Mobility Model for Tactical Networks

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Abstract. In this paper a synthetic mobility model which represents behavior and movement pattern of heterogeneous units in disaster relief and battlefield scenarios is proposed. These operations usually take place in environment without preexisting communication infrastructure and units thus have to be connected by wireless communication network. Units cooperate to fulfill common tasks and communication network has to serve high amount of communication requests, especially data, voice and video stream transmissions. To verify features of topology control, routing and interaction protocols software simulations are usually used, because of their scalability, repeatability and speed. Behavior of all these protocols relies on the mobility model of the network nodes, which has to resemble real-life movement pattern. Proposed mobility model is goal-driven and provides support for various types of units, group mobility and realistic environment model with obstacles. Basic characteristics of the mobility model like node spatial distribution and average node degree were analyzed.

Keywords: Mobility model, simulation, tactical networks.

1 Introduction

In the future field operations like a disaster relief operations, battlefield operations, or reconnaissance/surveillance will be carried out by mixed human-machine teams. Those teams may consist of a high number of autonomous robots, unmanned aerial vehicles, unattended ground sensors and humans. Operation of these heterogeneous teams brings challenging research problems: *(i)* missions usually take place in environments without pre-existing communication infrastructure and units are thus connected by ad hoc communication networks, *(ii)* there is no central component where all the information about field operation units, like their positions, abilities and plans can be stored and accessed by other team members and *(iii)* to operate efficiently, units need to interact one with the other to coordinate their activities, improve their situational awareness or to be able to plan future tactical missions.

Communication network thus has to deliver large volume of data (video and voice streams, application data). Communication resources must be utilized in

V. Mařík, T. Strasser, and A. Zoitl (Eds.): HoloMAS 2009, LNAI 5696, pp. 254–265, 2009.
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effective way to ensure quality of service provided to the users (like message delay and packet drop ratio) while minimizing the energy consumption and interference. To ensure the efficient utilization of resources various algorithms and interaction protocols are used, namely the topology control protocols, message routing protocols, negotiation protocols, etc. It is necessary to test these protocols thoroughly during the development phase to verify their robustness and scalability. These test are usually carried out using software simulations, because of their scalability, repeatability and ability to test scenarios under various settings and parameters.

Communication protocols built on the top of physical communication infrastructure have several limitations. Links in a wireless communication network have a limited range and bandwidth, they are subject to signal interference and the transmission over the link affects bandwidth of the links in its surrounding. Parameters of the communication links depend mainly on positions of network nodes. During the development and test it is thus necessary to simulate node mobility.

Existing mobility models are not suitable for simulation of complex dynamic movement patterns which occur in tactical networks consisting on numerous types of units operating in real environment with obstacles. Goal of this paper is to propose a goal-driven mobility model which will resemble mobility patterns of heterogeneous units during real-life field operations.

The rest of the paper is organized as follows. In Section 2 existing mobility models are described. In Section 3 problem formulation is given and our novel approach to solving the problem is described. Experimental evaluation of features of the proposed mobility model is described in Section 4. We conclude with a summary and an outline of future work is Section 5.

2 State of the Art

Mobility of the units has to be taken into account during the network/mission design process. Node mobility models are used to simulate the real world behavior to determine if the proposed protocols will satisfy given criteria when implemented. As the real-life movement patterns (traces) are very difficult to obtain, synthetic mobility models are used during the simulation and for verification of networking protocol features. Mobility models for ad hoc/sensor networks should try to fulfill two goals which are often conflicting [1]:

- resemble real-life movements – ad hoc and sensor networks are used in wide range of domains with various movement patterns, e.g. disaster relief operations, vehicular motion, sensors carried around by the ocean flows, movement of group of tourists, etc. Each of these domains usually requires its specific mobility model.
- be general/simple enough for simulation and formal analysis – to keep simulation times reasonable, mobility models should be simple enough. Moreover, using relatively simple mobility modes allows formal analysis of their behavior with respect to fundamental network parameters and influence of mobility on performance of networking protocols.

