H^3N – Analysis Toolbox for Hybrid Routing in Heterogeneous, Disruption-Tolerant First Responder Ad Hoc Networks

Dissertation zur Erlangung des
akademischen Grades Doktor-Ingenieur (Dr.-Ing.)

vorgelegt der Fakultät Elektrotechnik und Informationstechnik
der Technische Universität Ilmenau

von M. Sc. Silvia Krug

1. Gutachter:	Prof. Dr. rer. nat. Jochen Seitz
2. Gutachterin:	Prof. Dr. Martina Zitterbart
3. Gutachter:	Prof. Dr.-Ing. Lars Wolf

Tag der Einreichung:	12. 06. 2017
Tag der wissenschaftlichen Aussprache:	30. 11. 2017

urn:nbn:de:gbv:ilm1-2017000568

One never notices what has been done; one can only see what remains to be done.
– Marie Curie

Für Wilfried

Acknowledgements

It has been a long way over four years and the completion of this project would not have been possible without the support and encouragement from various friends and colleagues.

First, I thank Prof. Jochen Seitz for giving me the opportunity to perform the studies that finally led to this thesis and who gave me the freedom to explore my own ideas as well as test my abilities as teacher. Furthermore, I like to thank my external reviewers Prof. Martina Zitterbart and Prof. Lars Wolf for agreeing to read and asses this thesis. Especially, Prof. Zitterbart provided me with valuable professional advise and enabled me sharpen the ideas presented this thesis.

I thank my team mates Sebastian Schellenberg, Thomas Finke, Peggy Begerow, and Markus Hager at the Communication Networks Group for continuous discussions during coffee rounds. The same is true for my floor mates Tobias Simon, Andre Puschmann and Thomas Dietrich from other research groups at TU Ilmenau. Discussions with you created new ideas, helped me to see other aspects, and resulted in many joint papers.

Besides that, there are some other friends that supported and encouraged me to continue the work on this project, especially after most of my team mates finished their own work and left. Therefore, I have to thank Islam, Annette, Hannes, Tino, Wolfgang and Christian. Without you, I would have never finished this project.

There is one more person I have to thank at this point. My first math and physics teacher, Jens Günschmann, raised my interest in science at the very beginning and always supported me to develop my potential. He was the first one to suggest a scientific career, even before this was possible and without his idea planted in my head, I would have probably never asked for a change to work at Jochen Seitz' research group.

Finally, I have to thank my parents Annelo and Wilfried who always supported me and allowed me to follow my own way even if it was not as straight as it could have been.

Kurzfassung

Silvia Krug

H^{3}N – Analysewerkzeuge für hybride Wegewahl in heterogenen, unterbrechungstoleranten Ad-Hoc-Netzen für Rettungskräfte

Rettungskräfte müssen unter widrigen Bedingungen zuverlässig kommunizieren können, um in Rettungseinsätzen effizient arbeiten zu können und somit Leben zu retten. Idealerweise ist dazu ein selbstorganisiertes Ad-Hoc-Netz notwendig, weil die Kommunikationsinfrastruktur ggf. beschädigt oder überlastet sein kann. Um die geforderte Robustheit der Kommunikation auch in Szenarien mit größeren zu überbrückenden Entfernungen zu gewährleisten, werden zusätzlich Mechanismen benötigt, die eine Unterbrechungstoleranz ermöglichen. Verzögerungstolerante Netze (engl. Delay Tolerant Networks, kurz: DTN) stellen solche Mechanismen bereit, erfordern aber zusätzliche Verzögerungen, die für Rettungskommunikation nachteilig sind.

Deshalb werden intelligente hybride Wegewahlverfahren benötigt, um die Verzögerung durch DTN-Mechanismen zu begrenzen. Außerdem sollten entsprechende Verfahren heterogene Netze unterstützen. Das ermöglicht zusätzlich eine effizientere Weiterleitung durch die Nutzung von Geräten mit unterschiedlichen Kommunikationtechnologien und damit auch Reichweiten.

Um solche Systeme und die dafür benötigten Kommunikationsprotokolle zu entwickeln, werden verschiedene Analysewerkzeuge genutzt. Dazu gehören analytische Modelle, Simulationen und Experimente auf der Zielsystemhardware. Für jede Kategorie gibt es verschiedene Werkzeuge und Frameworks, die sich auf unterschiedliche Aspekte fokussieren. Dadurch unterstützen diese herkömmlichen Analysemethoden jedoch meistens nur einen der oben genannten Punkte, während die Untersuchung von hybriden und/oder heterogenen Ansätzen und Szenarien nicht ohne weiteres möglich ist. Im Falle von Rettungskräften kommt hinzu, dass die charakteristischen Merkmale hinsichtlich der Bewegung der Knoten und des erzeugten Datenverkehrs während eines Einsatzes ebenfalls nicht modelliert werden können.

In dieser Arbeit werden deshalb verschiedene Erweiterungen zu existierenden Analysewerkzeugen sowie neue Werkzeuge zur Analyse und Modelle zur Nachbildung realistischer Rettungsmissionen untersucht und entwickelt. Ziel ist es, die Vorteile existierender Werkzeuge miteinander zu kombinieren, um ganzheitliche, realitätsnahe Untersuchungen von hybriden Protokollen für heterogene Netze zu ermöglichen. Die Kombination erfolgt in Form von gezielten Erweiterungen und der Entwicklung ergänzender komplementärer Werkzeuge unter Verwendung existierender Schnittstellen. Erste Ergebnisse unter Verwendung der entwickelten Werkzeuge zeigen Verbesserungspotentiale bei der Verwendung traditioneller Protokolle und erlauben die Bewertung zusätzlicher Maßnahmen, um die Kommunikation zu verbessern. Szenarien zur Kommunikation von Rettungskräften werden dabei als ein Beispiel verwendet, die Tools sind jedoch nicht auf die Analyse dieses Anwendungsfalls beschränkt.

Über die reine Analyse verschiedener existierender Ansätze hinaus bildet die entwickelte Evaluationsumgebung eine Grundlage für die Entwicklung und Verifikation von neuartigen hybriden Protokollen für die entsprechenden Systeme.

Schlagwörter: Hybrides Routing; Heterogene Netze; Mobile Ad hoc Netze; Verzögerungstolerante Netze; Rettungsszenarien.

Abstract

Silvia Krug

H^3N – Analysis Toolbox for Hybrid Routing in Heterogeneous, Disruption-Tolerant First Responder Ad Hoc Networks

Communication between participating first responders is essential for efficient coordination of rescue missions and thus allowing to save human lives. Ideally, ad hoc-style communication networks are applied to this as the first responders cannot rely on infrastructure-based communication for two reasons. First, the infrastructure could be damaged by the disastrous event or not be available for economic reasons. Second, even if public infrastructure is available and functional, it might be overloaded by users. To guarantee the robustness and reliability requirements of first responders, the Mobile Ad Hoc Networks (MANETs) have to be combined with an approach to mitigate intermittent connectivity due to otherwise limited connectivity. Delay Tolerant Networks (DTNs) provide such a functionality but introduce additional delay which is problematic.

Therefore, intelligent hybrid routing approaches are required to limit the delay introduced by DTN mechanisms. Besides that, the approach should be applicable to heterogeneous networks in terms of communication technologies and device capabilities. This is required for cross multi-agency and volunteer communication but also enables the opportunistic exploitation of any given communication option.

To evaluate such systems and develop the corresponding communication protocols, various tools for the analysis are available. This includes analytical models, simulations and real-world experiments on target hardware. In each category a wide set of tools is available already. However, each tool is focused on specific aspects usually and thus does not provide methods to analyze hybrid approaches out of the box. Even if the tools are modular and allow an extension, there are often other tools that are better suited for partial aspects of hybrid systems. In addition to this, few tools exist to model the characteristics of first responder networks. Especially the generalized movement during missions and the generated data traffic are difficult to model and integrate into analyses.

The focus of this project is therefore to develop selected extensions to existing analysis and simulation tools as well as additional tools and models to realistically capture the characteristics of first responder networks. The goal is to combine the advantages of existing specialized simulation tools to enable thorough evaluations of hybrid protocols for heterogeneous networks based on realistic assumptions. To achieve this, the tools are extended by specifically designing tools that enable the interaction between tools and new tools that complement the existing analysis capabilities. First results obtained via the resulting toolbox clearly indicate further research directions as well as a potential for protocol enhancements. Besides that, the toolbox was used to evaluate various methods to enhance the connectivity between nodes in first responder networks. First responder scenarios are used as an example here. The toolbox itself is however not limited to this use case.

In addition to the analysis of existing approaches for hybrid and heterogeneous networks, the developed toolbox provides a base framework for the development and verification of newly developed protocols for such use cases.

Key words: Hybrid Routing; Heterogeneous Networks; Mobile Ad hoc Networks; Delay Tolerant Networks; First Responder Scenarios.

Erklärung

Ich versichere, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

Weitere Personen waren an der inhaltlich-materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder anderer Personen) in Anspruch genommen. Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer Prüfungsbehörde vorgelegt.

Ich bin darauf hingewiesen worden, dass die Unrichtigkeit der vorstehenden Erklärung als Täuschungsversuch bewertet wird und gemäß § 7 Abs. 10 der Promotionsordnung den Abbruch des Promotionsverfahrens zur Folge hat.

Ilmenau, den 12. Juni 2017 — Silvia Krug

Contents

List of Figures

List of Tables

Listings

CHAPTER 1

Introduction

Whenever there is a small accident, a fire or large scale natural disaster, *first responders* such as firefighters, emergency medical service members, and policemen among other emergency service units are deployed to prevent further damage and save human lives. Communication among all participating first responders and - in case of larger events - potentially volunteers is essential in order to fulfill the necessary tasks as efficiently as possible [9, 97]. However, it is challenging to establish a robust and reliable network that is capable of handling a wide variety of different missions [129]. This project presents several contributions to enable the evaluation of such networks and the development of suitable routing protocols.

1.1 Motivation

First responder ad hoc networks have to be robust against various harsh conditions and provide reliable communication services to the users in any case. Depending on the area to cover and the number and type of communication devices available, this is challenging because the coverage of the network is limited to the range of the communication technologies. Based on this, various challenges arise that are presented in Figure 1.1 as an abstract model of first responder networks that generally illustrates the different challenges.

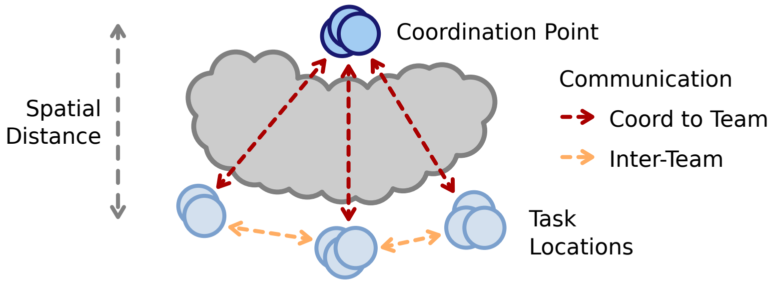


Figure 1.1: Abstract first responder scenario representation

This model allows the description of network requirements in any first responder scenario. In general, there is a central coordination team, which is not moving and has access to other networks such as the Internet. Besides this team, there are multiple further teams performing the specific tasks that are required to fulfill the mission. The connectivity between all members of each team is rather good while the communication between different teams and the coordinators cannot be guaranteed. How severe the degradation of the communication performance is, depends on the spatial distance that has to be covered and the envisioned networking technologies. In case of sparse scenarios such as *Search and Rescue* (SAR) missions, the distance between the participating nodes is too large to ensure good connectivity. The other extreme case are dense scenarios, where the distances between nodes are small. If there are too many nodes within communication range, they are blocking an efficient channel access or cause congestion in case of dense scenarios such as evacuations or larger fires.

Ideally, first responders require one network that is able to handle all possible situations [9] irrespectively of any typical mission characteristic. The common requirement is to ensure robust and reliable data delivery in a timely manner without requiring additional intervention by the users of the system, e. g. to retransmit lost messages [11]. Fulfilling these requirements becomes even more challenging, if heterogeneous systems are employed by first responders from different organizations or countries. All participants of a mission should ideally be reliably interconnected or at least be able to forward messages for others [129]. Therefore, the applied network protocols have to provide the required data delivery even under heterogeneous conditions challenging the connectivity.

1.2 Problem Statement

In order to provide good connectivity, the chosen network access technologies have a significant impact. Naturally, cellular mobile communication networks can provide connectivity for large areas, if the required infrastructure exists. Due to the fact that the disastrous event will affect the traditional utility infrastructure systems, it is very likely that communication infrastructures are affected as well, at least partially. However, the remaining infrastructure might be overloaded due to people trying to reach friends or relatives. This limits the usability of pure infrastructure-based communication for first responders in disaster scenarios [9, 129]. Besides this, the required infrastructure might not exist at all, if there are not enough users to run the network economically. This problem is not limited to remote regions of the world. Full coverage can be limited in mountainous or sparsely populated regions in developed countries as well due to terrain constraints.

Damaged infrastructure components will cause coverage holes which have to be filled using alternative technologies. Coverage holes also exist in cases of missing infrastructure deployment, for example in areas with low user density. Therefore, even if first responders are using a specifically setup infrastructure-based network, this is only able to mitigate the overload situation by other users but not the coverage problems. Besides that, international missions require a certain interoperability of communication devices, if first responders from multiple countries act together and thus need to communicate. Mobile Ad Hoc Networks (MANETs) are the main alternative to infrastructure-based communications. Multiple network access technologies are suitable for this type of network, each with unique characteristics. Depending on the communication technology employed by the first responders, various communication ranges might be possible and thus will directly affect the coverage range of the MANET. If the network is heterogeneous, different ranges are possible at the same time, if suitable devices exist to bridge the communication between the subnetworks. When compared to the model introduced in Figure 1.1, each team would represent one MANET and the coverage range affects the spatial distance between the teams.

Ideally, the first responder network is able to cover the complete disaster area and provide good connectivity to all participants. In sparse scenarios the connectivity is the main challenge due to coverage problems while in dense scenarios the connectivity is typically good but actual medium access and reliable data transfer is problematic due to the high number of nodes. Today, first responders usually use multiple separate channels to mitigate congestion problems [11]. Therefore, sparse scenarios are more challenging, because the coverage range of a single MANET is usually only sufficient to interconnect all team members while the distances between different teams are usually too large.

Several approaches are discussed to enhance the connectivity in case it is poor or missing. The first option is to deploy additional intermediate nodes that enhance the coverage of a MANET and ideally bridge the communication between multiple subnetworks. While this is an interesting approach theoretically, it is difficult to be realized in first responder scenarios. Within the mission or incident ares there are only limited resources available and any equipment has to be secured from theft or further damage. Therefore, several first responders would have to protect the communication equipment and are thus not available for their original task, which contradicts the goal to utilize the manpower as efficiently as possible.

Other approaches discuss alternative networking technologies in order to increase the communication range of the nodes or the employment of multiple networking technologies. The latter approaches include hybrid ad hoc and infrastructure-based networks. However, irrespective of any network access technology or further intermediate nodes employed to enhance the connectivity, intermittent connectivity cannot be excluded completely for two reasons: first, coverage holes cannot be eliminated in mobile scenarios, if the affected area is sufficiently large and the number of first responders is limited. Second, if the mission has to be accomplished in areas with sufficiently complex terrain structures, the terrain itself will act as an obstacle blocking communications. Therefore, a first responder network should be able to handle intermittent connectivity.

Disruption or Delay Tolerant Networks (DTNs) were designed to operate under extreme conditions. DTN principles can be applied to networks featuring large delays that would lead to timeouts in any other protocols and thus block the communication. Alternatively, DTNs can be employed to networks is case of irregular communication opportunities or *contacts* between nodes [45, 46] resulting in frequent disruptions of communications and long waiting times between subsequent contacts. Due to the ability to *store* messages until the further communication opportunities arise and physically transport (or *carry*) messages meanwhile, they are able to handle intermittent connectivity without further interactions from the users. Thus, DTNs fulfill two of the requirements for first responder networks. Besides that, the long term buffering capabilities of DTNs are also able to mitigate the congestion problems in dense scenarios.

However, the introduced delay will be larger than in traditional MANETs and is mainly depending on the underlying node mobility. This delay can be quite small, if the connectivity is good or frequent contacts between nodes are guaranteed. In other cases, this delay will be large. If no suitable contacts are available in the scenario, the delivery can take minutes or even hours, which is too long for mission-critical information in first responder networks. Therefore, the delay introduced by the DTN-principles has to be minimized under the given resource and movement constraints [64]. In this case, the disruption mitigation capabilities of DTNs are the required feature in an otherwise delay-sensitive environment.

Routing protocols determine possible paths through a network towards a destination and thus their decisions have a major impact of the achievable delay. In case of DTNs, several routing protocols have been described and various optimization goals have been exploited for both pure DTN and hybrid DTN-MANET approaches. However, disaster scenarios and their characteristics have not been the core focus of most studies resulting in limited applicability of the current protocols as described in the literature. Moreover, the tools used to analyze and evaluate the protocol performance often lack the required level of detail to capture realistic disaster scenarios and build better suited protocols. This is especially crucial for approaches with hybrid operation modes across heterogeneous networks.

1.3 Objectives and Contributions

The main objective of this work is to provide a toolset to enable a thorough analysis of communication protocols in hybrid DTN-MANET scenarios with support of potentially heterogeneous devices. Based on this toolset, it is later possible to develop novel disruption-tolerant routing approaches that are capable to deliver messages reliably under intermittent connectivity with minimum delay. Otherwise, the transferred information might be outdated by the time it can be delivered.

