Towards an Integrated Mobility Simulation for Communications Research

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***Abstract*—Mobile devices and new communication technologies gain ever more importance. Evaluating such technologies for critical domains, like disaster recovery, is a difficult task and is usually done by using simulations. Until today, research focused on the impact of mobility patterns on the investigated communication technology. We argue that the influence of the communication technology on the mobility patterns is also important to produce realistic simulations and meaningful results. In this paper, we present our agent-based mobility model and our simulation framework. This framework can be connected to a network simulator to execute mobility and network simulations in parallel, thus, influencing each other. The evaluation of our mobility model with real world experts in the field of disaster recovery indicated our approach to be accurate and also revealed potential for improvements.**

Keywords*—*mobility model; behavior-based; software agents; simulation; integration; disaster recovery

I. INTRODUCTION

Simulators for mobility and communication are popular research tools to investigate the applicability of new communication technologies under dynamic conditions. Especially in critical domains, like disaster recovery, new communication technologies can help saving human lives more efficiently. For example, a scalable communication network can be achieved by interconnecting hand-held mobile devices carried around by first responders to a peer-to-peer like network as proposed by Bradler et al. [4]. However, testing such prototypes during real disaster recovery missions is very dangerous and negligent because, if the prototype fails during the mission, human lives are threatened. Also, the testing possibilities under real conditions are very limited and results might not be easily reproducible due to many factors influencing the investigations. Using simulations to investigate new communication technologies is, therefore, much safer and more convenient.

Until today, the focus in communications research usually resided on the new communication technology under investigation. Random-based mobility models are commonly used to produce movement traces [6], [13] in a first step. Afterward, these movement traces are used as input data for network simulations [1]. We believe this approach to be insufficient, at least for the scenario of disaster recovery, since communication between first responders directly influences their movement. For example, if the network suffers a malfunction and, thus, new commands from the headquarter cannot be transmitted to first responders in the field, they cannot react on these commands. Conversely, if first responders communicate using wireless network devices, their movement directly influences the network since messages cannot be transmitted if first responders move out of each other's communication range.

We, therefore, propose a framework for mobility simulation to execute mobility simulations together with network simulations in parallel, enabling them to influence each other. Our mobility model is based on software-agents allowing us to simulate different kinds of scenarios by implementing different agent types and scenario specific rule sets. We implemented rule sets for different disaster relief forces because of our expert knowledge and experience in this field. Our simulation framework is targeted on interaction between agents and the environment as well as on communication between agents. These interactions are influencing their movement directly. We evaluated our approach using questionnaires targeted on real world experts most of which already participated in rescue missions. Our evaluation showed that, considering the level of abstraction, most of our assumptions are accurate and our approach is suitable in general. However, we were able to identify some weak spots in our mobility model which we fixed after evaluating the survey. The contributions of this paper are threefold:

1) we present our mobility and interaction model that generates realistic movement and communication patterns for simulations,
2) we describe the general architecture of our framework for integrated mobility and network simulations, and
3) we discuss the evaluation of our model using questionnaires targeted on real world first responders.

Our mobility model and simulation framework enable us to investigate the influence of different communication technologies on the efficiency of first responders during their missions in the future.

The remainder of this paper is organized as follows: in Section II, we discuss the related work on mobility models and focus on models targeted on disaster recovery in more detail. We then present our mobility model and our integrated simulation framework in Section III. The evaluation of our mobility model is discussed in Section IV and Section V presents concluding remarks as well as an overview on future work.

II. RELATED WORK

To simulate the movement of nodes in a mobile ad-hoc network (MANET) scenario, many mobility models have been proposed during the last two decades. In general, mobility models can be separated into two categories: trace-based models and synthetic models [6]. In trace-based models, movement traces are gathered and collected from real world systems. These traces are then replayed in simulations to correctly simulate mobility of network nodes. However, they are bound to the specific environment where they were gathered. Also, these models are not flexible enough to simulate variations of a single scenario.