In [2] authors propose classification of mobility models based according to different dependencies and restrictions:

- Random based - nodes move randomly without any restrictions or dependencies on environment and other nodes;
- Temporal dependencies - actual movement of the node is influenced by its previous movement;
- Spatial dependencies - movement of the node is affected by other nodes in its surrounding (e.g. group mobility, potential fields, etc.);
- Geographic restrictions - nodes are restricted to move only in some predefined areas;
- Hybrid characteristics - mobility model combines some or all of previous characteristics.

Below the mobility models most widely used for simulation of ad hoc wireless networks are described. For more detailed description see e.g. [2] [3].

The most widely used mobility model for ad hoc networks is the Random Waypoint Model (RWP) which has been introduced in [4]. In this model each node moves independently of each other and the environment is assumed to be obstacle-free. In RWP model each node is assigned an initial location and chooses a destination point (the *waypoint*) uniformly at random in region R. Example can be e.g. movement of people at the airport terminal or town square. Variant of this mobility model is a Random Direction Model which (unlike the RWP) maintains a uniform node spatial distribution during the simulation.

Example of mobility model with geographic restrictions can be the *Manhattan mobility model* [5], which emulates movement of people in metropolitan traffic. Manhattan-like map consists of horizontal and vertical streets. Nodes can move along the streets in both directions and any time they enter an intersection they randomly choose a new direction of movement - they can continue in the same direction, or turn left/right. Another map-based mobility is a *freeway mobility* model [5], which represents movement of cars on freeways. Several freeways, each composed of varying number of lanes in both directions, are located within the region R. Each node is restricted to its lane on the freeway and its velocity is temporarily dependant on previous velocity.

In many scenarios nodes are expected to move in groups (e.g. the battlefield scenarios or groups of tourists in the city). Various group-based mobility models has been introduced to model these scenarios. In case of the *reference point group mobility* model [6] a subset of the network nodes is defined as a set of group leaders $N_L \subset N$. Rest of the nodes is assigned randomly to the group leaders. After the simulation start, the group leader starts to move according to one of the previous mobility patterns and other group members follow the leader. Another instance of group-based mobility, *diamond group mobility* model which is suitable for ad hoc network in military scenarios is described in [7].

In [8] Aschenbruck et. al propose a hybrid mobility model for disaster area scenarios. Authors identify following main requirements for the mobility model: (i) heterogeneous velocity, (ii) tactical areas, (iii) optimal paths, (iv) obstacles,

(v) units join and leave the scenario and (vi) group movement. Their mobility model defines several areas typical for the catastrophe situations like the incident site or casualties treatment area and specialized units which operate within these areas (e.g. transport units or firefighters).

3 Mobility Model for Tactical Networks

In this section we propose a synthetic mobility model which is suitable for tactical networks. This model is a generalization of the disaster area mobility model described by Aschenbruck et. al in [8] and is inspired by several other mobility models, especially the group-based mobility.

3.1 Problem Formulation

Santi in [1] formulates the problem of node placement as follows:

Let N be a set of nodes with $|N| = n$. Nodes operate in a bounded region R. Let assume that R is a d-dimensional cube of side l. Formally, $R = [0, l]^d$ for some $l > 0$, where $d = 1, 2, 3$. Location of any node $u \in N$ in R is denoted $L(u)$ and is expressed in d-dimensional coordinates. Function $L : N \rightarrow R$ maps every node of the network to its physical location. In case of mobile networks, the physical location of nodes changes in time. Mobility can be represented by adding additional parameter into the placement function L, the time instant t (assuming that nodes move within R). Function $L : N \times T \rightarrow R$ assigns to every node of N and to any time $t \in T$ a set of d-dimensional coordinates representing the physical node's location at time t. A d-dimensional mobile ad hoc network is then represented by pair $M_d = (N, L)$.

Synthetic mobility models generate the placement function $L : N \times T \rightarrow R$ for each node $n \in N$ according to some algorithm. Each algorithm relies on several internal parameters which can in some cases significantly affect the placement function. These parameters have to be set carefully with respect to the real-world scenario the mobility model has to simulate.

3.2 Types of Nodes

Tactical networks are complex systems which consist of heterogeneous mixture of goal-driven nodes. Behavior of resulting mobility model depends heavily on the type of nodes involved in the mission, as each type has its individual mobility pattern. Generally we can distinguish following types of nodes:

- Autonomous robots – all autonomous computer-controlled units, like robots, aerial assets or ground vehicles. Each robot is running an internal path planner which can plan movement trajectory from the current position to the destination point. This trajectory can be described by a set of waypoints, time constraints in these waypoints and path elements between them (straight elements, turns, etc.). Robots autonomously select and fulfill tasks accordingly to the overall mission goal.