To achieve robust delivery, DTN principles are employed because they allow an efficient mitigation of intermittent connectivity among mobile nodes. The delay introduced by the *store-carry-and-forward* scheme has to be minimized under the given mobility and equipment constraints of the disaster scenarios. Existing DTN routing protocols are either developed based on generic and thus unrealistic scenarios or are tuned to very specific aspects of a single but usually non-disaster scenario. Therefore, the performance and applicability of these protocols to disaster scenarios has to be analyzed and verified. Such an analysis will provide the base for enhancements and the development of new routing approaches that are able to handle the scenario-specific challenges discussed above and are ideally designed with a focus on the wide variety of potential scenarios.

The contribution of this work is therefore related to the following four aspects:

Scenario Modeling – Disaster scenarios show a wide variety of actual missions and each mission features various specific characteristics. This leads to various communication problems depending of the scenario at hand. However, some communication-relevant mission characteristics are common in all mission types because they are related to emergency preparedness training of the first responders. Ideally, any communication protocol for such networks should be aware of these characteristics and exploit them where possible to achieve a better performance.

To enable this, the characteristics of the scenarios have to be modeled realistically. In disaster scenarios, the movement of the participants representing the communicating nodes and the traffic introduced to the network by the nodes as well as the traffic flows through the network are such characteristics. Commonly used models for traffic and mobility based on randomness are not suitable for such an analysis.

The first contribution of this thesis is therefore the development of realistic models describing first responder movements and first responder traffic. These models are designed to abstract the relevant characteristics and enable users to build specific scenarios if properly configured.

Scenario Analysis Toolbox – Based on the developed models, realistic first responder scenarios can be analyzed with respect to traditional metrics such as the delivery ratio or the achievable delay performance. This is traditionally done via simulations of the network components and protocols in question after configuring an appropriate protocol stack depending on the level of detail required. To build realistic scenarios more details are favorable.

In case of DTNs, the main focus of simulations is on the movement of the nodes and the resulting contact duration based on a given network access technology. Typically, the communication range and data rates that define the duration of the contact and a message transfer are simplified in tools such as the Opportunistic Network Environment (ONE) [76]. This can lead to too optimistic simulation results. Therefore, several enhancements to the popular Objective Modular Network Testbed in C++ (OMNeT++) simulator [159] were developed to enable DTN simulations in-cooperating detailed lower layer information and realistic 3D propagation. The simulations allow a more detailed analysis of propagation challenges in disaster scenarios as well as the benefit of hybrid DTN-MANET approaches in such scenarios.

Besides the simulations, another major contribution of this work is a framework that allows to employ traditional shortest path algorithms to analyze optimal forwarding paths in DTNs. This is challenging, because DTNs rarely show end-to-end connectivity and thus a graph representation of the connectivity at one point in time is incomplete due to constant changes of available edges over time. The store-carry-and-forward scheme enables DTN nodes to deliver messages even under such conditions as the messages are stored until the next nodes comes within communication range.

Time-varying graphs are used to describe such networks but traditional algorithms cannot be employed to this class of graphs. Therefore, the presented framework derives a suitable graph based on the corresponding movement traces and a list of messages to be delivered in order to obtain offline oracle solutions for any given scenario. This tool enables the analysis of a lower delay bound as well as optimal forwarding paths across a number of subsequent contacts for the given messages. Besides that, the framework enables a detailed analysis of different environmental factors such as data rates or communication ranges. DTNs or any other network with frequent disruptions and thus no constant end-to-end path between senders and receivers can be abstracted to a time-varying graph, where edges only exist at certain points in time. Therefore, the developed framework is not limited to first responder networks. Besides that, it allows to identify the potential for further enhancements to routing protocols in order to limit the experienced delay.

Finally, an outdoor capable Raspberry Pi-based hardware testbed is presented which allows communication-related measurements under realistic environments and the real-world evaluation of both pure DTN and hybrid DTN-MANET protocols.

Scenario Analysis – Using the tools and models developed within this project, a thorough analysis of existing routing protocols for both DTNs and MANETs was performed. These studies include a review of existing routing approaches, their classification and an analysis of suitable/interesting protocol mechanisms a theoretical comparison as well as various simulations and analyses using the developed tools to systematically analyze the impact of traditionally discussed approaches to enhance the delay.

The focus is on the one hand to show the feasibility and novel possibilities provided by the toolbox and on the other hand to identify protocol mechanisms that could help to mitigate the experienced delay based on available knowledge in the scenario.

Routing Approach – Finally, the results from previous studies are used to conceptually develop a novel context-based routing approach for hybrid and heterogeneous DTN-MANET environments. This approach will exploit context information that is available within the scenario as part of the situational awareness of the first responders regarding their current mission. Besides that, the hybrid approach will provide additional information on the underlying network topology and thus multi-contacts or those that are reachable via multiple hops in the underlying network only. Finally, a concept of adaptive segmentation is exploited at the DTN layer in order to adapt the message sizes to given contact durations. The latter concept allows the forwarding of different parts of a bigger message along different paths and thus provides efficient partial delivery of information at the receiver.

Dense scenarios are not the focus of this work, as existing strategies to use multiple channels in parallel are already good practice in first responder communications. However, all presented concepts should be applicable to dense first responder networks as well. Besides that, the tools presented are not limited to first responder scenarios.

1.4 Structure

Chapter 2 first reviews several example first responder scenarios and derives generic requirements for the communication of the first responders. Afterwards, insights from a measurement campaign on outdoor constraints are presented to highlight the need for hybrid approaches. Finally, a corresponding system architecture is presented as the base for the later analysis.

Based on the derived requirements, models for the movement and traffic representation are developed and evaluated in Chapter 3. These models are already part of the toolbox which is detailed in Chapter 4. The chapter gives an overview of the toolbox and their interactions as well as detailed descriptions of the additional tools.

Chapter 5 starts with a review of existing protocols that are relevant for hybrid DTN-MANET approaches. Later, these approaches are classified and compared theoretically. The remainder of the chapter focuses on the evaluation of a selection of protocols based on the comparison and often discussed options to enhance the connectivity. The evaluations are performed using the developed tools.

Based on the results of the previous analysis, the design considerations for hybrid protocols are presented in Chapter 6. This also includes the conceptual design of a novel context-based hybrid routing scheme that is designed specifically for first responder networks.

Finally, the work is summarized in Chapter 7. Besides that, future research directions and further extension options to the toolbox are presented in this chapter.

CHAPTER 2

First Responder Mission Background

This chapter will introduce more details on first responder missions and communication patterns. Based on the mission descriptions, the abstract model presented in Figure 1.1 will be verified and realistic assumptions and constraints for later modeling and analyses are derived. In addition to these theoretical considerations, measurements regarding the impact of environmental conditions complement further insights on communication characteristics under realistic circumstances.

2.1 Example Real World Scenarios and Generic Mission Description

In order to identify movement and traffic characteristics of first responders two scenarios were discussed with local firefighters. In addition to that, one real event was analyzed with respect to node positions and movement. To verify the found conclusions, additional descriptions of scenarios and requirements were included. In the following, it is assumed that each first responder as well as each vehicle represents a communication node and thus the terms are used synonymously. While this might not be true in every current scenario, it is one requirement for future systems [152].

2.1.1 Burning Building

The first scenario describes the efforts to fight a fire which destroyed the historic castle *Schloss Ehrenstein* (Ohrdruf, Germany) in November 2013. This mission involved several fire fighter units from the surrounding villages and several other rescue organizations such as the German Red Cross, the police, and the German Technisches Hilfswerk (THW). In total, 260 first responders along with 60 vehicles took part in the mission that lasted 35 hours. However, the number of nodes at the incident scene for one point in time is smaller as not all nodes were present for the whole duration of the mission, but are rather employed in shifts replacing their colleagues and resting in-between. The total area of the castle site and its surroundings is about $500\,\text{m} \times 400\,\text{m}$ and all nodes mentioned above are positioned within this area.

Figure 2.1 shows the positions of 224 first responders including their vehicles that were reconstructed according to different firefighter mission reports and press photos available online. It is clearly visible that different first responders form or are allocated to several supporting areas (colored rectangular areas). The organizational structure behind these areas corresponds to the command hierarchy of the fire fighters according to fire fighter service regulations in Germany [11]. Besides the fire fighters, positions of Emergency Medical Services (EMS) members and police officers are shown. They form their own organizational structure but cooperate with the other units by forming a unified incident command.

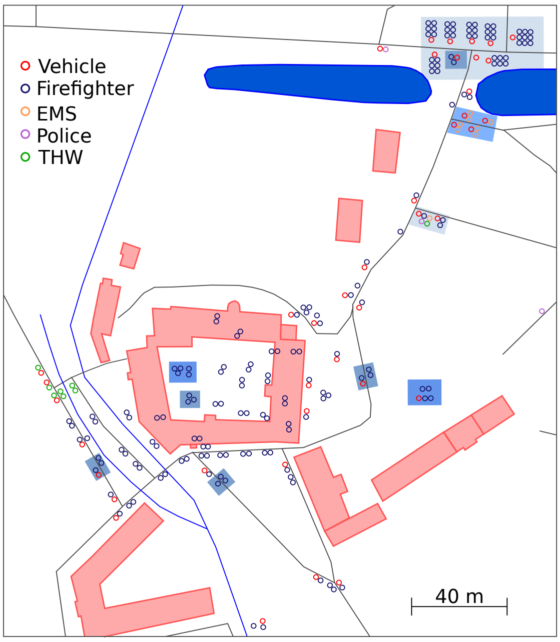


Figure 2.1: Reconstructed locations of first responders at Schloss Ehrenstein

In such a scenario, the fire fighters move according to the current mission needs and given training routines that are based on safety rules and regulations. For example, fire fighters should work in pairs of two and backup teams have to be ready to assist them if needed. Besides that, the timing of the movement is also related to the mission requirements. If the fire fighters wear a breathing apparatus, the available amount of air limits the duration of any activity and thus requires fire fighters to be replaced before they run out of air.

2.1.2 Search for Missing Persons

The second scenario represents a potential SAR mission in a hilly, forested area. It was derived in cooperation with a team using search and rescue dogs to show many possible issues that might occur during a typical SAR mission in such areas. Compared to the first scenario, the covered area is much larger (about 6000 m by 5000 m), while the number of nodes is slightly decreased to about 100 dog handlers, supporting personal, paramedics, and police officers. Each group brings their corresponding vehicles that are positioned at the common staging area. The dogs are considered as nodes as well, since they should be tracked using Global Positioning System (GPS) or similar positioning systems and report the location to the dog handler in charge of the dog. The goal is to verify and document that the whole area was covered.

In order to handle the complete area, it is separated in several smaller search sub-areas by the mission coordinator. He then assigns one team consisting of up to 6 dogs, their dog handlers and a group leader to each sub-area. If there are less teams than units, the teams start at one end of the area and get assigned to new sub-areas subsequently until either the whole area is covered or the target person is found. To get an indication where to start the search, special man-trailing dogs are employed first to cover the main hiking paths. These dogs are capable to find one specific human based on his scent. If they do not find the target, other dogs searching for any human in the area are used in the sub-areas.

Figure 2.2 shows the distribution of the nodes in the area and the defined sub-areas. The sub-areas correspond to a subset of a forest area. In a real mission the complete forest would have to be covered, extending the search areas further to the right. The terrain is rough and hilly which will lead to further communication problems.

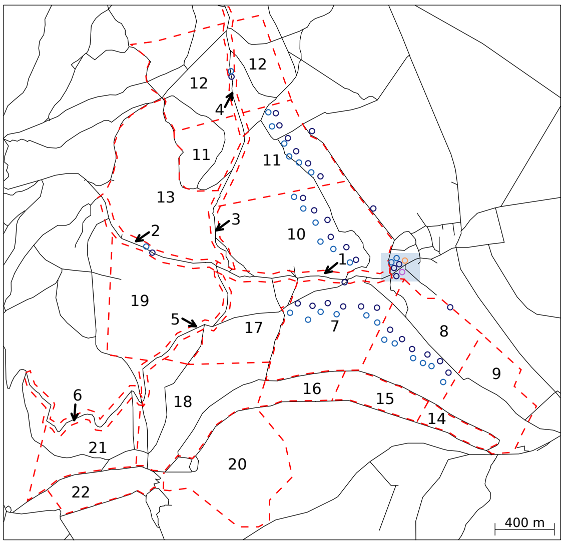


Figure 2.2: Example positions of nodes during SAR mission. Red dashed lines indicate example sub-areas to be searched.

Again, there is a tight coupling between the current mission needs and the movement of the nodes assigned to a task. This is especially true for the systematic search of the sub-areas. Timing is also based on the task and the speed that the nodes can achieve while searching each sub-area. The organizational structure is not as clear as in the last example but it is there as well. Due to the distances to cover, the nodes form separated groups with good connectivity within a group but no connectivity to the other groups. However, as teams return from their assigned task, they might get into contact with other groups or the central incident command eventually.

2.1.3 Flood

Finally, a flooding scenario is considered. This was developed as part of an emergency preparedness study for a rather small stream. However, the mechanisms applied to this scenario are also applicable to larger scale events. The scenario assumes a sudden rise of a stream of about 2 to 3 m above its normal level, due to heavy rain and partial blocking by floating material, such as branches and stones. The level of the rising water has been calculated using GrassGIS [109], a Geo Information System (GIS) with a specific function to calculate flood levels based on three dimensional map data. Based on this approximation of the flooded area, counter measures by the first responders were discussed. Among others these include the following tasks:

- evacuate people from flooded area
- fill sand bags
- build barriers with sand bags
- patrol area
- empty flooded cellars of water
- observe crucial positions such as bridges

The scale of the area is larger than before and the number of nodes is increased as well. Due to the large area, many volunteers, and if big rivers are concerned potentially the military, join the efforts to fight the flood. These additional first responders should also be integrated in the communication system because warnings or commands have to be distributed to them as well. Since the flood affects multiple communities, the coordination of the mission is extended and involves further hierarchical levels of coordination in addition to the local incident command. These coordinators are typically part of the regional government.

The available resources have to be spread throughout the area with specific focus on endangered sections. Therefore, they form islands of connectivity that might not be connected among each other. Whether communication between the groups is possible depends on the surviving communication infrastructure. Even if no infrastructure is functional anymore, the groups are moving and thus get into contact with other groups. Especially, groups that patrol different sections are interesting relays from a DTN perspective.

2.1.4 Discussion

Emergency response is a very diverse field with many different possible disastrous events that require specific reactions. However, as seen in Figure 1.1, these events can be described using an abstract scenario model. According to our abstract model, the events presented above can be classified into three categories based on the number of hierarchical levels employed and the area to cover.

- small scale event in small area
- small scale event in large rural area
- large scale event in large area

The first category reflects the first scenario but also other events such as accidents. In this category, the distance between the nodes/groups is small and the cloud in Figure 1.1 is rather small. Such events result in networks with many nodes communicating at the same time. Therefore, congestion and packet loss are the most critical issues.

The second category is a special case where a limited number of persons require aid in a large scale area. It therefore covers the second scenario but also different types of mountain rescue missions. Due to the size of the area, it is difficult to remain the connectivity between all parts of the network in this category because the distances abstracted with the cloud in Figure 1.1 becomes rather large.

Finally, the last category covers large scale events that usually require governmental coordination and possibly the aid from international rescue forces. These scenarios will most likely face the issues of the first two scenarios at the same time but in different sub-areas of the disaster site. In addition to that, the communication systems of different rescue organizations might not be compatible to each other and even if they are, different policies might apply and thus limit the cooperation further. For this project, the last two categories are more relevant, due to the challenges imposed by the scale of the area to cover. Therefore, the described SAR scenario will be used as an example for such networks.

In all scenarios, the organizational structure of the first responders is reflected in the required information flow towards a central incident command via intermediate group and section commanders [18]. This will also apply to larger missions. In that case, additional hierarchical command levels are added as needed. German fire fighters follow a rule that two to five organizational units require one commander [11]. This rule is applied to all command levels and gives a hint whether additional intermediate command nodes are required during a mission [79].

Besides that, there are different special areas that are common for all scenarios: central incident command, staging area, and other mission-specific areas, such as search sub-areas, patrol areas, and other areas where the actual task is fulfilled. If many people are affected, this will also include areas as described in [7] for patient treatment and transport. First responders assigned to one of these areas will remain in that area until their task is completed or they are replaced by others. All nodes return to the staging area regularly. This introduces a periodic behavior in the long term, where different characteristic movement patterns form a mission [89]. These patterns are specific to the current task of each node which depends on the current stage of the mission.

In general, any first responder mission can be described as a sequence of characteristic patterns that can be repeated partially. Figure 2.3 describes the general flow of events in any given mission as a finite state machine.

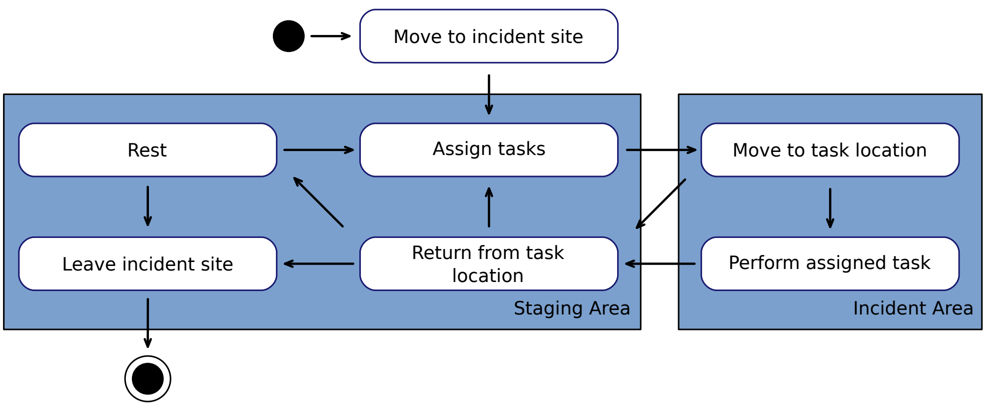


Figure 2.3: Generic mission modeling using common task patterns [82]

Each state is assigned to an area in which the node should move. Most states are directly linked to a specific node movement, except the assignment of the next task.