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To simulate other environments or different variations of a single scenario, synthetic models can be used. These models create artificial movement traces for mobile nodes without replaying recorded real world movement traces. However, these models are supposed to create movement traces similar to real world traces and, thus, simulate realistic movement patterns. To accomplish this goal the behavior of single nodes is reproduced in a realistic fashion.

We categorize the approaches for synthetic mobility models into random mobility models and behavior-based mobility models.

A. Random Mobility

Until today, many mobility models based on random movement have been proposed. Although these models are rather simple, they are particularly popular and have been examined extensively in the past [12]. The three most commonly used mobility models that generate random movement traces are:

- *Random Walk Model [7].* In this model, every node picks a direction of the interval $[0, 2\pi)$ at random and a random velocity. Then, the node moves for a random time span before it picks a new direction and a new velocity.
- *Random Direction Model [13].* Here, every node picks a random direction of the interval $[0, 2\pi)$ and a random velocity. The node then moves to the border of the simulation environment where it picks a new direction and velocity.
- *Random Waypoint Model [10].* In this model, every node picks a random point in the simulation environment as well as a random velocity. It then moves until the point is reach and picks a new waypoint and velocity.

Although these simple random mobility models above are commonly used they have different unexpected properties and create a behavior that is not usually intended. Yoon et al. [17] showed that in these models the average movement speed of nodes decreases over time because slow nodes need more time to reach their destination than faster nodes. Furthermore, mobility models exist that try to incorporate a behavior oriented component into the otherwise random models:

- *Pursue Model [14].* Using this mobility model, nodes can be simulated that follow a specific moving target defining the movement as: $p_{new} = p_{old} + a(p_{target} - p_{old}) + v_{random}$. The vector v_{random} defines the influence of the random number generator on the node movement. The acceleration $a(x)$ describes the influence of the moving target on the node movement.
- *Column Model [14].* In this mobility model, nodes move on predefined lines. These lines move forward toward a random direction from the interval $[0, \pi)$ and a random distance. This model is suited for search-like activities where nodes move forward forming a front line.
- *Reference Point Group Model [9].* This mobility model arranges nodes into groups. The center of a group moves on a random path and the group members move randomly around a predefined reference point which depends on the logical group center.

A more detailed overview and a simulation based comparison of different mobility models can also be found in the work of Camp et al. [6].

B. Behavior-Based Mobility

Our main goal is to reproduce real world mobility in a simulated environment. As we look on disaster recovery missions as a concrete scenario it is clear, that a mobility model based on random movement cannot reproduce real world movement and behavior of first responders during rescue missions. Especially the different organizations like police, fire fighters and paramedics have very specific roles when entering a disaster area [12]. Therefore, a mobility model is needed that incorporates these different roles so that the nodes move and act according to their specific behavior. We now highlight three types of behavior-based mobility models capable of reproducing real world behavior and movement of first responders.

1) Role-Based Mobility: Nelson et al. describe a generic event and role-based mobility model [12]. Every node is assigned a role or a set of roles generating actions the node will perform on a given event. The entire movement pattern of a node in disaster recovery is then described by a triple (r, e, a): role r reacts on an event e by performing the activity a. By instantiating the triples with the characteristics for different node types operating in disaster recovery a movement pattern for the scenario can be generated. This way it is also possible that a node follows different movement patterns during one simulation. Four different categories of actions are assumed:

- *Repelling*: This role is mainly used for civilians during a disaster. Also, this role can include a property describing the curiosity of the civilian defining the possibility the civilian stops at the periphery of a disaster area, thus, simulating watchers.
- *Attracting*: This role is typically used for police men and fire fighters moving fast towards one or more events.
- *Oscillating*: This role is mainly used to model ambulances moving between the disaster area and hospitals. The nodes move towards an event and directly after arriving there they move to a predefined location and repeat the movement pattern continuously.
- *Immobile*: This role is used to model naturally static objects like hospitals. But also nodes that become immobile after an event (e.g. injured persons) can be modeled with this role.