- Wireless sensors – they remain stationary during the entire simulation time. They can be distributed either randomly over the whole region R or according to some pattern, simulating the case of being spread from a moving airplane or vehicle.
- Humans – like the autonomous robots humans participate on the task execution process. However their movement trajectory cannot be easily described by a set of waypoints, as their exact movement is highly unpredictable.
- On-demand communication nodes – these nodes represent special units dedicated to improve the topology of the communication network. They proactively move to the positions where they can improve connectivity of the network. Their movement is fully controlled by the networking protocols and they thus cannot be modeled by this low level algorithm.

3.3 Mobility Model Description

Tactical network mobility model can be formalized as follows:

In environment operate m different types of nodes (e.g. humans, robots, UAVs, etc.). Each type can be described by following parameters:
$type = \langle type_{id}, v[v_{min}, v_{max}], mobility\ pattern\rangle$, where v_{min} and v_{max} are minimum and maximum velocity of the node and mobility pattern describes allowed maneuvers with respect to the physical constraints of the node. E.g. ground units are allowed to stop and turn in place while UAVs must move continuously with speed higher then v_{min} and turn maneuvers must respect minimum turn radius of the UAV.

Let N be a set of all nodes with $|N| = n$. Subset $N_s \subset N$ represents set of all stationary sensors. Number of sensors $n_s = |N_s| \in [0, n]$. If $n_s = 0$ no wireless sensors are placed in R, in case of $n_s = n$ problem can be transformed to wireless sensor network (WSN). Set of stationary nodes can be selected randomly using the probability parameter p_{stat} (in the case of the random node placement) or can be predefined (when nodes were spread according to some pattern).

Remaining nodes belong to the set of mobile nodes $N_m = N \setminus N_s$. Each node is described by a following tuple $\langle type_{id}, R_n\rangle$, where $type_{id}$ represents type of the unit and $R_n \in R$ is a set of areas the node is allowed to operate in. At the beginning of the simulation nodes can be placed uniformly at random at the any of the area R_n. Number of members of individual types can either be given at the beginning of the simulation (e.g. number of robots is known) or can be set according to some parameter p_{type}, which represents the probability that a node belongs to given type.

Areas are defined as a set of polygons in case of 2D scenarios and as a set of polyhedrons in 3D. Environment may contain a set of obstacles O. Nodes have to avoid these obstacles during their movement while respecting the areas they are allowed to operate in. Specific path planning algorithm thus has to be implemented to compute the node trajectories for each mobility pattern. Typically, methods of robot motion planning can be used to plan trajectories of ground units (robots, UGVs, cars) and specific 3D planning algorithms (e.g. [9]) have to be used for air traffic simulation (airplanes, UAVs, helicopters).

Area in which unit can operate is than defined as a union of all allowed areas minus the obstacles $R_{allowed} = \bigcup_{R_n} - \bigcup_{O}$. Example of such an area is shown in Figure 1, where $R_n = \{R_1, R_2, R_3\}$ and obstacles are represented by polygons $O = \{O_1, O_2, O_3\}$.

As stated above, nodes try to fulfill a set of tasks. In real-life scenarios several units usually have to participate on the task execution process. Task tk thus can be described by a tuple $tk = \langle L(tk), P(type_{id_1}, \ldots, type_{id_m}), t_{tk}, p\rangle$, where function L gives the physical location in R where the task must be executed, set of participants P specifies a number of nodes of each type (with m different types of nodes) required to fulfill the task. Parameter t_{tk} represents the duration of the task and p is a task priority. Maximum number of each type of participating nodes parameters tk_{type_max}. Batch of random tasks TK is generated. Number of tasks in one batch is given by the parameter tk_{batch} – $|TK| = tk_{batch}$.