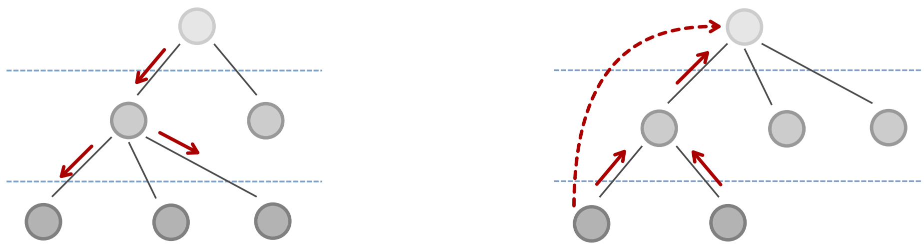
Modeling the way to and from the incident scene might not be required for any mission, but for scenarios of the last two categories this is important as additional first responders will arrive later on to replace exhausted first responders who in turn will leave the area. Whether there is a transition from one state to another, can be described using probabilities for each transition. But the probabilities have to be adaptive. For example, if a node fulfilled multiple tasks already, it is likely that this node will rest after returning from the current task.

2.2 First Responder Communication Requirements

Today, first responders mainly rely on direct voice communication in an asynchronous walkie-talkie style. This is either achieved using analogue radio or devices using the Terrestrial Trunked Radio (TETRA)[1] standard. While the first system is working in an ad hoc point-to-point style where nodes using the same channel can overhear the whole communication [18], the second one is usually infrastructure-based and supports security features such as authentication of devices and encrypted messages.

These systems are sufficient for voice communication, but as new sensors are developed further data transmissions are required, especially for images and video data [53, 61]. Other text-based data as well as recorded audio files should be considered [11, 53, 152] to enhance the *situational awareness* of the mission coordinators and all other participants. This also includes updates for users in the field with relevant information such as map data or potential hazard locations. Future systems should therefore handle all kinds of data.

The organizational structure of the first responders involved in a disaster event can be represented as a tree-like structure with the central mission coordination as root [11, 53] as shown in Figure 1.1. Different organizations will form separate branches in this tree, each organization following its own policies. The information flow follows this logical tree structure either in a top-down scheme as commands are issued at higher levels or in a bottom-up scheme as reports are provided by nodes at lower levels [79]. Figure 2.4 shows this concept.



(a) Top down **(b)** Bottom up

Figure 2.4: Information flow between different hierarchical levels [83]

From the organizational perspective, the nodes of the tree communicate directly using point-to-point style message exchange in a parent-child relationship. This also reflects the walkie-talkie capabilities of currently employed radios. At each level the information received is evaluated by the respective commander who then

1 ETSI standard EN 300 392-X http://www.etsi.org/technologies-clusters/technologies/tetra

decides what to forward to the next level. If the information has to be forwarded, it therefore represents a new message from an application perspective and might be forwarded using another physical device/interface, if a different technology is used on the next level. Inter-organizational communication ideally has to traverse the complete tree up to the level were the corresponding branches meet.

The tree is a logical concept that does not reflect the underlying network topology. Therefore, nodes assigned to different levels or even branches could be within communication range of each other and thus be used as potential relays due to the broadcast nature of the wireless medium. Besides that, additional nodes such as vehicles or sensors can act as relays. Such nodes might act as relay only or in case that sensors send their information either periodically or based on detected events to predefined destinations automatically [18]. This topology creates additional forwarding opportunities using neighboring nodes that are able to overhear messages in order to act as relays but might not be able to decode them for security reasons [83]. Therefore, all messages experience *multi-hop forwarding* in the underlying network in order to reach their destination even if it is a point-to-point communication from the DTN or application perspective.

Since the current communication is mainly voice-based, it is highly interactive and requires real-time characteristics as well as the *timely delivery* of the messages. If changing to a new channel, the connection should be acknowledged within 3 minutes [43], otherwise it is considered as broken. This is therefore a good estimate for a maximum round trip delay requirement for all communication types. Ideally, all messages should be transferred successfully faster, but this time limit represents a worst case successful delivery.

While all messages should be *delivered reliably and robust*, some messages will have higher *priorities*, depending on the importance of a message for the overall mission success. Whether a message is important, could be defined based on its novelty with respect to the situational awareness of the incident coordinators. First responders will report their findings constantly when fulfilling their actual task in the field. Such messages contain rather new information and should be transferred with highest priority, while messages to assign tasks or task locations to groups are important but do not provide any additional information to the coordinators' situational awareness. However, warnings should always be processed with highest priority.

Besides that, it is important to allow *partial delivery* of portions of data since these would already improve the situational awareness of the coordinators. This is important in cases where messages have to be fragmented into multiple parts for the transmission, the contacts are too short to deliver complete messages, or some fragments get corrupted due to error-prone links. How to fragment the messages in order to retrieve useful information fragments is however out of the scope of this work. In case of errors or disruptions, the system should provide a reliable data delivery service for the applications, without requiring additional manual interaction with the user. This is crucial in order to limit the communication overhead of the users and allow them to focus on their actual task.

Finally, one important factor is the current *ability to overhear* the communication from neighboring groups, even if they are not part of the same hierarchical level.

This allows a fast information dissemination among first responders with the same task, without the additional delay introduced by the hierarchical information flow. Any communication system should support this as well, but at the same time ensure that this is only possible for authenticated users. Besides that, this concept might also help to mitigate the impact of introduced additional delays in DTNs.

2.3 Evaluation of Outdoor Communication Constraints

2.3.1 Measurement Goals

The previous section discussed the requirements for first responder communication from a user perspective and provided some insights on possible services as well as first quality constraints. The technical constraints of any envisioned networking technology will also have a significant impact on the overall network performance, because these characteristics define among other aspects how much data can be transferred at a given distance. While this is well researched for indoor [170] or urban use cases, outdoor communication and the impact of terrains, buildings, and foliage are often neglected even for simulations. As described in Section 2.1, most first responder missions take place in outdoor environments and under extreme conditions. Therefore, the impact of these environmental conditions have to be considered during the evaluation of systems and protocols.

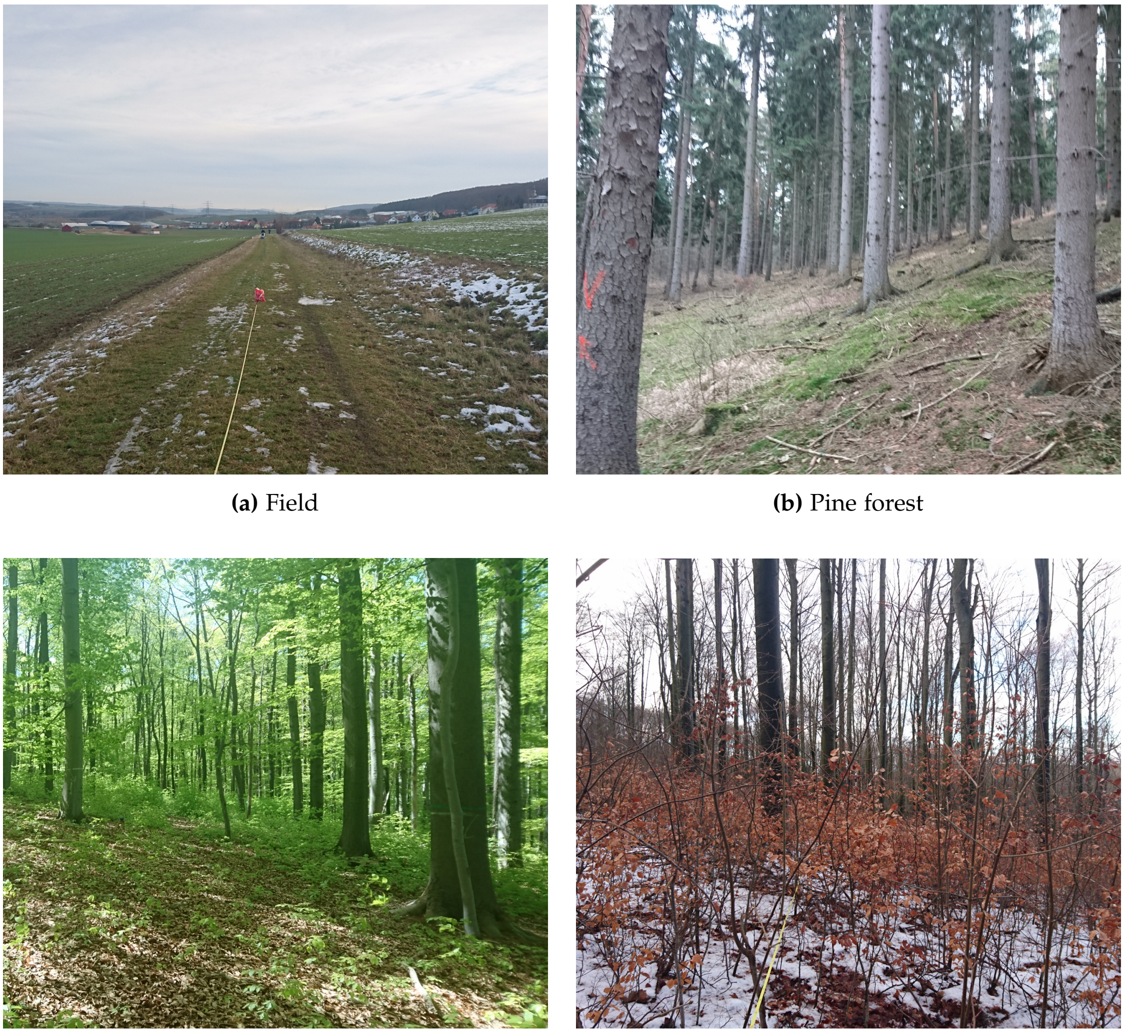
WiFi was already discussed as the choice network access technology for disaster scenarios (e. g. [128, 155, 172]). Three main characteristics are responsible for this discussion. First, WiFi interfaces are widely available in various devices, providing a large base for potential communication networks based on existing equipment. Second, WiFi provides an ad hoc mode [68], which enables devices to form spontaneous networks without requiring any infrastructure support. These MANETs are flexible, self-organized, and enabling the integration of further users without any need for specialized equipment. Third, WiFi is able to provide data rates that are sufficient for the envisioned applications, form voice over video streams to large map files at least for short ranges and deployments using the infrastructure mode [68, 170].

However, only few experiments have been reported using WiFi [4] or other wireless technologies [42, 98, 165] under realistic outdoor environmental conditions.

2.3.2 Selected Environmental Areas

In order to estimate the performance of WiFi links and derive assumptions for later simulations, a measurement campaign was performed using selected realistic outdoor environments (cf. Figure 2.5) that reflect possible areas in a SAR scenario. The measurements capture the impact of terrain, weather, and vegetation over the complete vegetation period and shall provide insights on possible communication ranges and achievable data rates based on these environmental conditions.

Originally, five representative areas were selected for the measurements, each with unique characteristics as described below. However, two of the areas were neglected later on, because the hilly area showed the expected result of the terrain blocking the signal effectively once the line of sight is lost and the beech forest showed similar conditions as the pine forest. For all other areas, the measurements were performed at least once a month in 2016, except for August due to vacations.



(a) Field

(b) Pine forest

(c) Beech forest

(d) Beech forest shrubs

Figure 2.5: Outdoor terrains for measurements [87]

Field a relatively flat area along a hiking path through fields with low crops or grass. This area represents an unobstructed free space propagation scenario. Figure 2.5(a) shows this area in January.

Hill an area with multiple hills covered by a mixture of pine and beech forest. The envisioned measurements were performed across a ditch and a hill and thus allow to estimate the impact of the terrain.

Pine Forest an area with a pure pine forest. This time, the measurements are performed along the hillside almost on the same elevation level. The undergrowth consists of few shrubs and multiple large pines are blocking the line of sight. Therefore, this area should provide insights on the impact of coniferous forest, were trees have leaves throughout the vegetation period. Figure 2.5(b) shows this area in March.

Beech Forest instead of pines this area is covered by a pure beech forest, again with large trees blocking the line of sight. It therefore resembles a similar terrain and forest structure as the previous area. However, the trees in this forest show changing leaves (none in winter, green in summer) throughout the year. Figure 2.5(c) shows this area in May with freshly developed leaves.

Beech Forest Shrubs the final area is a variation of the pure beech forest. In this case, a lot of young trees and shrubs grow underneath older trees. This results in a reduced line of sight. Figure 2.5(d) shows this area in February with dry old leaves and a remainder of snow.

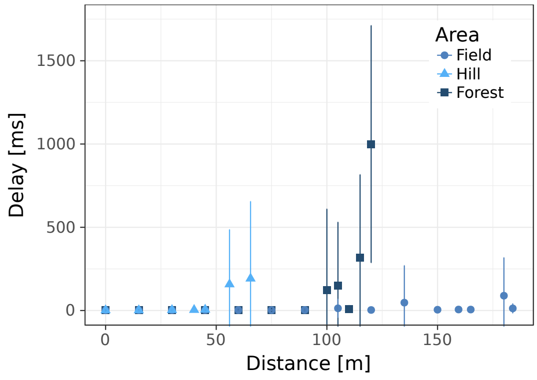
2.3.3 Performed Measurements and Derived Results

The goal of these measurements is to obtain information about the maximum outdoor communication ranges as well as the achievable throughput of WiFi-based ad hoc networks operating at 2.4 GHz with a specified range of about 100 m. Therefore, two nodes of the outdoor-capable testbed (cf. Section 4.6 and [81]) are used for the measurements with a direct point-to-point WiFi link between them. To obtain the maximum distance, the distance between the nodes is increased between each measurement step. At each step three measurements are performed: a connectivity measurement via *ping* and transport layer throughput measurements of both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) via *iperf*. Similar studies to characterize the link performance of WiFi devices were performed by the Unmanned Aerial Vehicle (UAV) community [60, 175] but with transceivers operating at 5 GHz.

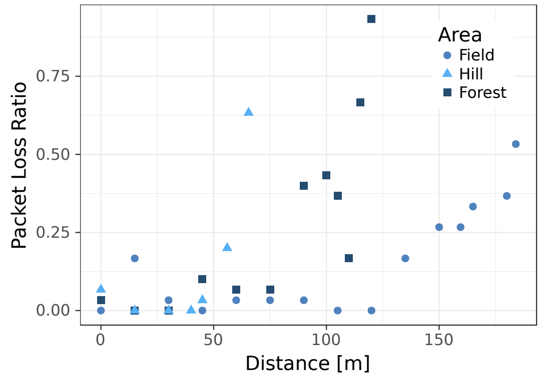
One node is placed at a fixed position acting as receiver while the other one acting as sender is constantly moved away on a straight line as far as possible under given terrain constraints. The movement takes place in-between each individual measurement. During a measurement the nodes are not moved. A measurement point is placed about 15 m away from the previous one at the beginning. Towards the end of the observed range, there are more frequent points in order to identify the maximum possible range. More details on the setup as well as a detailed list of the encountered environmental conditions at each measurement are available in Section A.1 and Section A.2.

First, the network performance of the selected areas was compared to identify the impact of the areas. Therefore, the results of all three measurement types from one individual measurement day (9 January 2016 in this case) were compared [81]. These measurements covered three areas (Field, Hill, and Beech Forest Shrubs) under almost stable external conditions which were rather good (cf. Section A.2). The results of the comparison are presented in Figure 2.6. Each figure contains the maximum range achievable with the given measurement type as well as the measured metric. The round trip delay (Round Trip Time (RTT)), loss ratio, and interrupts were obtained via *ping* while the throughput in Figure 2.6(d) was obtained via *iperf*.