2) Gravity-Based Mobility: If several independent disaster areas are simulated, a mobility model based on gravity (proposed by Nelson et al. [12]) can be used to describe how nodes move towards or away from the individual areas. In this model, every disaster area is modeled as a gravity source. The force F a disaster area has on a node can be described by the intensity I as $F = I/d^2$ with d being the distance between the node and the disaster area. I also describes whether the node moves towards a disaster area or away from it. For a particular node, the force vectors $\vec{F}$ from all disaster areas are then combined to the vector sum $\vec{F}_{total}$ describing it's resulting speed and direction of movement.

3) Zone-Based Mobility: Aschenbruck et al. [2] describe a partitioning of the entire disaster area according to handbooks for first responders in Germany [11], [15]. This partitioning then influences how nodes move. The disaster area is divided into four different zones:

- The *incident site* is the zone where the actual disaster occurs. In this zone casualties are to be expected and the effects of the disaster have to be combated (e.g., fire).

- In the *treatment zone* the injured wait for their treatment after they have been rescued from the incident site. Paramedics give first aid to injured and bring them to the transport zone. Usually, the treatment zone is close to the incident site.
- In the *transport zone* transportation vehicles such as ambulances and helicopters wait to take injured to the hospitals.
- The *hospitals* (or the *hospital zone*) are typically further away from the incident site and are not part of the actual disaster area. Injured are being transported here via transportation vehicles for further treatment.

In this model, every node belongs to one of the different zones. Some transportation nodes move between zones, others only move inside one zone, for instance, fire fighters.

The zone-based mobility model, as well as some of the random models described above, are implemented in the software BonnMotion [1], a rich Java-based software that generates synthetic movement traces to investigate mobility in different scenarios. The generated movement traces can also be exported as input data for several supported network simulators (cmp. Figure 3a). However, BonnMotion, and also other mobility simulation frameworks, lack an online interface for network simulators because they are not intended to be executed with such simulators in parallel. Also, none of the mobility models above consider communication between simulated nodes to influence the resulting movement.

III. Mobility Simulation Framework

In the last section, we presented different mobility models to be used for general purpose and for disaster recovery simulation. In this section, we introduce our approach for integrated simulation using disaster recovery missions as an example. In our approach, we focus on a deep interaction between network simulation and mobility simulation to realistically simulate complex scenarios where movement of nodes is also based on communication between them.

We first introduce the environment where the simulated nodes move and operate in. These simulated nodes are implemented as software agents based on rule sets which we present afterward. Third, we describe the key concept of our approach: the communication between agents and the interaction of agents with the environment. Finally, we present the general system architecture of our simulation framework.

A. Environment Model

The basis for mobility simulation is always formed by the environment where mobile nodes move in. Typically, this environment is modeled as a two dimensional plane where mobile nodes and obstacles are placed on. During the mobility simulation, the nodes are moved on this plane, thus, generating movement traces. In many cases, this movement is based on a random mobility model. However, in realistic scenarios, like disaster recovery missions, nodes (e.g., first responders) move according to certain properties in their surrounding environment. First responders use vehicles to move on streets to, from, and between incident sites, fire fighters extinguish fires in buildings or in the environment, and so on. Therefore, information about the environment is essential to disaster simulation and for realistic movement patterns in general.