Function

$$available(u) = \begin{cases} 0 & \text{if node } u \in N_m \text{ is already assigned to some task } tk \\ 1 & \text{otherwise} \end{cases}$$

With given sets of nodes and tasks the mobility model works as follows:

1. Select random task $tk \in TK$ and try to assign required number of nodes to the task. Path planner filters out nodes that cannot reach the task location. Available nodes are ordered by their distance from the task location $L(tk)$ and the closest ones are assigned to the task. If sufficient number of nodes is not available, other task from the TK is selected. In case that none of the tasks can be executed, wait until some other task is completed and more nodes will become available.
2. When new task is assigned to the group of nodes, it is removed from the batch of tasks $TK = TK \setminus tk$ and all the group members start to move to the *rendezvous point*. This node is placed in the middle of the group of nodes assigned to the task (average value of their coordinates). Note that the predefined rendezvous point can be used as well. Nodes do not move exactly to that point, but stay somewhere within the ϵ-neighborhood to simulate some pattern. In more realistic scenarios form of that pattern can be specified in details.
3. Individual nodes move according to their node mobility. Following mobility models when approaching the rendezvous point were used in our simulation:
   - robotic nodes move along a straight line with a velocity v_{max};
   - humans can either move or remain stationary in given time step, which simulates their engagement in other event, e.g. analysis of the map updates received. When their move, their motion is a variant of the Brownian-like movement – their position in the next time step is in square of side $2m$, which is not centered at the current node location at this case, but current location is in the center of square side and square lies on the joint of current position and rendezvous point, see Figure 2. Parameter m represents the average motion speed of the human.

Different mobility models can be used for each node type. Example of unit movement is shown in Figure 3.

4. After the group is formed, group leader node is selected and all members have to agree on a common group velocity. Then the group starts to move to the task location point $L(tk)$. Group velocity is set to the minimum from the v_{max} of the slowest node and m. All the humans try to stay within some δ-vicinity of the group leader. If they are getting out of this region they temporarily modify their m parameter.
5. When all the group members reach the ϵ-neighborhood of $L(tk)$, they remain stationary for the time interval t_{tk} to simulate task duration. After that time period their availability status is set to 1 and new task assignment process is invoked.
6. If $TK = \{\emptyset\}$, generate new batch of tasks. Two variants of batch generation process were studied – (i) *continuous*, when new batch is generated immediately after the last task from previous batch is assigned to some unit(s) and (ii) *delayed*, when next batch is generated once the last task from the previous batch is completed. By generating tasks in batches sequential nature and precedences of tasks are simulated.

3.4 Model Extensions

Mobility model can be extended with a feature which allows units join and leave the scenario as mentioned in [8]. This feature is very important for testing of higher-level control algorithms, as it brings additional dynamics to the system. It could be used to test to test ability of routing protocols to dynamically modify the routing tables, adaptivity of clustering algorithms or response time of topology control protocols.

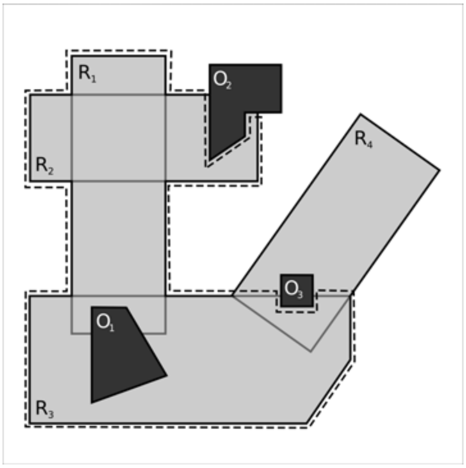

Fig. 1. Example of the field operation scenario. Units are allowed to operate only within the predefined areas and have to avoid the obstacles.

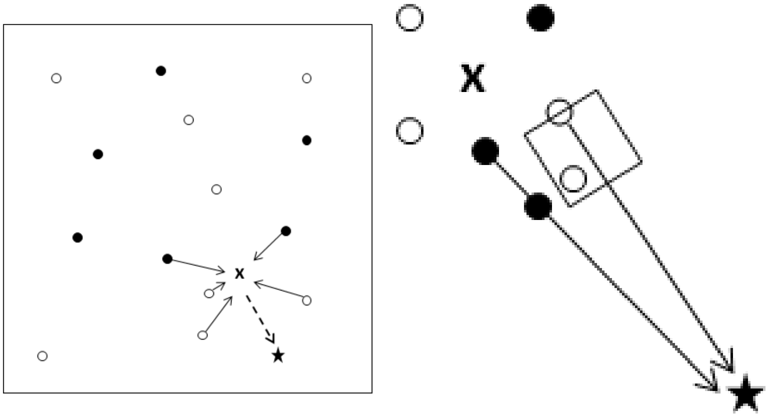

Fig. 2. Example of topology network mobility model: 3 humans and 2 robots that will participate on the task are moving towards the rendezvous point (a), detail of the motion model (b)