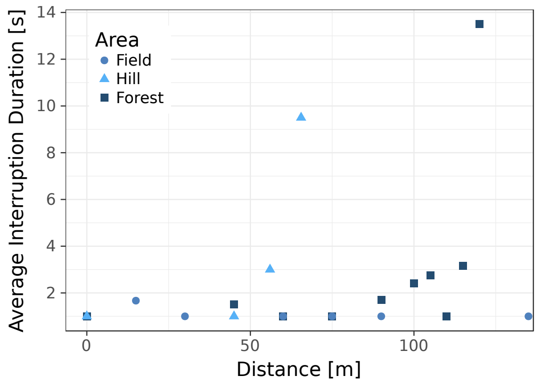
The first result was expected as a hill effectively blocked all communication attempts after 65 m. While this is not surprising it means that, in rough terrains with many hills and valleys communication might be blocked quite fast and the nominal specified range of 100 m in this case cannot be assumed as guaranteed. With regard to the abstract scenario model, this also means that even at relatively small distances the communication problems can be similar to those in sparse scenarios resulting in increased intermittent connectivity. Rather surprising was



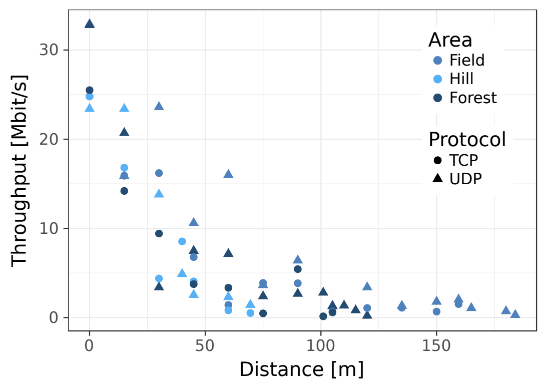
(a) Delay - RTT



(b) Packet loss ratio



(c) Interrupt duration



(d) Throughput

Figure 2.6: Initial results characterizing outdoor scenarios (cf. [81])

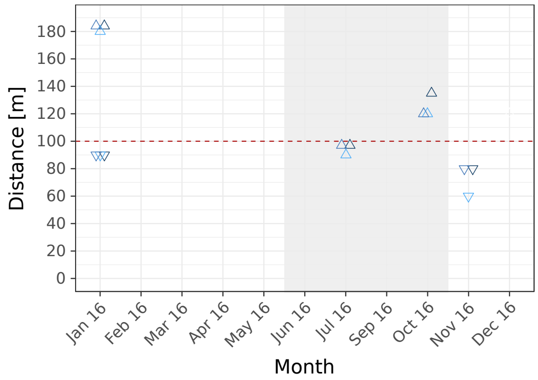
the fact that under free space conditions the maximum range is almost doubled to the nominal range. However, this range cannot be exploited as efficiently as shorter distances, because starting around 75 m the connection becomes increasingly intermittent with higher packet loss ratios and longer interrupt durations.

This also results in a reduced throughput with an increasing distance. As expected, UDP is able to handle the conditions better than TCP because of its connectionless service. Any communication system that requires long distances should therefore use UDP as choice transport layer protocol and ensure the required quality of service on the higher layers.

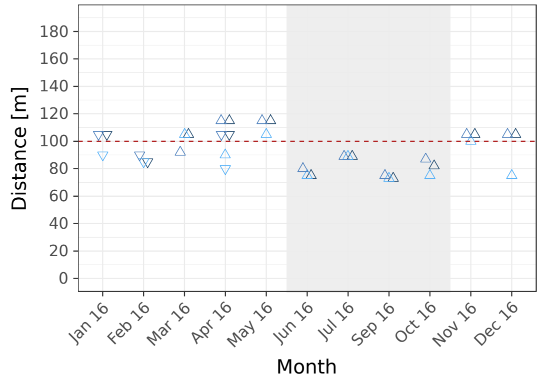
These initial results were confirmed in general during the year-round measurements [87]. The individual performance is however quite diverse depending on the following two factors:

1. the weather conditions
2. in case of summer-green trees, the state of the leaves

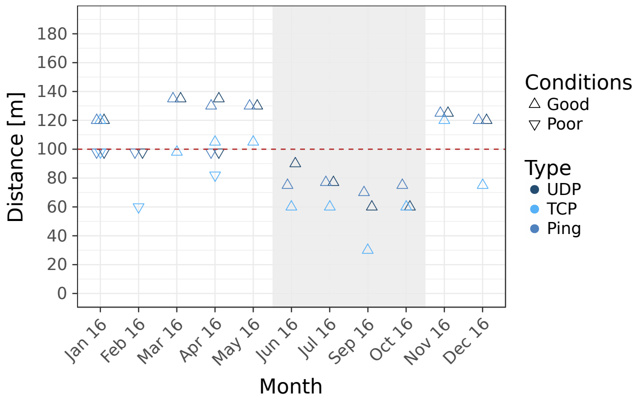
Figure 2.7 shows this for the maximum achievable distance for the three remaining environments that was defined as the point where no reception is possible anymore via *ping*. To capture possible multipath characteristics, the measurements were not stopped at the first point with 100 % loss. Instead, the distance was increased and decreased gradually with constantly sending *ping* requests. If no reception was possible in this case, the connection is assumed as broken and the last measurement point with valid results is taken as maximum range. The weather conditions were classified into *good* in case of rather dry and sunny conditions and *poor* in case of wet (e. g. rain, fog, or snow) and stormy conditions. Besides that, the gray area marks the time of the year when the leaves of beech trees are fully developed.



(a) Field



(b) Pine forest

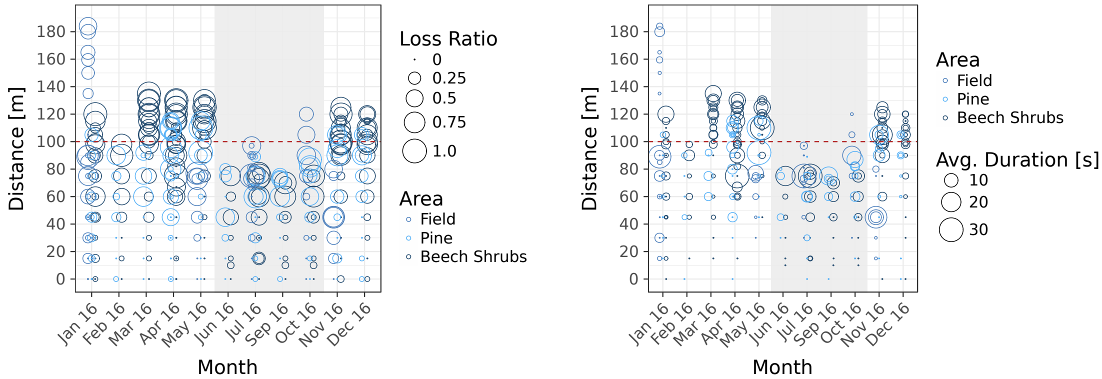


(c) Beech forest shrubs

Figure 2.7: Achievable maximum distance per application and environmental condition

In case of the free space environment, only the weather conditions show some influence on the performance of the link with a maximum range that is above the specified range in good conditions and below it, if it is wet. A similar behavior is observed for the pine forest. Here, the difference between good and poor conditions is not as significant as in the field environment and the maximum range is somewhat reduced. Even if pine trees do not change their leaves over the seasons, the effect of fully developed leaves in summer and autumn is evident and shows a similar impact as otherwise poor weather conditions. Finally, the beech forest shows a more distinct behavior in terms of leave status. While the leaves show no impact in early stages of their development until about May, fully developed leaves reduce the network performance significantly even below the level of poor weather conditions without leaves. Especially, the TCP throughput is reduced dramatically and the maximum range drops to about 45 to 60 m.

Another important insight from these measurements is the significant difference between the possibility to reach a node via Internet Control Message Protocol (ICMP) or *ping*, respectively, and the ability to actually transfer data via the same link. To better understand this behavior, the following figures show the variations of packet loss and corresponding interrupt duration from the beech forest throughout the year. In Figure 2.8(a) the size of the circles indicates the actual loss ratio and in Figure 2.8(b) it describes the average duration of interrupts. The two metrics are tightly coupled. Without packet loss there are no interrupts and the higher the loss ratio the longer is the interrupt duration.



(a) Packet loss ratio

(b) Average interrupt duration

Figure 2.8: Distribution of packet loss and corresponding interrupts for the beech forest shrubs area measurements over the complete year

Both results indicate the maximum distance shown before in Figure 2.7. In addition to this, it becomes obvious that interrupts occur at every distance with an increasing number of interrupts for larger distances. Such an outdoor environment features therefore highly intermittent links and reduced communication ranges. When considering the abstract model, these results show that even if the distances are small the network has to cope with frequent partitioning and reduced transmission capacities depending on the given terrain, foliage, and weather conditions. Any communication system for first responders that operate in similar environments has to be able to handle these characteristics and provide robust and reliable message delivery.

2.4 Resulting System Architecture

Based on the results from the outdoor measurements, it is obvious that one single short-range network technology will not be able to cover a complete disaster area. Even if other technologies are used, the terrain will remain a major obstacle [115] and nominal data rates are low at higher ranges (e. g. [69]), limiting the transmission capacity further. In addition to the experienced intermittent connectivity, the network conditions in single partitions can change quite fast in different parts of the network. Therefore, the resulting network has to provide mechanisms to handle both aspects. Ideally, these mechanisms are able to adapt themselves to given conditions.

To achieve this, a combined hybrid DTN-MANET architecture is proposed based on existing previous research [50, 136] on MANETs for disaster scenarios. The focus of the previous work was on concepts for adaptive routing on the network layer [50, 51] and concepts for efficient name resolution based on the adaptive routing approach [137, 138]. Both aspects are important to any MANET and complement the underlying networking aspects of this work. These developments resulted in an architecture for connected MANETs that supports multiple routing protocols on the network layer and *Border Nodes* coupling subnetworks with different routing protocols [139]. Suitable nodes are selected as Border Nodes in a self-organized way.

Besides that, the MANET architecture provides some network services that are vital for a working first responder network. First, efficient, flexible, and robust routing on the network layer is required to avoid unnecessary transfers. If a valid multi-hop path to a neighboring DTN node is provided via the network layer, this can be used as shortcut and might enhance the overall network performance. Second, DTN routing is based on names or Endpoint Identifiers (EIDs) [29, 142]. These names have to be mapped to IP addresses. The previously presented name resolution scheme [138] can provide this using a fully distributed approach required for MANETs. Finally, the existing name resolution service is able to provide location-aware service discovery [140].

Because this architecture assumes relatively stable connectivity between the different subnetworks where only individual nodes move between the subnetworks, it is suitable to describe zones of good connectivity. When applied to a larger area or in rough terrain under conditions similar to the results from Section 2.3, partitioning cannot be avoided completely and the communication between the subnetworks remains a challenge. This is true for the communication between teams at different task locations and the communication between the teams and the central coordination point. To mitigate this effect, the architecture was extended by DTN-enabled Border Nodes and DTN-gateways [80]. In this architecture all DTN-enabled nodes can act as message ferries and thus provide additional data transfer opportunities. Gateways take care of messages from non-DTN nodes and thus allow them to benefit from the *store-carry-and-forward* principle used by the DTN nodes. This is crucial to fulfill the requirement to support communication to affected people or integrate volunteers without special equipment or pre-installed software. Figure 2.9 shows a conceptual view of the proposed architecture reflecting the previous work [80] as well as the abstract scenario description.

Teams or groups of first responders will form MANETs at every incident/task location based on the locally available network access technology. Using *Border Nodes* (in green) enables the communication between neighboring MANETs or affected people/volunteers (red nodes), if these subnetworks run a supported routing protocol. In addition to that, the DTN communication is employed to cover the spatial distance between the coordination point and the other network parts. This is achieved via a partially mobile backbone concept, where any DTN-enabled mobile node in the scenario (e. g. vehicles, humans, dogs, or UAVs [144]) as well as other relay nodes at fixed positions are exploited as potential relay or ferry (orange nodes).

Due to the employed DTN principles, the backbone is able to bridge hybrid access networks [14]. This is an essential feature of the proposed concept, as it allows to integrate different MANETs but also remaining or reconstructed infrastructure-based networks given nodes with appropriate network interfaces. Since a mission can involve large areas, the support and integration of underlying infrastructure-based communications is important to limit the delays as such networks usually provide means for long-range communication and thus help to cover the spatial

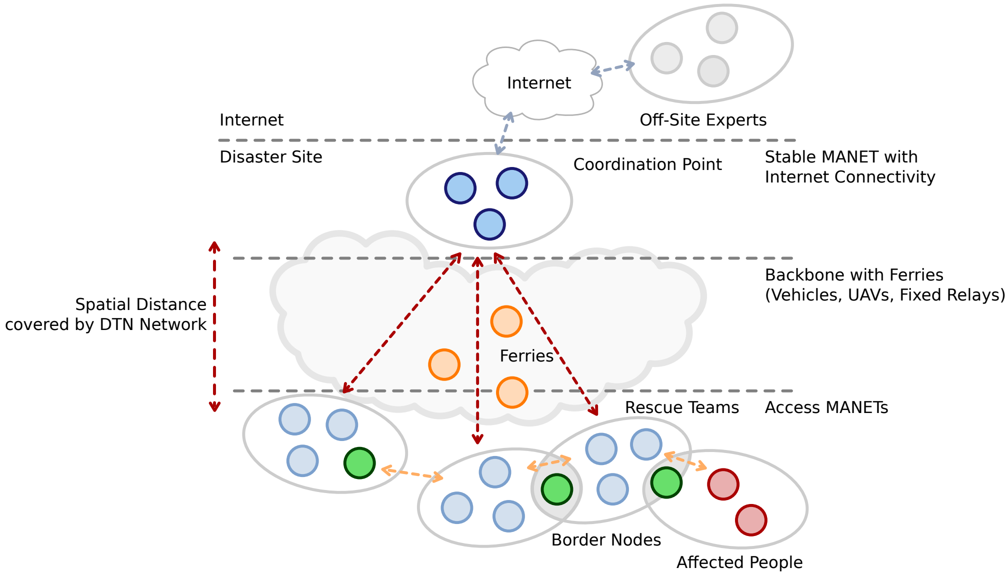


Figure 2.9: Proposed first responder network architecture

distance. Besides that, devices with multiple interfaces can either act as bridging border node or they can adaptively switch between different network access schemes [14] and thus exploit the best communication option available at a certain location.

A similar hybrid DTN-MANET testbed is introduced in [120], with WiFi interfaces and a specialized infrastructure-based long range WiFi connection as wireless backbone solution. This work is an extension of a previous work [134], where the basic structure of a multi-tier network architecture is introduced in order to manage the different hierarchical levels of rescue organizations. In these works, the backbone is assumed to be fixed and reliable in order to provide the necessary Quality of Service (QoS) required by the first responder communication. Besides that, their scenario is limited to communication of first responders and predefined shelter areas located within the disaster site. The envisioned long range wireless infrastructure nodes are mounted on or located at the shelter points and are assumed as fully functional. This is, however, unrealistic even if backup energy generators are available to provide the power supply for such an infrastructure. It is more likely that some of the shelters might also suffer from damage or might not be available depending on the area of the disaster.

Other hybrid DTN-MANET approaches usually focus on the combination of routing aspects (cf. Section 5.3.2) without detailing the actual underlying network architecture or employed network access technologies. This also complies to the classification of hybrid DTN-MANET approaches introduced in [127]. Most approaches assume homogeneous protocols in the underlying network layer and/or focus on a single very specialized scenario. The described specialization does however limit the applicability in other scenarios, due to limited adaptivity. This adaptivity is however crucial for first responder networks under fast changing external conditions.

The presented approach in this work does not rely on such restricting assumptions, but rather provides a flexible interface to interconnect whatever remaining infrastructure is there and otherwise to exploit available mobile devices in order to provide communications under extreme external conditions.

CHAPTER 3

First Responder Scenario Modeling

This chapter provides models characterizing both the movement and the traffic generated by first responders in different scenarios. These models will be used later for the analysis of various scenarios as well as for evaluation purposes. The underlying characteristics of the models are derived from the described real world scenarios as well as the communication requirements of first responders. Finally, the chapter shows the need for these models by comparing them to existing models based on randomness.

3.1 Common Modeling Requirements

The previous chapter introduced node movement and traffic aspects during different disaster scenarios. Both aspects showed specific properties that can highly affect the protocol performance [55, 64] and should therefore be considered during the design of first responder communication systems and protocols.

One common tool to evaluate the performance of novel systems and protocols are simulations based on appropriate, realistic scenarios capturing the envisioned target environment. In order to generate realistic first responder scenarios, the traffic and movement characteristics of first responders discussed in Chapter 2 have to be modeled in addition to assumed propagation characteristics. Finally, these models have to be integrated into the chosen simulation environments in order to perform the desired evaluations.

Each simulation environment usually comes with various options to configure or build different scenarios based on more or less specialized models for signal propagation, node movement, or network traffic. These existing models are usually configurable and can be tuned to some extent in order to support multiple use cases. This adaptivity to other use cases is one important requirement for any model used for simulative evaluations. Another requirement is to model the desired behavior as detailed as needed and as generic as possible. This is required to capture the interesting details or behavior while keeping the simulations simple and thus fast [93].

Given these requirements, the need for new, more realistic and thus detailed models is in question. For first responder scenarios, as described in the previous chapter, detailed realistic models are required if the characteristics described by the models shall be exploited to design novel protocols or have a significant impact on the protocol performance as it is the case in DTN communication. It is however challenging to model the scenarios described in Section 2.1 with existing movement and traffic models because these models are often based on random features only. Therefore, the remainder of this chapter describes models providing a better representation of disaster events that are still generic and configurable to cover multiple events.

3.2 Generic Pattern-Based Movement Model

As seen in Section 2.1, the movement of the nodes is not random but rather following several patterns depending on the role of the nodes and the current tactical requirements of the mission. Moreover, the patterns show a periodic repetition that allows to model the behavior of nodes throughout a whole mission according to the generic model presented in Figure 2.3. Movement models that use randomly selected destinations such as the Random Walk Model or the Random Way Point (RWP) Model [25] are only capable to model some specific patterns but not the whole mission. The same applies to more specific movement models that focus on single aspects of disaster mobility [7, 108, 157] but do not capture the diversity of node movements and different patterns in the movement of single nodes throughout their mission. This would require an option to change the movement characteristics during the simulation runtime depending on the current mission phase of the node. Ideally, that would result in a switching between different models.

The model presented in this section avoids to focus on single individual aspects of a chosen scenario by assigning a sequence of different patterns to the available nodes according to the mission structure. A similar approach [41] uses several patterns to describe the daily routines or activities of people. The available patterns are however limited to non-disaster scenarios and not applicable as is for first responder movements. Only a small part of the first responder patterns can be modeled using the described activities, while the crucial mission-specific patterns cannot be captured. Besides that, the described movements in [41] require a corresponding map defining all allowed paths, which is not feasible for cross-country patterns in rough terrain.