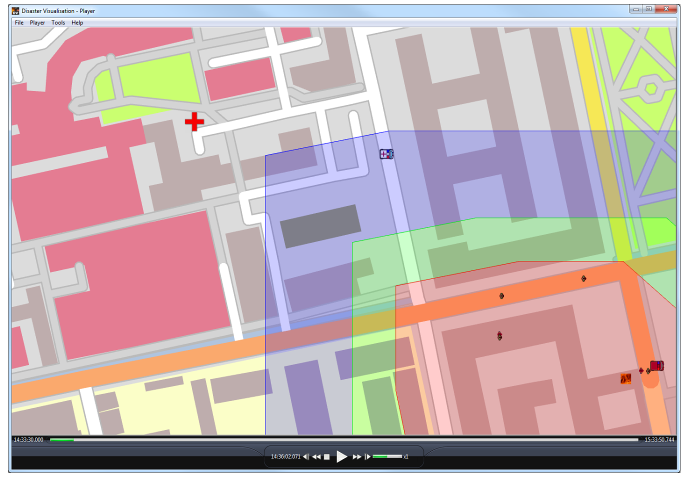

Figure 1. The graphical representation of the environment

For this reason, we use data from the OpenStreetMap project [8] to generate the environment. This data provides information about streets, buildings, fields, woods and other environmental properties. If nodes move on streets, their speed can be adapted according to the streets' speed limit, for instance. Information about hospitals can be used in the simulation as targets for ambulances to transport injured to. This data greatly helps to generate realistic movement traces.

Based on this environmental data, seats of fire can be placed manually on the map as a starting point for the disaster simulation. During the simulation, fire spreads with an average speed of $0.25m^2$ per minute (according to DIN 18232) or it gets extinguished by fire fighters. Also, we use the state of the art work by Aschenbruck et al. [2] to create the three aforementioned virtual zones *incident site* (red), *treatment zone* (green), and *transport zone* (blue) surrounding the fire places, also depicted in Figure 1. The information about hospitals is used to create the *hospital zones* (red cross in the top left corner of Figure 1).

B. Mobility Model

The implementation of our mobility model is based on the concept of software agents [3]. This means, every node is represented by a software agent that generates the movement patterns for that particular node. Agents, on the other hand, are instances of an agent type. Every agent type contains a set of rules describing how to react in specific situations and on different events. In the case of disaster recovery, agent types are *fire fighter* and *police car*, for example, and the individual fire fighters or police cars are then instances of the *fire fighter* or *police car* agent types, respectively.

Each agent has limited knowledge about the simulated world including other agents and the environment. In particular, the knowledge of each agent consists of the environmental map, that is the road network and the positions of the associated institutions such as hospitals or police and fire stations. At the beginning of each simulation, every first responder agent has initial information about the type and location of the disaster areas, injured people in these areas, the partitioning into zones, and the positions of their colleagues. Based on its current information, every agent chooses specific targets in the environment and moves towards them considering the

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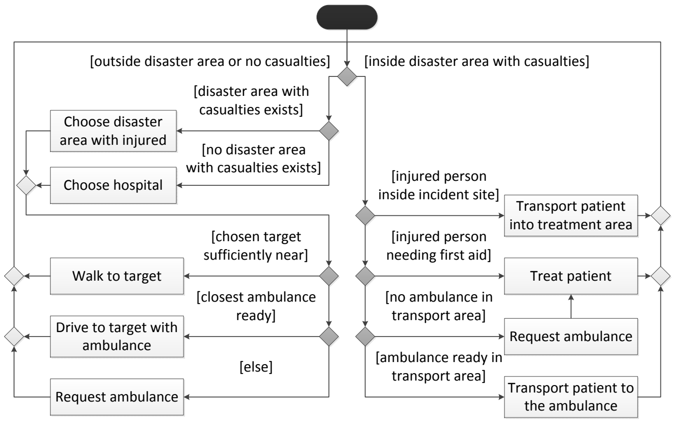

Figure 2. Rule set of a paramedic

available geographical information or retains its position for a specified time span. The choice of targets determines the movement pattern characteristic to that particular agent type. Our behavior-based mobility model differentiates not only between the various types of first responders such as police men or fire fighters, but also between the ways of moving such as *by motor vehicle* or *by foot*. Therefore, agents are moving specifically to their roles in order to obtain most realistic behavior-based movement patterns.

