN: 0-471-55723-4, Wiley-Interscience, January 1995.

[28] E.I. Pas, “Recent Advances in Activity-Based Travel Demand Modeling”, Proceedings of Activity-Based Travel Forecasting Conference, June 2-5, 1996.

[29] C.W. Reynolds, “Flocks, Herds, and Schools: A Distributed Behavioral Model”, Computer Graphics, 21(4) (SIGGRAPH '87 Conference Proceedings), pages 25-34.

[30] C.W. Reynolds, “Steering Behaviors For Autonomous Characters”, Proceedings of the Game Developers Conference, pages 763-782, 1999.

[31] I. Seskar, S.V. Marie, J. Holtzman, J. Wasserman, “Rate of Location Area Updates in Cellular Systems”, Proceedings of IEEE VTC'92, Denver, CO, May 1992.

[32] J. Tian, J. Hähner, C. Becker, I. Stepanov, K. Rothermel, “Graph-based Mobility Model for Mobile Ad Hoc Network Simulation”, Proceedings of the 35th Annual Simulation Symposium, in cooperation with the IEEE Computer Society and ACM, San Diego, California, April 2002.

[33] M. Treiber and D. Helbing, “Explanation of Observed Features of Self-Organization in Traffic Flow”, Preprint cond-mat/9901239 (1999).

[34] Y. Zhang, W. Li, “An Integrated Environment for Testing Mobile Ad-Hoc Networks”, Proceedings of the Third ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'02), Lausanne, Switzerland, June 2002.

[35] P. Zheng, L. M. Ni, “EMWIN: Emulating a Mobile Wireless Network using a Wired Network”, Proceedings of the Fifth International Workshop on Wireless Mobile Multimedia (WoWMoM 2002), Atlanta, Georgia, U.S.A., 2002.