Depending on the simulation environment chosen for the evaluation, different models will be available as part of the distribution. All tools provide several relatively generic models based on randomness (e. g. the RWP model). In addition to that, the tools usually provide an option to import mobility information that was either recorded during experiments or generated via an external trace generation tool such as BonnMotion [6]. Such specific tools provide a more diverse set of movement models besides the random ones. In case of BonnMotion, the disaster area mobility model [7] is included with a complete example script to generate one example scenario. However, even these tools do not support scenarios featuring multiple regions with different movement characteristics at the same time.

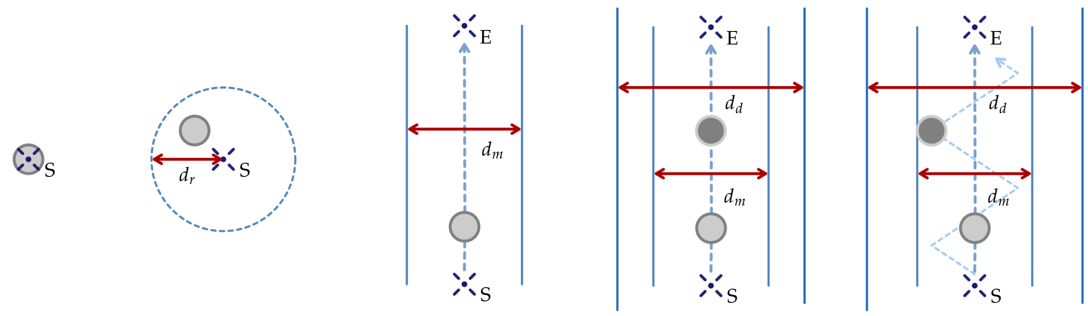
3.2.1 Generic Movement Patterns

While the movement in the discussed scenarios is very diverse, several patterns reoccur frequently [89] and can be assigned to a mission state (cf. Figure 2.3) depending on the current role of a node and the tactical requirements related to this role. The following generic patterns were identified based on the scenarios discussed in Section 2.1:

- Static movement
- Quasi-static movement
- Group/node moving along given path
- Area search using dog team
- Path search using man trailing dog

Static movement represents nodes that stay in one location for a larger period of time, such as parked vehicles or mission coordinators that remain at their post for some time. *Quasi-static movement* describes nodes that remain close to a given location, but move freely within a threshold range to that location. Compared to the size of the overall area, this movement is relatively static. Therefore, this pattern is suitable to model the movement within any of the special areas. The third pattern describes the *movement of nodes along a given path*, which can be derived using real world map data in Well Known Text (WKT) format. It models for example the movement from and to incident areas or any other movement along given paths such as a patrolling task. While these patterns are very generic, they allow to model various mission types, if configured properly.

The remaining patterns describe specific movements that are used within an incident area and thus are not as generic as the previous ones. In this case, these two patterns are required to cover the more realistic SAR scenario [82] as they model the interaction of search dogs and their handlers. Both patterns model the interaction of one dog and its handler. To model a complete search of a single sub area, the *area search pattern* has to be applied multiple times to build the required formation of a group consisting of several individually moving search teams. Further patterns for more specific tasks are possible, but were not designed within this project, because the SAR scenario is chosen as the exploited example of sparse first responder networks.



(a) Static **(b)** Quasi-static **(c)** Line movement **(d)** Mantrail search **(e)** Area search

Figure 3.1: Conceptual movement patterns

Figure 3.1 depicts the characteristic movement of each pattern for one node or a pair of nodes consisting of a dog and its handler. As the last three patterns are related to movements along given existing paths or imaginary paths between starting (S) and end (E) points, they are modeled along that path with certain threshold values d_m (for humans) and d_d (for dogs, with larger movement ranges) resulting in a range in which nodes can move. The quasi-static movement (Figure 3.1(b)) follows a different approach. In this pattern, the threshold d_r defines a circular range in which the node can move to randomly selected places similar to the default RWP model. Finally, the static pattern (Figure 3.1(a)) is modeled using a fixed target position and a given waiting duration at this position.

The deviations allowed by employing the thresholds mimick *straying* and allow small scale random movements of individual nodes. For the humans, this represents movements to avoid small obstacles or deviations to use the full path width. For the dogs, the threshold is bigger and pattern-dependent, modeling a straying behavior, e. g. if they catch an interesting scent and leave their original path for a longer distance.

In order to cover a complete mission, each pattern has to support two features besides the straying: if nodes board a vehicle, they do not move themselves but are moved by the vehicle. In this case, the mobility characteristics of the vehicle has to overrule the nodes individual one. Such a change in the nodes mobility pattern is also required, if obstacles block the planned path of a node. To model this, a simple approach to detect the nearest edge of the obstacle and then following the shape of it is used [89, 130].

Besides these points, the last three patterns support group movements. If multiple nodes move along a given path, ideally the first node defines the general movement and the others follow the leading node. There are several possible and simple options to implement this behavior: the following nodes use a fixed offset time, but follow the exact same path, the nodes follow with fixed spatial offsets, or they follow according to steering mechanism [130]. In this work, the first and the last option are applied.

Since the first three patterns are generic, they are able to model any movement if combined accordingly. Therefore, the pattern concept is applicable to other scenarios as well and is not limited to first responder scenarios.

3.2.2 Movement Framework

In order to build scenarios, the described patterns were implemented in Java and integrated into a framework to allow the modeling of complete rescue missions. Figure 3.2 shows the architecture of the framework that includes several additional components besides the movement patterns.

The individual patterns form a toolbox, from which patterns are selected according to the desired scenario. For each pattern the relevant parameters have to be specified as well. Mission-specific map data is used to build more realistic scenarios and helps to select appropriate movement distances for each mission stage. This map data can be extracted for example from OpenStreetMap[1] or by using OpenJump[2] to modify or create maps in the required format.

1 http://www.openstreetmap.org/export

2 an open source GIS tool http://www.openjump.org/

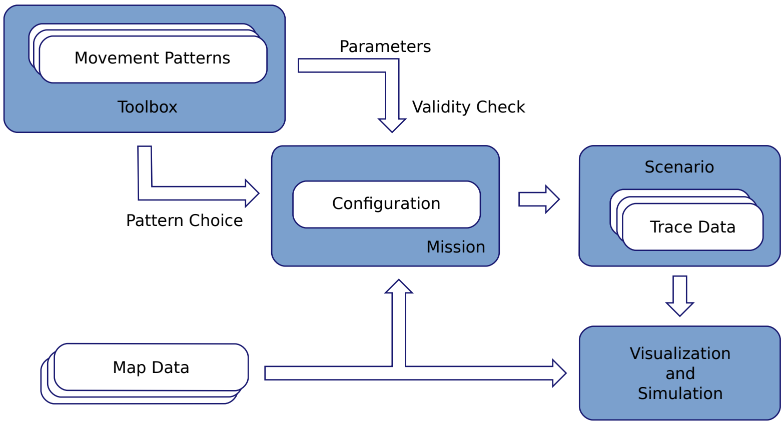


Figure 3.2: Structure of the modeling framework [82]

The configuration file is the central component of this framework. All state transitions performed by individual nodes according to the mission model (cf. Figure 2.3) have to be specified using this file. To achieve this, all nodes are assigned to groups and movement patterns are defined for each corresponding mission phase. This also includes start and end points based on the map data for each pattern as well as further parameters of each pattern. Based on the configuration file and provided parameters, the framework first performs a validity check and then generates trace files for each node.

The format of the traces is configurable, allowing the usage of the generated traces within different simulation environments. Currently, three simulation tools are supported: ONE, OMNeT++, and ns-3. The traces can be imported into the corresponding environment and represent the basic node movement of a simulation scenario. Optionally, the map data used during the trace generation can be imported as well to visualize the scenario (e. g. in ONE via the osm2wkt tool [101]). Such a modeling concept provides a flexible approach to combine existing models in order to build complex, realistic scenarios. However, it requires expert knowledge in order to properly configure realistic rescue missions.

To generate traces, all individual patterns are implemented based on the functional description provided above. Therefore, in the following only selected crucial steps are explained in more detail. All patterns involving a path use the provided map data in WKT-format as a base for the path, if such information is available. In cases where no map data is available, or when nodes do not follow given paths, a straight line between the configured start and end points is assumed as base using S and E as waypoints. Depending on the distance between any two waypoints and the required time resolution (e.g for ONE-type traces), additional waypoints are calculated to add intermediate positions.

The dog movement in the search pattern is approximated by a sine wave ($y = sin(x)$) using the direct line between S and E of the pattern as x-axis. Amplitude (A) and wavelength (λ) are parameters of the pattern. The amplitude is defined by the distance that two neighboring search teams can cover and is therefore configurable. It corresponds to d_d in Figure 3.1. The wavelength is not configurable, because this parameter is set according to the average speeds of the dog and the dog handler to allow the dog to cover the path defined by the graph of the sine wave fast enough to stay in front of the dog handler. The distance along the arc of the sine wave is calculated using Equation (3.1) where a and b define the step-size between two subsequent waypoints. How many of these waypoints are required between the start point S and the end point E of the pattern (cf. Figure 3.1) depends on the time granularity required by the simulation.

$$dist_{wave} = A \cdot \int_{a}^{b} \sqrt{1 + \cos^2(x)} \quad dx \tag{3.1}$$

Any required random numbers are generated using several normal distributions. In case of potential deviations according to the thresholds, the configured threshold value of the pattern is used as standard deviation of the distribution. For each calculated waypoint, a deviation can be calculated, if configured, by drawing further random numbers from the generator. A negative random number represents a deviation to the left according to the current movement direction and a positive number a deviation to the right.

The speed of the nodes are also sampled from normal distributions, using the mean and a standard deviation as configurable parameters. If no parameters are specified, each node type (human, dog, and vehicle) is provided with default values. However, these values might be suboptimal in some cases, especially if the average speeds vary due to the current mission requirements. To allow such changes, the initial configuration can be changed for each mission stage and the corresponding pattern.

3.2.3 Validation and Comparison

To check the pattern implementation each pattern was tested individually. Figure 3.3 shows an example trace resulting from the search pattern with six teams of dogs and handlers.

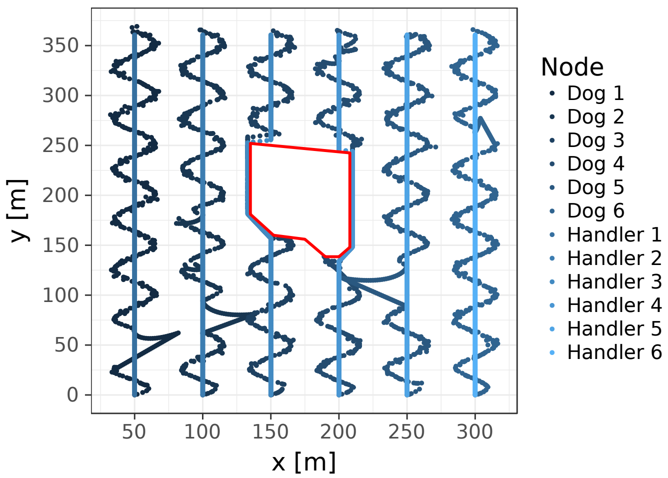


Figure 3.3: Generated example trace for search pattern (cf. [89]) with dog movement modeled as sine wave with an amplitude of ±25 m and spikes representing deviations

These traces show a realistic search scenario with straying dogs and an obstacle (in red) blocking the planned path of two teams in one example area. The effect of the simple obstacle avoidance algorithm for the teams three and four is obvious. Besides that, the strong deviation of the straying dogs shows that it is valid to model the dogs as nodes as well. Due to the straying, the dog does not cover the area as expected. The dog handler is able to intervene, if the dogs are equipped with sensors and communication devices to inform the dog handler about the position of his dog.

In order to verify the assumptions regarding average speeds and possible deviations, a GPS trace was recorded in one typical search area. Figure 3.4 shows the trace points with color-coded speed values according to the captured speed values of the GPS track.

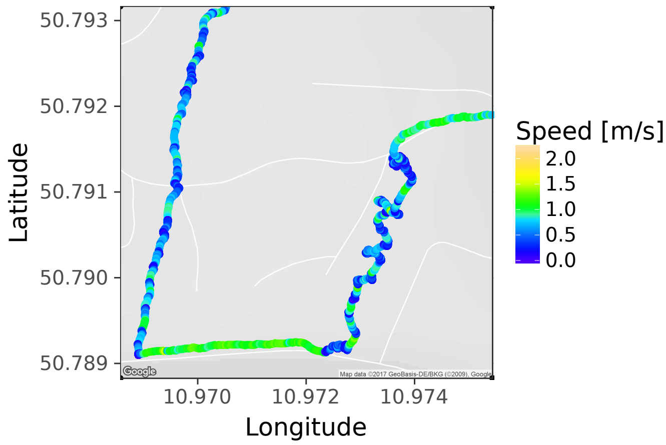


Figure 3.4: Captured GPS track of search mission

The figure shows a selected section of the track with multiple different movement phases corresponding to the search pattern in open terrain and the movement along given paths. The movement corresponds to example movements of first responders as described in the example scenario presented in Figure 2.2 and was captured in the terrain corresponding to sub-area number 7. The trace starts from the upper left and the node moves uphill towards the lower left until it reaches the end of the search area on a hiking path. Such a movement represents the dog handler movements in a search pattern. Afterwards, the node uses a path to reach the next search area on the right and is moving downhill in a zig-zag style to mimic the search and then leaves the section on a path towards the right.

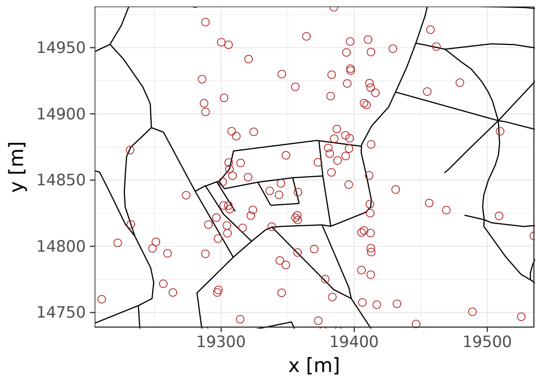
In the uphill section, the goal was to follow a straight line trough the terrain, if possible. However, the straight line could not be achieved due to trees and other small obstacles as well as terrain features. These features resulted in small scale deviations as modeled in the patterns above. For the downhill section, the goal was to cover a given area using the zig-zag approach and find boundary marks. The marker stones are set roughly opposite of each other in different distances and can be overgrown. Therefore, the resulting trace shows some similarity with the dog movement in the search pattern, even if the node moves slower than a trained dog. The zig-zag movement is clearly visible and a comparison with the generated dog movement proves that the sine wave is a valid choice to model this movement type.

During the search phases the node is relatively slow with an average speed of 0.5 m/s compared to the average human hiking speed in plain terrain of 1.1 m/s [162]. This could be explained by the uphill movement direction, which usually requires more time [162]. But while this terrain feature might have some impact, the search task overrules it. Otherwise the downhill movement should have been faster than the uphill movement. When using the paths, the movement is significantly faster with an average of 1.1 m/s matching the assumed average value for hikers. This clearly shows the need to configure a pattern and mission phase dependent average speed to reflect different mobility states. Besides that, the patterns could be enhanced with an average speed depending on the terrain as well. This is especially interesting, if the timing information regarding node positions (e. g. when a node reaches a certain position) is crucial for the simulation.

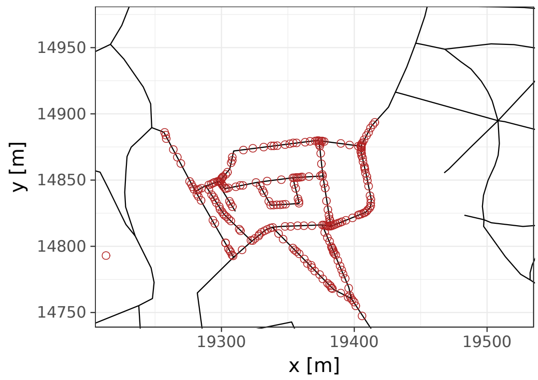
The next verification step includes a comparison of the generated trace files with synthetically generated movements using existing mobility models provided by the simulation environment ONE. First, the ability to position and group nodes into several teams is verified using the scenario described in Section 2.1.1. Figure 3.5 shows two plots of the positions obtained via corresponding simulations in ONE.On the left, Figure 3.5(a) show randomly positioned nodes without any constraints. The right figure shows nodes positioned using the *Shortest Path Map-based Movement* [76] where nodes chose a random position but are restricted to available paths. Finally, Figure 3.5(c) shows the positions obtained by the pattern model using estimated positions from press photographs as input.

It is obvious that the trace-based simulation shows more realistic positions irrespective of any given paths. Using the random model, all nodes are placed next to each other and even if they select new destinations this parallelism remains the same, due to the restriction on available paths [79]. While this could be avoided using the RWP model, grouping of selected nodes based on their mission goals is not possible with this model as well. But the grouping of nodes based on tactical requirements is essential in order to capture the organizational and mission-related dependencies of the node movement.