Typically we distinguish two basic cases when units leave the scenario:

1. randomly - units are disposed at random time to simulate their failures, to simplify the simulation process remaining nodes continue in task execution and do not try to look for additional nodes to substitute the missing one;
2. when task is completed - units leave the predefined areas (i.e. task location point $L(tk)$ is not selected randomly, but rather set to some predefined point on a border of allowed area.) or their communication devices are turned off.

Units may join the scenario in a similar way - either they enter the area at predefined points on area border or turn on their communication devices (which allows to randomly deploy nodes inside the area).

According to the simulation scenario setup number of active nodes may not excess predefined number of nodes n. In such a case several nodes have to leave the scenario before new nodes are allowed to join.

4 Experimental Evaluation

Set of experiments was carried out to illustrate basic characteristics of the mobility model. Nodes were operating in 2D flat, obstacle-free environment, area was a square 1000x1000m. Communication range was set to 100m.

As could be seen in Figure 4, critical transmitting range (CTR) for connectivity for proposed mobility model is higher for the same number of nodes deployed over the area compared to the RWP mobility model. Obviously this is caused by the fact that nodes form groups and move in close formations in contrast to the independent random node movement in case of RWP. Generally there are dense parts of the area that represent the clusters and whole network can be seen as a sparse configuration of clusters. Longer distances between the clusters lead to higher required CTR to prevent the network partitioning. In experiments for the tactical network mobility model one half of the nodes were robots and the second half humans, maximum group size was $\frac{n}{10}$ and each batch consisted of $|TK| = 10$ tasks.

Average node degree distribution (Figure 4 (b)) shows that average number of neighbors increases with the number of nodes required to complete the task. In case of RWP the distribution has a small variance, while with increasing number of nodes in group the variance grows.

Average length of the trajectories is shorter than in the case of RWP mobility (see Figure 3), because for each task a group of nearest units is chosen. This matches the real-world behavior, where closest units are chosen as well to minimize the travel time and energy consumption.

Spatial density distribution varies for each batch generation process:

- Continuous batch generation – in this case a node density is similar to one of RWP model. During the detailed analysis of the RWP model it has been shown, that model generates node spatial distribution which is independent of the initial node placement and that the nodes are concentrated in the center of the region R (*border effect*) [10].Strength of the border effect in this case depends on the number of nodes participating on task execution. The higher is the ratio of participating nodes compared to the total number of nodes the more distinct is the effect, because only few groups can be formed and they have to travel around whole area. On the other hand, if only a few nodes are required to fulfil the task, robots travel short distances and node density is more uniform.
- Delayed batch generation – as in the previous case, characteristic of the node spatial density strongly depends on the size of the groups required to complete the tasks. Furthermore it also depends on the number of tasks in a batch. If the number of tasks is low and small number of robots is required, we can observe *reverse border effect*, when nodes tend to stay around the border of the area. Reason for this behavior is, that nodes wait until completion of all tasks in the batch, after that new batch of tasks is generated and assigned to the nodes. But tasks are assigned to nodes in their vicinity and nodes close to the border are very likely to remain in their positions. With increasing number of tasks and size of the groups distribution becomes more uniform and for big groups the distribution is similar to the RWP model. Node spatial density for delayed batch generation process is shown in Figure 5.

So by adjusting model parameters and batch generation process various characteristics of node spatial densities can be achieved.