The precise movement of the agents roughly follows the simple high-level actions *repelling*, *attracting*, *oscillating*, and *immobile* used in the generic event- and role-based mobility model described by Nelson et al. [12]. However, targets selected by the agents will depend on a substantially more fine-grained behavioral simulation which simulates the performed tasks, that are specific for the respective agent type, directly at the level of the agents. For example, fire fighters have two primary tasks. First, casualties have to be transported from the *incident site* (where other first responders cannot operate due to the dangers) to the *treatment zone* (where the injured can be treated by paramedics). The second task is to fight disasters, for example, to extinguish fire.

The task of medical personnel during rescue missions is to bring injured people out of danger to the *treatment zone*, to treat them there, and then bring them to the *transport zone*, where they are picked up and transported to a *hospital*. For that, a paramedic is moving together with the injured person from the *treatment zone* to the *transport zone*. This injured person is then transported to a *hospital* for further treatments and the paramedic heads for another injured person in order to prepare him for transportation. Figure 2 shows an example rule set for the paramedic agent type.

The police has the task to secure disaster areas. This means that the traffic hubs (cross roads) need to be secured to prevent civilians from entering the disaster area. Police officers might have to patrol between several intersections and possibly expel civilians who are already within the disaster area.

The movement of civilians is based on the physics-based gravitational mobility model described by Nelson et al. [12], that allows nodes to respond to the presence of multiple disaster events. Agents can flee from several independent disaster events or approach them.

This agent-based concept provides us with the opportunity to simulate other scenarios as well, for instance, a public transportation system. Buses or trams and trains in cities can be modeled using our mobility model by implementing the rule sets for such transportation agents.

C. Interaction and Communication

The rules above clearly show that the movement as well as the behavior of agents are directly based on interaction between agents and with the environment. For example, fire fighters extinguish fires in the environment (e.g., in buildings) and paramedics carry injured people to ambulances to be transported to the hospitals.

Furthermore, first responders can send requests to other rescuers, if they need help or a transportation vehicle. For example, paramedics request ambulances to allow patients to be transported to a hospital. An ambulance, that is available for transportation, can then acknowledge the request and move to the requested location. The transportation of first responders to the disaster area and back to the headquarters is carried out in the same manner, as well. Also, first responders inform their colleagues about their new position as soon as they proceed to a new location. This helps to keep the information on the colleagues' positions up to date for all first responders. First responder agents use this information to decide who should be assigned to which disaster event.

Finally, first responders inform their colleagues and the commander about the progress of the rescue mission. Especially, if the fire is extinguished, the fire fighter agents inform their colleagues about the finished task. Also, paramedics inform their colleagues about rescued persons. Based on this information, first responders know what tasks are remaining and who is available for a new task.

This shows how the movement of agents also depends on the communication between them. Only, if the information exchange between first responder agents is reliable, the rescue mission is accomplished successfully and efficiently. Conversely, the communication of the agents also depends on their movement and the communication technology used. If a real network based on wireless technology is considered for message transportation, the agents need to be in transmission range to each other for messages to arrive at the destination. Hence, the network simulation cannot be launched after the mobility simulation, but both simulations have to run together in parallel to account for the influence of both simulations.

D. System Architecture

Our simulation framework focuses on these influences between mobility and network simulations. It is based on a discrete event-driven simulation engine. This means, events occur at definite points in time during the simulation and the simulation can be described as a chronological sequence of events. In a typical state of the art simulation setup, the mobility simulation is executed first, creating movement traces to be imported into the network simulation afterward (cmp. Figure 3a). Our system, on the other hand, allows for an integrated simulation where network and mobility simulations are executed in parallel, thus, influencing each other (cmp. Figure 3b). However, this requires the mobility model to not only generate basic movement but communication patterns, as well (as described above). Assuming such a model, this provides the advantage of simulating communication between nodes more realistically, since their communication can directly influence their movement (e.g., nodes calling for help).