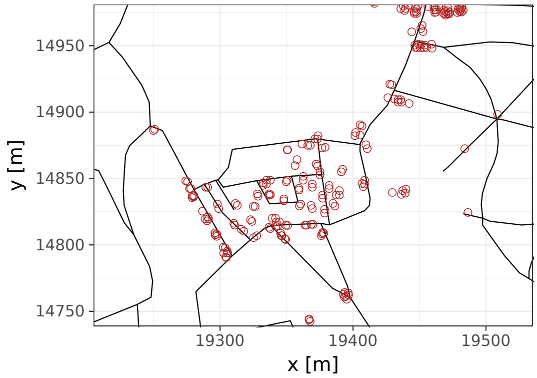
Due to the limited capability to position nodes at exact locations, random models are also not able to reproduce realistic contact opportunities. Such contact opportunities are however one of the main metrics for DTN routing approaches and have a strong influence on the achievable latency [63, 123]. Therefore, a realistic modeling of the movement is important for any DTN evaluation. Figure 3.6 compares the resulting distribution of contact durations for the search scenario presented in Section 2.1.2 using the random model and the trace-based approach. Both versions cover the involved first responders, their vehicles, and the rescue dogs only. No further nodes to potentially enhance the connectivity were employed in this evaluation. The resulting scenarios thus represent devices currently available without any additional relay nodes specifically deployed to support the communication. Each node is configured with a fixed transmission range of 150 m. This range represents an intermediate range between good and poor environmental conditions as presented in Section 2.3. Using a range of 150 m thus allows to model some of the environmental characteristics while it might provide somewhat optimistic contact durations for poor conditions. As a first analysis on potential communication problems in sparse first responder networks



(a) Random waypoint mobility



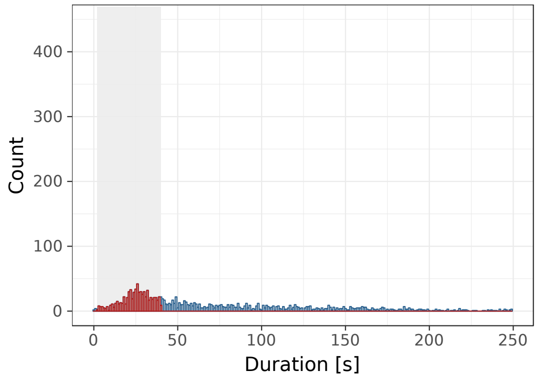
(b) Random path-based mobility



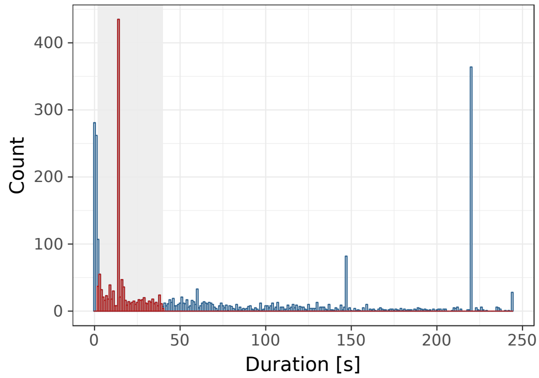
(c) Pattern-based mobility

Figure 3.5: Distribution of Nodes in the Fire Scenario (cf. Section 2.1.1 and [79])

it is however convenient. The data was generated using the reporting functionality in ONE to capture individual link-related events between any two nodes with some post processing in R.



(a) Random path-based mobility



(b) Pattern-based mobility

Figure 3.6: Distribution of contact durations for the SAR scenario (cf. Section 2.1.2)

While the random model generates in total 1844 contacts the traces produced more contacts (8356). This proves that the random movement results in fewer and overall shorter forwarding opportunities.

But the quality of the forwarding opportunity is also important and has to be considered for further evaluations. If the contact is too short to exchange messages, it is not usable for communication. This is the case for 13 % of the contacts generated by traces. It is however realistic, because the nodes have to perform their mission-related task and thus cannot react on potential communication needs. On the other hand, if a contact lasts for a long time, this indicates either stable conditions where no DTN forwarding would be required or only to cover short interruptions. Such situations happen in disaster scenarios, if nodes form a team and thus work in close proximity of each other (cf. task locations in Figure 1.1) or if nodes are part of higher organizational levels and thus remain in one place for a longer time period (cf. coordination point in Figure 1.1). To better indicate the useful contacts, they were highlighted in red for both cases.

The difference in contacts clearly indicates the need for realistic models if the movement characteristics of the nodes shall be exploited for better communication systems.

3.3 Hierarchical Traffic Model

Section 2.2 described the hierarchical aspect of the traffic produced by first responders. Besides that, the generation of corresponding traffic flows should consider the current role of the nodes in the hierarchy as well as their current task and corresponding position. This will apply to any kind of traffic including sensor data, text-based messages, and multimedia content besides the traditional voice traffic and might provide additional context to aid the forwarding decisions. It is therefore essential to consider this aspect when evaluating different protocols either by simulation or experiment.

Previous research related to first responder traffic characteristics focused mainly on modeling voice traffic only. The model in [8] represents the calling behavior of nodes based on real-time traces. This model is however limited to the traffic in one channel only and thus cannot reproduce the hierarchical aspects of the communication because higher organizational-layers might employ different channels and future systems might not be limited to current half-duplex walkie-talkie style communications. Other approaches related to DTN-based communication presented applications that support a Push-to-Talk-style [70] or instant-messaging-style [54] communication for the deployment on real devices to show that asynchronous communication is possible in such scenarios in general. Both approaches were designed for non-disaster use-cases and provide no options to manage the given hierarchical information flow, as such a structure is specific for first responder communication. Besides that, these applications are not available for simulative evaluations of the protocol performance. However, the authors of [54, 70] provide valuable insights regarding several metrics such as the required overhead, available voice codecs, and required data rates [83] for voice communication. These values can be used to generate realistic traffic volumes, even if the model itself is incapable of recreating the traffic flow.

3.3.1 Simulation-Based Traffic Generation

There are several generic possibilities to generate traffic in simulations. The remainder of this section will focus on the options available in ONE, a simulation environment specifically designed for DTN evaluation [76]. Figure 3.7 shows the described components in ONE and how the components interact with the routing layer. Since ONE models the bundle protocol [142] only, both the routing and the application layer are located in the application layer of the Open Systems Interconnection (OSI) reference model. The underlying protocol stack is excluded except for simplistic assumptions on Network Interface Card (NIC) range and data rate. ONE supports three options to generate traffic: *external events*, *random event generators*, and customized *applications*.

Messages can be created externally and injected into the simulation at a specified point in time using appropriate event queues. Such *external events* require detailed a priori knowledge of each individual message in order to cover all requirements and characteristics of first responder communication but also provide the highest level of realism. The main drawback is the increased effort to generate sensible event lists for each scenario and potentially multiple runs.

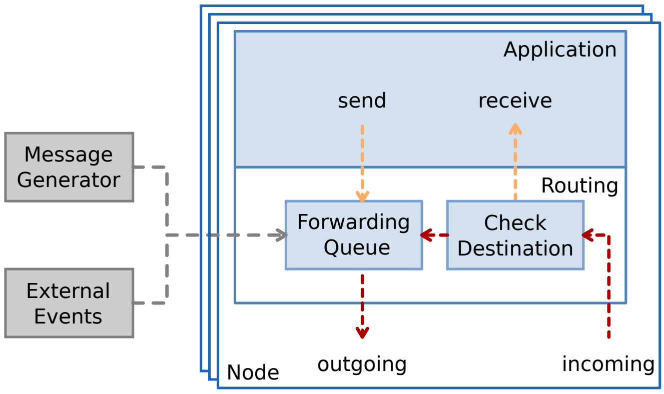


Figure 3.7: Options to generate traffic in ONE and their interaction with the routing layer

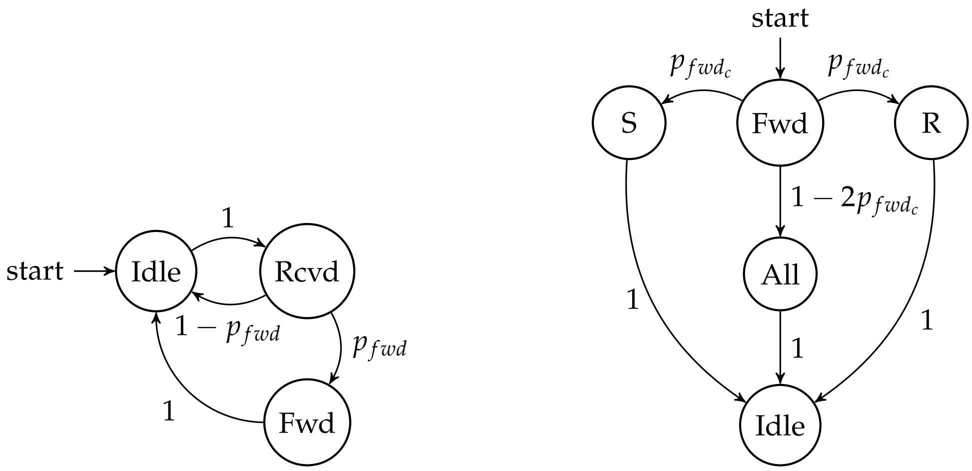
Another option is to configure a set of *random event generators* provided by the simulation environment. This allows a selection of random sending and receiving nodes from a given range of node IDs and generating one message within a given time interval. Another configuration with an exact specification of each sender and receiver pair is also possible but creates rather static traffic due to constant time intervals and message sizes. Therefore, changes of the traffic intensity depending on a nodes activity patterns cannot be covered. While such schemes are able to verify the protocol functionality in general, they are not able to cover the specific requirements of first responder traffic. This is especially true, if traffic characteristics are considered in the routing process in order to limit the latency.

Finally, ONE provides an option to add *application* modules that generate new messages and appropriate responses to received messages. This ensures that the messages are uniquely addressed to participating nodes and are only delivered to the application if the node is the intended recipient [83]. Otherwise, the message remains in the queue of the routing layer. This allows an efficient modeling of the hierarchical traffic flow and the usage of all other nodes as potential relays. Therefore, the traffic generation of first responders will be modeled as an application.

3.3.2 Traffic Flow Representation

Applications in ONE are assigned to one or multiple groups of nodes. To model the hierarchy, the application uses a simple parent-child relationship that has to be configured by assigning the corresponding nodes for each hierarchical level. The current application instance at level n uses the nodes in level $n+1$ as parents and those of level $n-1$ as children in the same sub-branch of the logical tree. This results in multiple child and parent nodes assigned to an application instance. Multiple parent or intermediate nodes are required if one logical command post is actually formed by multiple first responders each equipped with its own device.

The information flow is generated using two state machines (cf. Figure 3.8) to evaluate whether a received message (state *Rcvd*) should be forwarded (state *Fwd*) or not, based on probabilistic transitions. This forwarding decision of the application is taken by the content evaluation module at the application layer and is independent of the decisions taken at the routing layer [83]. The first parameter (p_{fwd}) defines whether a message is forwarded at all, independently of the flow direction. The second parameter (p_{fwd_c}) defines whether a message is forwarded in top-down mode to a single child node (state *S*), a randomly chosen subset of child nodes (state *R*), or all child nodes (state *All*). This is a second decision after the initial decision to forward the message at all by the first state machine. For the bottom-up mode, the message is always forwarded to one randomly chosen parent node, if multiple parents are available. Otherwise, the configured parent node is selected.



(a) Forwarding decision **(b)** Child selection

Figure 3.8: State machines for application forwarding decisions

Messages are generated based on parameters defining the time between calls (generation rate) and the call holding time (message size). In [8], the authors modeled real-time voice calls using a message size of 21 Byte created every 67.5 ms. The message size for intermittent DTN-based communication can be obtained from the call holding time distribution, assuming that the corresponding data is recorded for 5 to 15 s and encoded as described in [70]. This allows us to model realistic DTN-enabled voice traffic of first responders. Other message types can either be abstracted to this type of asynchronous traffic or can also be generated by defining additional message types.

Initial message generation happens mainly at leaf nodes in case of reports or at the root node in case of commands. The nodes at intermediate levels employ the same application and thus can generate further messages either by forwarding a received message as a new one (cf. Section 2.2) or generate messages on their own. When a node choses to forward a message, it can select a new size and the number of recipients from the configured children in case of top-down flows. By selecting appropriate values for the state transition parameters (p_{fwd} and p_{fwd_c}), the number of generated messages is controllable.

This scheme allows to create different configurable message loads. To some extent the resulting load is also depending on available communication opportunities, as forwarding decisions are taken only once the message is delivered to a corresponding node. Such a model covers the real behavior of users and allows to evaluate the impact of actual delays on the communication flow. Besides this general setup, an application provides easy formatting of the messages in order to add further control fields for further context evaluation.

3.3.3 Implementation Details

Similar to the movement framework, the following section will focus on crucial implementation aspects only.

The application was implemented in Java using the default configuration options provided by ONE. This allows an easy configuration of the application and the assignment to the corresponding nodes but also has a drawback. Given the hierarchical structure with multiple nodes within one group, one specific configuration (or instance) of the application should be assigned to that group only once. Since random numbers are used to select whether a message is forwarded or generated, this group-wise assignment causes all nodes of a group to take the same decision at the same time. This behavior is highly unrealistic and adds additional collisions. To avoid this, two things had to be added to the implementation:

1. an application-specific time offset and
2. a class variable counting the generated instances of the application.

Based on these values each application instance calculates an individual seed value for the random number generation. This ensures that different decisions are possible. The time offset is used additionally to vary the timestamps triggering when messages are generated between different members of a group in order to avoid collisions.

Similar to this, a node decides whether to forward a message or not based on a random number (*rand*) drawn from a uniform distribution using a corresponding random number generator initialized with the individual seed of that node. The actual selection happens by comparing the random number to the configured parameters for forwarding and child selection. If the random number is smaller than p_{fwd} the message is forwarded. When forwarding a top-down message, the number of messages (n) are selected according to Equation (3.2).

$$n = \begin{cases} \text{single child} & \text{if } rand > 1 - p_{fwd_c} \\ \text{random children subset} & \text{if } rand < p_{fwd_c} \\ \text{all children} & \text{if else} \end{cases} \tag{3.2}$$

The actual receiving child nodes are then chosen randomly among the available child nodes.

3.3.4 Validation

To evaluate the impact of the two state transition parameters, several simulations in ONE were executed using the Epidemic routing protocol [158] as base. Epidemic uses flooding to ensure low delivery delays and a high delivery ratio. It is therefore a suitable candidate protocol for benchmarks related to these two metrics given that enough resources in terms of buffer size are available. The scenario applied is the search scenario presented in Section 2.1.2 with trace-based mobility. Figure 3.9 shows the configured node relationships according to the organizational structure in the mission with the corresponding node IDs in ONE. The node IDs are not numbered in ascending order, due to the node configuration supported by ONE that only supports ascending node IDs over all groups. To model the scenario, eight vehicles and corresponding crew members have been modeled. The initial node IDs are assigned to the vehicles (nodes 0–7), followed by the dog handlers (8–36), the dogs (nodes 37–57), the police officers (nodes 58–59), and finally the EMS personal (nodes 60–61). In this scenario, only the human nodes are configured with the application and crew members from different vehicles can be assigned to one common search team.

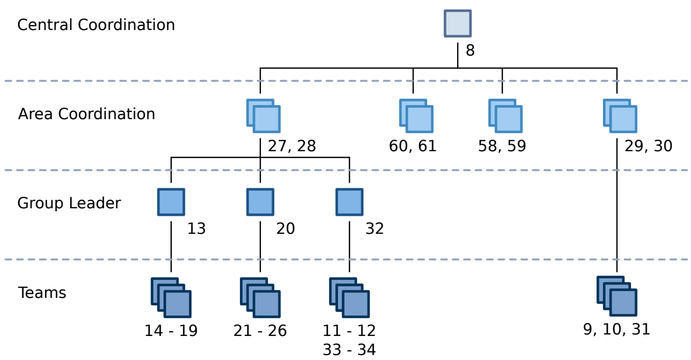
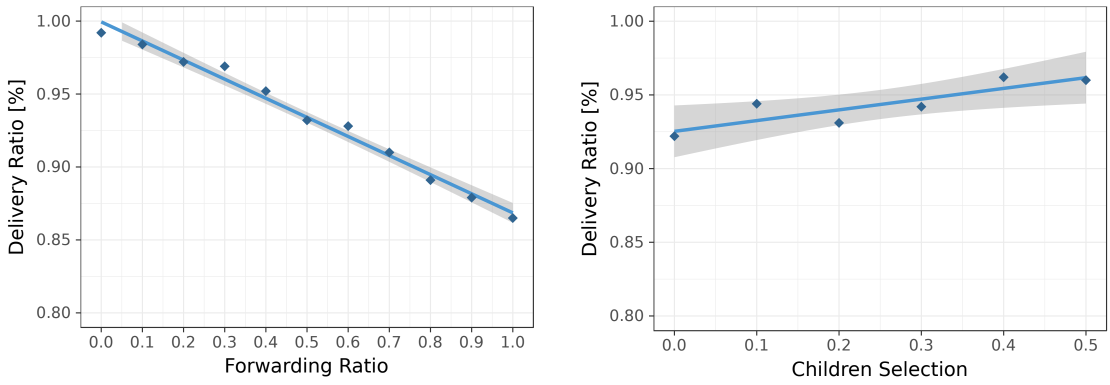


Figure 3.9: Configured first responder organizational structure of nodes

Figure 3.10 shows the impact on the delivery ratio of different parameter settings for the forwarding decision and the selection of recipient child nodes. The first parameter (p_{fwd}) is varied from no forwarding (set to 0.0) to always forward (set to 1.0). To evaluate the impact of the traffic load, one message is generated per forwarding decision. Possible values of the second parameter (p_{fwd_c}) can be varied from 0.0 (always forward to all children) to 0.5 (never forward to all children). All runs for this validation were performed once to get an insight on the parameter effects. This also explains the variance in the delivery ratio, if the chosen setups were suboptimal for the given mobility. To still evaluate the quality of the results, a linear model was fitted to the resulting values. Both figures include the fitted curve as well as the 95 % confidence intervals.