As in some other mobility models the probability distribution of the initial locations and velocities of the nodes differs from the distributions later in the simulation. There are in general two basic approaches how to deal with this problem – *(i)* discard an initial sequence of observations from simulation and *(ii)* use *steady-state* mobility generator which will choose initial locations and speeds from the stationary distribution [11]. In our case we have chosen the first

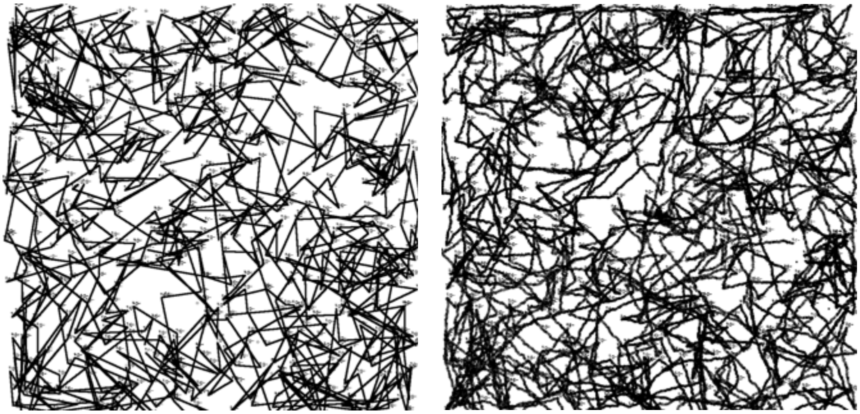

Fig. 3. Example of movement of robotic (a) and human (b) units

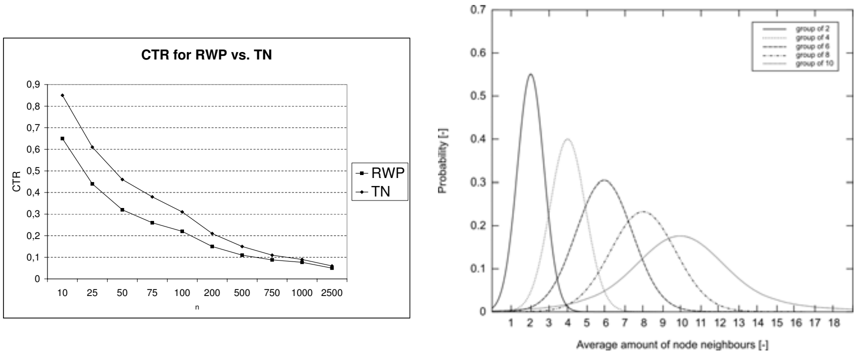

Fig. 4. CTR for connectivity - RWP mobility model vs. tactical network mobility model (a), average node degree distribution (b)

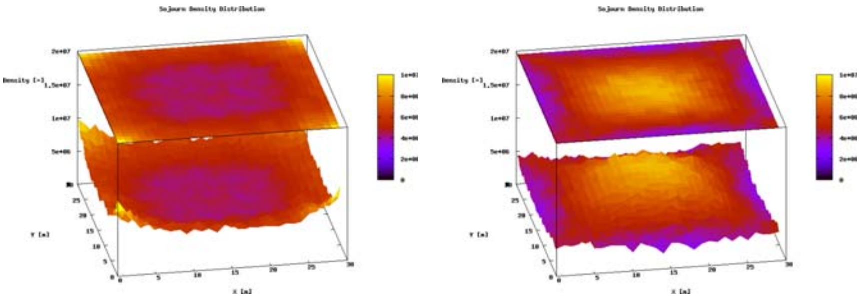

Fig. 5. Node spatial density distribution for delayed batch generation process. Figure shows situations for small groups and limited batch size (a) and for big groups (b).

approach and we discard a whole sequence at the beginning of simulation, until the first task is completed.

5 Conclusion

We have described a problem of modeling mobility of nodes in field operations and proposed a novel synthetic mobility model which addresses this problem. Unlike the other existing models it is able to simulate complex scenarios and is general enough to allow modeling of various scenarios. Behavior of nodes in our mobility model is goal-driven, i.e. fulfilment of common application scenario-related goals is simulated. Model is providing support for multiple types of mobile units as well as stationary wireless sensors. Depending on the generated goals nodes may form temporary groups and move in formations throughout the environment, which resembles real-life behavior patterns of units in tactical missions. Various features of the proposed model were studied and discussed, especially the role of goal-generating process on the overall behavior of the placement algorithm.

Acknowledgement

We gratefully acknowledge the support of the presented research by US Army project no. W911NF-08-1-0505 and research programme no. 1M0567 funded by the Ministry of Education of the Czech Republic.

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