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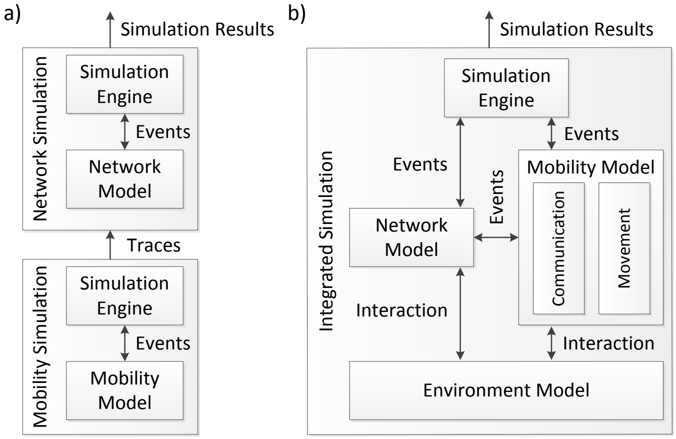

Figure 3. a) Typical simulation setup – b) Integrated simulation framework

To connect our proposed mobility model to a network simulator, a shared simulation engine is needed to dispatch mobility and network related events. This does not necessarily require events to be compatible with both, the network and the mobility simulators. However, for simplicity the events are compatible with both simulators in our current implementation. We connected our framework to the state of the art discrete event-driven network simulator PeerfactSim.KOM [16]. This simulator can now be used to simulate different communication technologies in combination with our mobility model.

In the future, using the disaster recovery example, this integrated simulation enables us to investigate the influence of different modern communication technologies on the works of first responders during their missions. A simulation without a network simulator is possible, as well. In this case, we assume that messages are being transmitted immediately and without any packet loss. This can be used to very basically mimic traditional radio communication, however, not realistically. Furthermore, due to the generic design, other event-driven simulators can be connected to our simulation framework as well, for instance, a road traffic simulator.

We used our first response communication sandbox [5] as a starting point for the mobility simulation framework. However, many improvements and changes were necessary to integrate our new mobility model with the network simulator and the environment. We implemented a graphical user interface called *DisVis*, short for Disaster Visualization, to create and modify scenarios for simulation and to visualize simulation results afterward (depicted in Figure 1). In the future, we intend to investigate different communication technologies for disaster recovery missions using our integrated simulation framework.

IV. Evaluation

To evaluate our mobility model described in the last Section we have drawn on expert knowledge. We created a questionnaire targeted at experts from *police departments*, *fire fighting departments*, and *medical facilities*. With this survey, we intended to extract different types of information. This resulted into three similar questionnaires, one for each of the first responder groups listed above. Each questionnaire was separated in four parts to get information about *a)* activities of first responders during missions, *b)* communication between them, *c)* details about the works of each group, and *d)* the four disaster zones described above.

Our call to fill out the survey was followed by 84 individuals most of which already participated in disaster recovery missions. This number divides into 44 individuals from medical facilities, 32 individuals from fire fighting departments, and 8 individuals from police departments. As the number of participating members from police departments shows, their role during disaster recovery missions is not as big as that of the other groups. Usually fire fighters are the first to arrive and take over certain roles associated with the police. The main role of the police is investigation and criminal prosecution which usually is a long term activity and starts after the disaster recovery mission is finished. This was also reflected in the answers by both, the participants associated with the police departments as well as the participants associated with the fire fighting departments.

A. Activities

First, we presented the atomic activities we implemented in our mobility model to abstract the behavior of the three first responder agent types. The goal was to determine the priorities and rules for these atomic activities as well as to identify important but missing activities.

Our assumption about the priorities was accurate in general. However, participants emphasized the first activity to be *examining the situation on-site*. This activity is not explicitly modeled in our rule set. But, as stated before, the agents know about the situation in the disaster areas at the beginning of the simulation and incorporate this knowledge into their decisions and activities. Therefore, this activity is modeled implicitly in our rule set.