(a) Forwarding decision configuration

(b) Children subset configuration

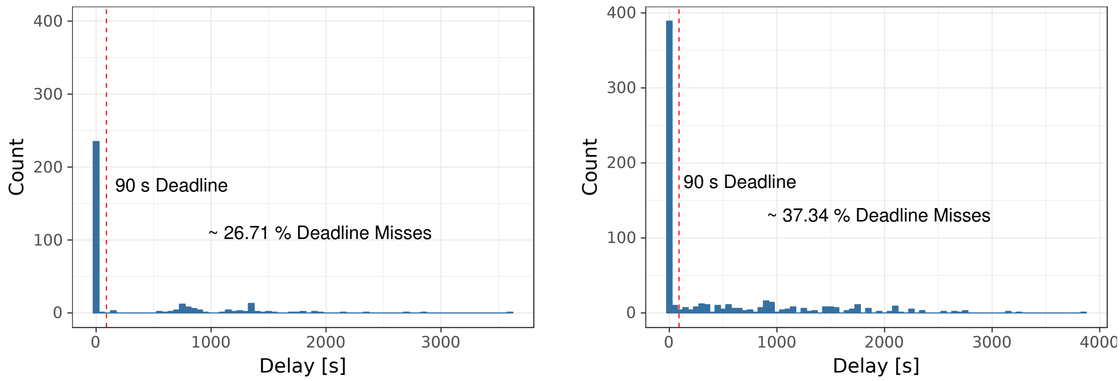
Figure 3.10: Impact of application forwarding parameters

Selecting a forwarding ratio of 0.0 represents the base load of the application defined by the message size (500 kB in this case) and the message generation rate configured. Apparently, in none of the configured scenarios all messages can be delivered successfully. In the first setup, this happens due to messages that are generated towards the end of the simulation time and could not be delivered within the simulation time limit. When increasing the traffic load, the delivery ratio is decreasing while the total number of messages created and delivered is increasing from 480 to 822 and from 476 to 711, respectively. The strong decrease of the delivery ratio for scenarios with higher load happens partially due to late message generation but limited buffer space has a higher impact in this case. Based on these results, a configured value of p_{fwd} between 0.2 and 0.3 provides a decent forwarding capability without affecting the delivery ratio with a high message load.

Besides the general decision to forward a message at all, the second parameter allows to generate further load, if multiple child nodes are used as receivers. The values presented in Figure 3.10(b) were obtained with p_{fwd} set to 0.3. In this case, the best delivery ratio is achieved if p_{fwd_c} is set to 0.4 which corresponds to scenarios where most messages are forwarded to single nodes or a small subset of the children. Therefore, the following simulations are performed with the following settings: $p_{fwd} = 0.3$ and $p_{fwd_c} = 0.4$.

Based on the previous results, we compared the message generation and the achieved delay performance of traffic generated by the application and external event-based traffic that was generated manually by aligning messages to the current position and role of the corresponding senders and receivers. Figure 3.11 shows the histograms of the delay distribution. The application generated more messages in the same period of time, which explains the higher total values. However, the delivery ratio is similar with 0.887 for the application and 0.997 for the manually matched messages, respectively.

Both histograms show a similar distribution with many messages that are delivered immediately and a long tail of messages with large delays. These messages, that



(a) Manual event-based traffic **(b)** Application traffic

Figure 3.11: Comparison of delay distributions in SAR scenarios with external events and application traffic

miss the envisioned 90 s deadline, amount to about 30 % of all delivered messages in both cases. Again, the behavior of the application traffic follows that of the externally generated events. This shows that the application is able to reconstruct a realistic node behavior.

When evaluating the results more closely, it is obvious that the mean value is not a good metric for the delay in this case. Due to the large number of messages that are sent to nodes which are reachable through an available path immediately, the average would be too optimistic while the variance is high. Even filtering of the instantly deliverable messages will not show the desired effect to better describe the distribution, because the smaller peaks in the tail correspond to the potential distances between the different areas and thus the groups. Therefore, the *ratio of messages missing the 90 s deadline* is used as metric instead.

There are many messages that are sent when a group is fulfilling its task without connectivity to other nodes for some amount of time and these messages show an unacceptably large delay when missing the deadline. While the percentage of such messages is relatively low compared to those delivered in time, these messages are actually more crucial because there is another semantics-related problem related to them. They are highly important due to two reasons. First, these messages represent reports that are required by the coordinators in order to correctly assess the current situation in the disaster and provide new additional information. The second case are commands by the coordinators that should reach the teams fast, especially in case of warnings.

With an increased mission duration (e. g. further areas to be searched) the distance that has to be covered in order to reach the next task location will become larger and thus the tail of the distribution also becomes longer. Actually, the overall delay distribution as shown in Figure 3.11 is an overlay of several smaller distributions each corresponding to a certain distance that the groups have to cover for a given task. Comparing to the abstract scenario, this again shows the need to handle the intermittent connectivity resulting from the spatial distance between groups. Therefore, the protocol design should focus on reducing the delay experienced by these messages.

3.4 Impact of Dedicated First Responder Models

To evaluate the impact of our realistic models on the actual DTN performance, we simulated the described mobility and traffic models as well as two alternatives for each model type in ONE. The models considered for comparison are listed in Table 3.1. Out of nine possible combinations of mobility model and traffic generation options, eight were selected for the evaluation it was infeasible to generate manual events for the disaster area model.

Table 3.1: Models used for impact evaluation

Mobility	Traffic
Random	Random
Disaster Area [7]	Manual Events
Pattern [89]	Application [83]

Both the random and the pattern-based movement represent the search scenario with an overall area size of 6000 m by 5000 m and 62 nodes equipped with WiFi devices with a transmission range of 150 m and a fixed data rate of 2 Mbit/s. The simulation time, the underlying map, and the node number are kept constant for both movement scenarios. To compare with another existing movement model, a third scenario was generated using the disaster area model described in [7]. The authors provided an example script in the BonnMotion distribution [6] that creates a scenario with 150 nodes in an area of 350 by 200 m with several obstacles. This scenario represents a disaster event with a limited area but many first responders with different responsibilities and thus can be used to model for example a fire or an evacuation of a larger building. In this setup, the node density is much higher and represents an indoor environment at least partially. A limitation of the transmission range to 50 m was applied in order to introduce at least short term disruptions. This model represents a rather dense network while the SAR scenario is rather sparse. The traffic corresponds to the three options for traffic generation available in ONE as described in Section 3.3.1. Each option was configured to produce a comparable number of messages. More detailed parameters of the simulations are given in Section B.1. Figure 3.12 presents the average delay and loss achieved during the simulations.

The average delay was used in this case instead of the ratio of messages missing the deadline, because the focus lay on a comparison of the introduced models. In this case, the variance and average values (cf. Table B.4 for the exact values) can indicate differences in the combination of different models. The green diamond marker in Figure 3.12 represents the ideal QoS requirement of the first responders as defined in Section 2.2 with robust, loss free communication and small delays.

Employing the realistic traffic options has an impact on the packet loss ratio which is significantly reduced with these models (indicated by the right most vertical dashed line). Similar to that, realistic movement models show a significant impact (indicated by the horizontal red dashed line) on the achievable delay performance because they ensure regular, periodic contacts between the different nodes while scenarios with random mobility are not able to reproduce this. The left most vertical dashed line indicates the 90 s-deadline indicating the maximum delay

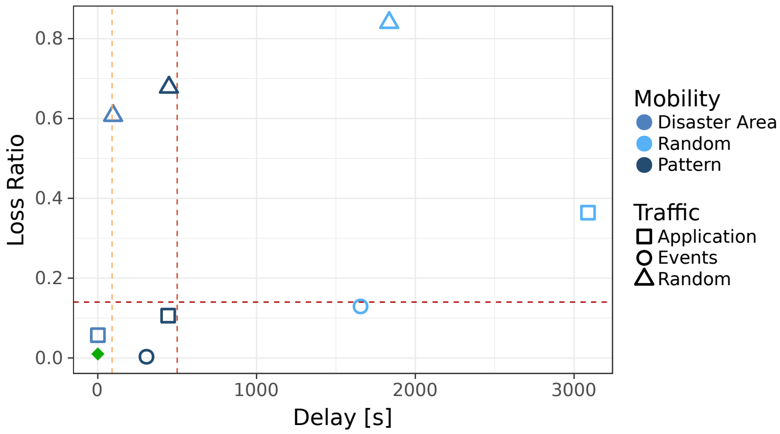


Figure 3.12: Impact of evaluated models on achievable delay and loss

which would be acceptable for one-way messages. The disaster area model shows the best performance, because it represents a dense network where most nodes are directly connected or leave the coverage of the others for short time periods only. It should be noted that the combination of disaster area model and the application-based traffic model are able to reflect the good connectivity with an average delay value below one second even if DTN principles are used.

On the other hand, a scenario generated using the mobility framework representing a sparse network with distributed nodes and large distances to cover still shows a much better performance than the purely random model. The only exception is the realistic application traffic in combination with random movements which show a higher loss almost equal to that of random traffic and the highest delay of all setups. This happens because the hierarchical information flow is normally directly correlated to the movement of the nodes and thus to the mission phase. While the application enforces the flow along the configured hierarchy, the random movement does not reflect this but instead results in by chance meetings and thus decreases the probability to meet the destination.

Differences in the observed performance values result directly from the contact opportunities that each movement model generates (cf. Section 3.2). This also explains the misleading nature of the average delay as shown in the previous section. If nodes in a search scenario experience long intervals without any connectivity due to their task-dependent mobility the delay will be high. However, the challenge is to mitigate these delays by exploiting intelligent routing approaches and further potential relay nodes to support the connectivity.

The developed models enable the setup of a wide range of realistic simulation first responder scenarios. This was not possible before, because existing models are either too generic to reflect the reality or were designed for one very specialized scenario only. First evaluation and comparison results already indicate the importance of such realistic scenarios for further research in order to design communication systems that are able to fulfill the requirements of first responders.

CHAPTER 4

First Responder Scenario Analysis Toolbox

Simulations are one common option to evaluate communication characteristics and protocol performance of disaster scenarios. However, the simulations require a realistic setup that is able to reflect the relevant characteristics in order to allow a thorough analysis. In case of disaster scenarios, with a heterogeneous and constantly changing network, performing such an analysis is difficult if only one specific tool is used because each tool captures a subset of relevant aspects only. Which aspects can be captured by a specific tool depends on the available models or features of the given tool and their configuration options.

Based on the preliminary results obtained during the model evaluation (cf. Section 3.4) and the outdoor measurements (cf. Section 2.3.3), it becomes clear that additional features are required to evaluate hybrid networks as well as the network heterogeneity, if the underlying features of the network as well as the characteristics of DTNs shall be captured and analyzed. Therefore, this chapter introduces several extensions to existing simulation tools that enable a better understanding of hybrid DTNs as well as an option to calculate oracle forwarding decisions.

All extensions and tools developed are combined into a toolbox for DTN evaluations which is complemented by an outdoor-capable DTN-enabled testbed platform for real-world verifications.

4.1 Motivation for Additional Evaluation Tools

Simulations are the most common analysis technique for novel networking concepts. Other tools such as analytical models or testbed evaluations usually have some drawbacks. In case of Analytical Models, the required assumptions in order to provide a reasonable complexity are typically very restrictive and thus not able to capture all aspects. Testbeds, on the other hand, provide valuable insights on implementation details as well as the actual performance in the target environment. However, testbeds are usually limited with respect to the number of available nodes and thus often represent a proof of concept only. Scalability issues cannot be captured in this case.

Simulative DTN evaluations are performed using ONE in most cases, because this tool provides implementations for several well-understood state of the art routing protocols. However, ONE only covers the DTN layers and does not reflect any underlying networking technologies. It takes simplistic assumptions on the available communication range using a unit-disk propagation model and a corresponding data rate. This results in contacts and perfect reception of messages as soon as two nodes are within communication range of each other [76]. As such, it is not possible to model the observed effects of terrain and foliage as well as underlying multi-hop connectivity. The latter is of special interest, in case of well connected MANETs of individual first responder groups at a given task location.

Possible alternatives to ONE are the traditional network simulators (e. g. Network Simulator version 3 (ns-3) or OMNeT++ [159]). These tools provide modules to build the complete protocol stack of MANET nodes based on IP and include various detailed signal propagation models. Using these tools allows to describe the underlying network structure including link failures and bit errors during the message transfer [163, 164]. However, there is only one implementation [91] of the Bundle Protocol specified in Request for Comments (RFC) 5050 [142] in ns-3 with limited routing protocol support. In case of OMNeT++, there is an implementation [160] that places the DTN functionality into the network layer, which again is not compliant to the RFC [142]. Other implementations are described in the literature. These are either not available as source code for reuse (e. g. [177]) or too old supporting only earlier versions of the simulator (e. g. [63]).

Therefore, a thorough evaluation of hybrid DTN-MANET approaches is not possible with any of the discussed tools without further changes to the existing tools [105]. While each tool has its unique characteristics and capabilities implementing the advantages of one tool into the other one is rather infeasible and inefficient because the advantages could be combined into a more powerful tool set.

4.2 Analysis Toolbox Overview

To overcome the limitation a combined *Analysis Toolbox* is proposed that consists of several extensions to the existing simulation tools as well as additional tools such as the presented *Movement Framework* [89] and the *OracleSolver Framework* [84], an analytical tool. Figure 4.1 shows the components of the toolbox, including the existing tools, new features, and their interactions. Dark blue boxes show tools that were already described and discussed in Chapter 3. Light blue boxed describe further tools or modules that will be explained in more detail in the remaining chapter and that were developed within this project. Finally, gray boxes indicate a selection of existing modules within the simulation tools that are relevant for hybrid DTN/MANET or pure DTN studies. Dashed arrows indicate the information flow between the different components: data export (green), data import (red), data generation or usage by external tools (orange), and selected configurable interactions within the simulation tools (blueish gray).

The core idea of this concept is to enable on the one hand simulations in ONE with a more detailed level of the underlying network characteristics and on the other hand add DTN capabilities to OMNeT++ and thus allow the combination of different analysis methods. While one such setup might be enough, the combination allows research on multiple levels depending on the desired level of detail and the focus of the project in question. The combination of different environments and tools is enabled through the existing functionality in ONE to import external events of any kind (e. g. message creation time, movement traces or contact traces)

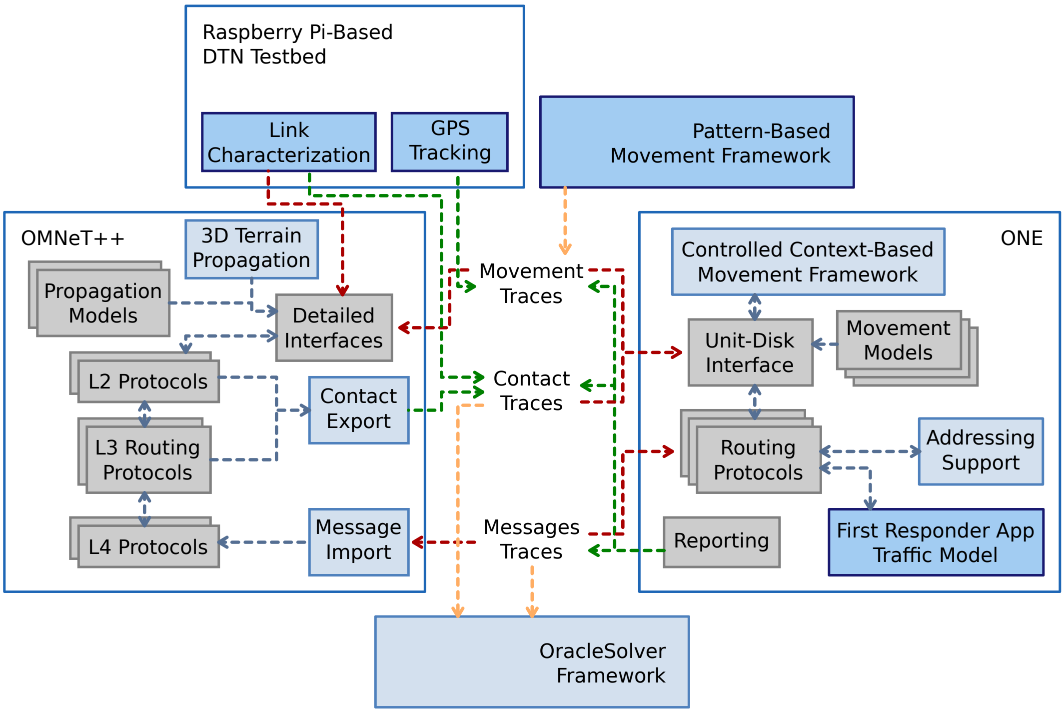


Figure 4.1: DTN scenario Analysis Toolbox components and interactions

and to write corresponding report files based on events generated during the simulations. Originally, this functionality was designed to enable research on social interactions between users and thus exploit real-world movement or contact traces into the simulations. To actually integrate traces generated via other simulation tools is a novel aspect of this principle.

Besides that, ONE was extended to actually support name-based addresses or EIDs during the simulations instead of generic simulation-dependent identifiers. This feature enables the simulation of other traffic types such as multicast or broadcast besides unicast, which was the only option before. Such a module is helpful to estimate a realistic message load, in case of multicast messages. In case of first responder networks, commands to all team members are typically such multicast messages.