B. Communication

Second, we checked our assumptions made about the importance of communication between first responders. This also included the organizational structures. We found that our assumptions about the highly hierarchical organizational structures of first responders is accurate in general and that communication is very important in disaster recovery missions. In fact, most activities are only executed by command. Commands are either given in a briefing at the beginning of the rescue mission or during the mission via (radio) communication.

Furthermore, the survey exhibited the explicit importance of small first responder groups. For example, a team of fire fighters and a fire engine form a group that moves and operates together. The same applies to police officers and paramedics. This effects the movement of every unit that is part of a group. It also impacts the communication, which is simulated hierarchically so that the members of these groups primarily communicate among themselves and only the group leaders communicate between different groups. We implemented this behavior into the rule sets of our mobility model.

C. Details

Third, we intended to get details about typical walking and driving distances. We also tried to get a rough estimate about the average time paramedics need to stabilize patients and about the average time fire fighters need to extinguish a fire in apartments. In general, these details can only be estimated very roughly and depend on various factors. However, we found that typically distances of up to 400 meters are walked by foot. To stabilize patients paramedics assess 2 to 10 minutes. Fire fighters asses roughly 30 to 90 minutes to extinguish a fire in apartments, although, the participants explicitly pointed out that the time is highly situation dependent and cannot be easily generalized. This also is hard to be mapped to our simulation. Therefore, fire fighters in our model extinguish fire at a rate of $1.5m^2$ burning area per minute.

D. Disaster Zones

Finally, we evaluated the assumptions made about the partitioning into different zones and their sizes. The existence of different zones was confirmed by the participants, as expected. Usually, first responders define locations and sizes of these zones before the recovery mission is started. This is also captured in our simulation model. The size of the *incident site* highly depends on the affected region (e.g., 20 to 50 meters or 100 to 150 meters perimeter). In our simulation model we use 20 meters around the affected region, for instance, a building with a burning apartment.

Usually, the *treatment zone* is rather small and can be combined with the *transport zone* into one zone under some circumstances. Depending on the situation, the *treatment zone* is at most half in size compared to the *incident site*. The *transport zone*, on the other hand, is rather large and can be up to twice as large as the *incident site*. Usually, the *transport zone* is dependent on qualified locations for transport vehicles to access the zone. These locations should be as close as possible to the *treatment zone*. In our simulation model we use at least 20 meters for the *treatment zone* and at least 50 meters for the *transport zone*.

Additionally, the initial partitioning of the disaster area into zones can change over time when disasters are spreading or are averted. This fact is reflected in our simulation model. Details about the sizes of zones were incorporated after the survey.

V. CONCLUSION

In this paper, we presented an overview of basic and commonly used methods for mobility simulation in network simulations as well as in disaster scenario simulations. We argued that, especially in disaster simulations, the interaction and communication between the simulated agents are crucial to the resulting simulation. Both aspects require that mobility and network simulators are executed together in parallel so both simulations can influence each other. We presented our approach to simulate movement and communication patterns in disaster recovery missions based on state of the art work and expert knowledge. Our environment and mobility model is based on OpenStreetMap data and software agents, respectively. The event-driven mobility simulation framework is capable of stand alone simulation. But it can also be integrated with network simulators like PeerfactSim.KOM [16] enriching the simulation with realistic network models.

We evaluated our mobility model with questionnaires targeted at experts from police departments, fire fighting departments, and medical facilities. Especially medical personnel and fire fighters participated in the surveys. The responses gathered from the surveys allowed us to further improve our rule sets of the different agent types.

In the future, we plan to evaluate different communication technologies and mechanisms like routing algorithms in the field of disaster relief. We are especially interested in how such technologies influence the works of first responders. Furthermore, we want to enrich our rule set with more detailed rules from handbooks for first responders [11], [15] to further increase the realism of our simulation. Finally, we also plan to implement different agent types for other scenarios like public transportation to analyze communication possibilities between buses and trains in smart cities.

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