Another feature that is valuable for disaster scenarios but also other ferry-based networks is a module that enables the simulation of context-controlled movements. *Message Ferrying* algorithms are usually employed to define the path of the ferry based on the messages in its buffer [143]. However, the evaluations of such approaches are done with traces that were calculated offline or in special tools without realistic traffic characteristics and thus in-network interactions are hard to capture. At the same time, it is impossible to predict the impact of dedicated message ferries that take their decisions independently on the performance of the routing protocol. This is solved by the developed Framework for *Controlled Context-Based Ferry Movements*. It allows to simulate the dynamic movements of a dedicated ferry throughout the simulation based on events during the simulations and builds the base for the integration of message ferry algorithms into ONE.

The evaluations in OMNeT++ are based on the INETMANET framework [3] which contains experimental implementations of various protocols required for MANET analysis [3, 146]. INETMANET includes multiple models for signal propagation, network interfaces and medium access control (L2), and several traditional as well as some opportunistic MANET routing protocols (L3). Therefore, this framework is a good choice to analyze the underlying network conditions. In order to provide support for hybrid DTN-MANET approaches, a working DTN module has to be added, including the *Bundle Protocol* [142] and the required *Convergence Layers* for the adaptation of messages to and the interaction with transport layer (L4) protocols.

Besides that, the measurements in Section 2.3.3 clearly showed an impact of the surrounding terrain in which the scenario is set. Terrain features acting as obstacles for communication processes are however not considered in OMNeT++ which might result in too optimistic contact estimates. There are only few works, discussing the impact of terrain features in simulations at all. An implementation for Network Simulator version 2 (ns-2) is provided in [48]. The authors later introduced several enhancements to their model [37]. Since ns-2 has been replaced by ns-3 which is not backwards-compatible, this model is however not available for evaluations of protocols that were developed recently. Therefore, a new implementation of the underlying propagation model was ported to OMNeT++.

The import and export extensions to OMNeT++ are less prominent. OMNeT++ already provides some utilities to import events via files in Extensible Markup Language (XML) format. This is exploited to read the external messages and create the appropriate simulation events. To the export of contact information, the logging features of OMNeT++ were used to report the already existing events from within the simulation. Afterwards a simple bash-script is used to filter the relevant messages and format the output to the desired report.

The software toolbox is complemented with a customized hardware test platform based on Raspberry Pi devices and embedded Linux as operating system. Even if testbeds cannot provide insights on the scalability, they have one big advantage: using a testbed which reflects potentially the real-system, detailed information on link characteristics as well as movements can be captured. If this information is measured and logged accordingly, it can replace or complement the traces that are generated via simulations. Additionally, measurement results can be employed to configure simulation models in order to build realistic scenarios.

In the following, the introduced components of the toolbox are explained and discussed in detail.

4.3 OracleSolver Framework

4.3.1 Motivation

The definition of an *optimal path* or solution in case of routing/forwarding decisions depends on the metric that is employed and the associated cost. Therefore, in different situations the solution can vary quite significantly. In this project, the goal is to limit and minimize the experienced message delivery delay (t_{deliv}). This delivery delay consists of two components in DTNs: the actual transmission delay (t_{trans}) between two nodes (i, j) that exchange a message and the waiting time

(t_{wait}) at node i buffering the message until a forwarding opportunity arises. These two components have to be accumulated for each hop required between the source node (src) and destination node ($dest$) according to Equation (4.1).

$$t_{deliv}(src, dest) = \sum_{\forall\ hops(i,j) \in path(src,dest)} t_{wait}(i) + t_{trans}(i,j) \tag{4.1}$$

In traditional networks, the optimal forwarding path through a network is calculated via graph-based shortest path algorithms using for example the delay introduced by each hop as cost. The network is abstracted to a graph where vertices correspond to nodes and edges represent links between the nodes with weights associated to the edges. The weights are then used as cost parameter for the algorithms [111]. Traditional well-known shortest path algorithms such as the *Dijkstra Algorithm* assume that the network remains stable for a reasonable amount of time. This is, however, not true for DTNs and only to a limited extend for MANETs.

These networks can be described as graphs as well. However, the edges between the nodes are not active at all points in time. They are active only for a short period of time during a contact between the nodes in question. This activity phase can also be periodic, if two nodes meet frequently. Graphs representing this kind of behavior are *time-varying graphs* or dynamic graphs [65].

DTNs have been described as time-varying graphs previously (e. g. in [27, 66, 67]) mainly to identify social communities among nodes and later exploit these for routing decisions (e. g. [94, 173]). While these approaches describe the network as graph and then analyze common graph-related metrics such as node degree, communities, closeness, and betweenness [106], they do not use the graph representation for routing. This is used in the Contact Graph Routing protocol [2, 24]. However, by using this approach the graph is built based on predictable contacts that are available for deterministic movements of objects in space. This assumption does not apply for terrestrial networks such as the first responder network considered here. Another analysis is presented in [12] where different hop limits are used to evaluate path metrics based on graphs that aggregate the contacts over given time intervals. The results indicate that multi-hop communication provides better paths and hop limits should be within 2 to 4 hops in order to allow optimal forwarding.

Besides these approaches that utilize the time-varying graph as tool, there are also many studies on algorithmic aspects of these graphs. Related approaches handle the reachability in time-varying graphs [169], the temporal distance [26], and the connectivity of time-varying graphs [28]. However, the focus is on the analysis of the resulting graphs but without a relation to the routing decisions taken by nodes in the network or an option to analyze resulting forwarding paths. This was presented in [34], where shortest path algorithm variants for dynamic networks are discussed. The authors however mainly focus on the required frequent updates to keep routing information up-to-date instead of employing those algorithms to calculate an optimal solution. The authors in [75] follow a different strategy. They use OMNeT++ to simulate randomly generated graphs and perform some performance evaluations with respect to graph properties. However, the protocols analyzed with their framework are rather simplistic and a network stack featuring all communication-related aspects is missing. Paths based on the graph topology are also not the focus of their analysis.

Algorithms to solve shortest path problems on dynamic graphs have also been described [107, 174]. These approaches however focus on algorithmic properties and not on the application to network routing. One approach attempting to evaluate the routing protocol performance based on graphs is presented in [47]. To do that, the authors implemented a suitable graph-based algorithm in ns-2 and used it to build a MANET routing protocol based on perfect knowledge represented by the graph. When comparing with traditional MANET protocols, the graph-based version outperforms the others and thus indicates that a theoretically optimal solution must exist. This approach is again not available for further research and thus cannot be applied to similar problems in hybrid DTN-MANET or pure DTN schemes.

None of the approaches does exploit the graph in order to calculate optimal paths through the network over multiple contacts. This calculation of the optimal path is challenging, because traditional shortest path algorithms cannot be applied to the time-varying graph without modifications. However, modifications to the well-known algorithms should be avoided as far as possible. The alternative is to derive sub-graphs, which allow the usage of traditional algorithms for further analysis. Using such an approach, it is possible to derive the optimal path for each message and thus provide a lower bound for the theoretically achievable minimum delivery delay, an upper bound on the delivery ratio, and it helps to identify crucial nodes that are involved in many transfers via the path information.

4.3.2 OracleSolver Framework Components and Design Considerations

In order to calculate a solution that is optimal with respect to the achievable delay, several things are required, besides suitable graphs and a shortest path algorithm. Figure 4.2 shows the components and the structure of the framework. Based on two input data files (gray) the framework first derives a forwarding graph per message. These intermediate graphs are then used as a base to determine optimal solution and the shortest path from source to destination using an appropriate shortest path algorithm. Currently, only the Dijkstra Algorithm is supported. However, the framework is build in a modular way to guarantee easy extensions with further algorithms as well as the integration of additional criteria during the forwarding graph construction.

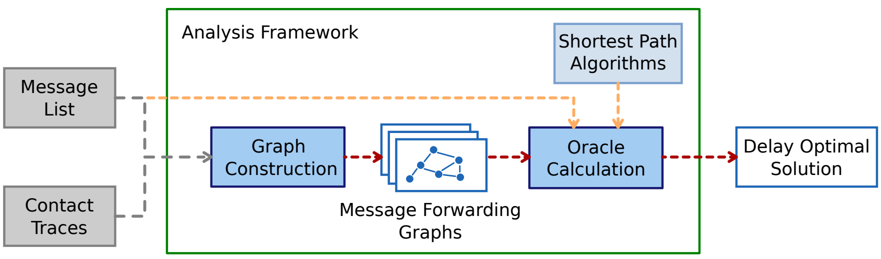


Figure 4.2: Structure of the oracle analysis framework (cf. [84])

The core of the framework is the construction of a *Weighted Directed Graph*, in which the direction of an edge indicates that time passes when using this edge in the given direction and the weight associated to the edge corresponds to t_{trans}. The waiting time t_{wait} is associated to each vertex, indicating the minimal required buffering time at the nodes represented by this vertex. To construct this graph for a given message, information when two nodes are within communication range of each other is required besides the source and destination nodes.

A *Contact Trace* is one option to provide this information. ONE provides a report that logs all connection events such as link up or link down for the corresponding nodes. The log entries used by the framework have the structure of a 5-tuple (cf. Equation (4.2)). This corresponds to a re-ordered version of the report format in ONE complemented with information on the available data rate of the link ($rate_l(t_e, from, to)$) in question. If the data rate is not available per link or a homogeneous setup is used, the last value is optional and defaults to configurable homogeneous link characteristics. Each tuple is unique as a combination of $\langle t_e, from, to \rangle$ only due to the time-varying nature of the network topology. Therefore, multiple sub-sequent contacts between the same pair of nodes are possible. The event type ($type_e$) has only two possible values (*up* or *down*) corresponding to the connection event reported by the given entry.

$$TraceEntry := \langle t_e, from, to, type_e, rate_l(from, to, t_e) \rangle \tag{4.2}$$

Another option to obtain these contact traces is to perform measurements on real hardware and log the communication opportunities accordingly. Example data from different sources is available on CRAWDAD[1]. Besides this, any simulation environment is able to produce corresponding synthetic traces based on configured network access technology and the node mobility. Any networking scenario can be evaluated using this approach. The only requirement is to document changes of individual connections and thus the ability of nodes to communicate for a certain amount of time as a corresponding contact trace. This also includes heterogeneous networks with different link characteristics as well as nodes with multiple interfaces and thus possibly multiple contacts at the same time.

Besides the contact trace, the size of each message is required in order to identify contacts that last long enough to enable the successful delivery of the message and to determine t_{trans} based on the given link characteristics. Using this information the framework is able to calculate an oracle solution with minimum delay and shortest path between source and destination if such a path exists based on the contact trace. If no path exists over time, the message is assumed as lost and thus the solution also indicates the maximum possible delivery ratio.

The result is therefore an ideal solution since it is calculated based on perfect knowledge about all up-coming contacts and some simplifying assumptions. But actual protocol implementations might not be able to achieve the found lower bound on delay and the upper bound on successful delivered messages and they might not follow the identified optimal path. Main reason for the difference

1 http://crawdad.org/

between the ideal solution and the real-world implementations are the following assumptions:

- immediate message forwarding upon a contact, without considering any transmission order
- focus on single message only
- no notation of simultaneous transfers of neighboring nodes
- no buffer management
- no restrictions on the available number of copies per message
- availability of symmetric and bidirectional links

The first two assumptions are directly related to the transfer mechanism of any given DTN protocol such as initial handshake, followed by an identification of potential messages to be exchanged as well as underlying aspects such as medium access. By simplifying this, we omit the processing delay introduced for these steps. This is however valid, since t_{wait} is usually in the order of seconds. Compared to this value the exchange of small control packets in the order of milliseconds can be neglected. The only case where this might be crucial are very short contacts, whose duration is sufficient to transfer one message only. To capture this effect, a threshold value can be configured to add some additional guard time to t_{trans} for each transfer.

The third and fourth assumptions are related to the buffering strategies that each DTN node supports in order to enable the *store-carry-and-forward* principle. If the goal is to calculate a lower bound for the delay and an upper bound for the delivery ratio, it is valid to state that the message in question is transferred to the next hop as soon as a communication opportunity comes up and that the buffer space is unlimited to avoid that messages get dropped due to missing space. The immediate forwarding to any contact requires an unlimited number of copies, otherwise not all contacts or resulting paths can be exploited during the analysis. In real implementations, these options are not fulfilled and thus the results will be somewhat optimistic.

In terms of the buffer management strategy, there are two aspects that are not considered but will have an impact on the protocol performance. The most prominent one is the dropping strategy, if the buffer space is exceeded. This will directly affect the delivery ratio, if single copy schemes are used and will also have an impact on the delay, if potential paths are omitted by dropping the message. Besides this, the order of the messages within the buffer might affect the point in time when a message is transferred during a contact if there are multiple messages for the next hop. In the worst-case scenario, the message in question is not transferred during a contact at all and has to wait for the next opportunity. This results in an increased value for t_{wait}.

Finally, the links described in the contact trace are assumed to be bidirectional and symmetrical. Typically, this is not true for realistic environments. But as long as no additional information on asymmetric link characteristics are available in the contact traces, any other assumptions are not possible.

Further details on the implementation of the framework are provided in the next section.

4.3.3 Implementation Details

As before, this section will introduce the relevant implementation aspects only.

In order to derive forwarding graphs based on the two input files, some preprocessing is required. The *Contact Trace* captures all link-related events and thus also the duration of a contact but this information is not directly accessible in the current format. Since individual events (e. g. link up or link down) are captured, the contact duration is available as difference of the link down time stamp and the preceding link up event of the same node pair only and the two events in question are not neighboring lines.

The first step is therefore to parse the contact trace file and derive the duration of each contact. As a result there is only one line per unique contact as described in Equation (4.3). In case of contacts that do not finish within the given observation period, the end of this period is set as the time stamp of the link down event. While other aggregation-based approaches report all edges that are active during an aggregation window at some point in time or only if they exist over the complete duration, this approach reports all edges as observed. This has the advantage that the timing information remains unchanged and still represents the full level of detail.

$$EdgeListEntry := \langle from, to, duration, rate_e \rangle \tag{4.3}$$

The resulting data structure represents a *timed edge list*, which is one option to describe a time-varying graph. In this notation, the nodes (from, to) represent graph vertices and active connections between the nodes are corresponding edges with additional parameters (duration, $rate_e$). However, the data rate of each timed edge list entry ($rate_e$) is optional and not necessarily required for the graph description. This value, if present, is used to determine $t_{trans}(from, to)$ for the given edge. If the value is unspecified, a globally configured default value is used instead.

As a next step, a weighted directed graph is derived from the timed edge list and the message trace for each message. This *Forwarding Graph* represents all forwarding opportunities for a given message in a timely order. Each graph is stored as an adjacency list of outgoing edges at each vertex.

The passing of time is indicated by the direction of outgoing edges and the weights of an edge corresponds to time stamps describing the start of the given contact (t_{start}) and the time a message has to wait at the previous vertex (t_{wait}) if this edge is used. t_{start} indicates the earliest time at which the current message can use the given contact. This can be different from the actual starting time of the contact, if it was available before the message arrived at the current node. Algorithm 1 describes the complete construction process.

The algorithm starts with the vertex representing the source node at the point in time when the current message is created at that node. All entries in the contact trace that are not related to this node are omitted to reduce the computation effort. Besides that, filters are applied to further exclude contacts that are in the past

Algorithm 1 Forwarding Graph Construction

```
Input: Message msg; TimedEdgeList
  Initialization :
  Initialize Queue Q, Graph G
  Add mgs.src as Vertex to Q and G
  Initialize time = msg.created
  Graph Construction :
  while not ( Q.isEmpty or current v is msg.dest ) do
    get first Vertex v in Q
    for all edges v → u do
      if u not visited then
        add u to G
        add edge v → u to G including start and waiting time
      else
        update time stamp of u if edge v → u provides faster path
      end if
    end for
    sort Q to ensure smallest time stamp as first element
  end while
  Finalization :
  return G(msg) as Adjacency List
```

as well as contacts that are too short for a successful message transfer based on the message size and the $rate_e$ of the edge in question. A time stamp is used at each vertex to indicate the earliest reception time (t_{rcvd}) of a message at this vertex according to all incoming edges.

Following a *Breadth First Search* [132] variant, the weights of outgoing edges are calculated for the given node and added to the graph including vertices as required. If an edge points to an existing vertex, the algorithm checks, whether the current edge reduces the t_{rcvd} of the message at this vertex and thus provides a faster path. In this case, t_{rcvd} is updated accordingly. Before adding an edge, two checks are performed: one to exclude *duplicated edges* and another one to exclude edges that would potentially generate *transient loops*. Both checks are required to ensure the strict timely order of the edges. They are valid, because to calculate the delay-optimal solution it is sufficient to receive the message once. Any later reception would add delay and thus represents a suboptimal decision.

After processing all outgoing edges, the queue holding vertices that were not processed so far is sorted based on t_{rcvd} and the vertex with the smallest value for t_{rcvd} is processed next. The algorithm terminates either once the vertex representing the destination node has been processed or if no further vertices can be processed and the queue is empty. In the latter case, there was no valid forwarding path for the given message within the contact trace.

Due to this construction, the value of t_{rcvd} already corresponds to the shorted delivery time for the given message, if a forwarding path between source and destination exists over time in the contact trace. However, the path leading to this minimal delay has not been extracted. If only the delay is relevant, no further processing is needed. To obtain the path for further evaluations, any graph-based shortest path algorithm could be applied. In this project, the Dijkstra's algorithm was implemented. The framework supports the modular extension with further algorithms as needed.

Finally, the graphs and an updated version of the message trace including the delay and forwarding path are returned by the framework for further analyses.

4.3.4 Concept Validation

To prove the feasibility of the presented approach, it was first evaluated based on a small manually generated contact trace and few messages that capture the relevant special conditions. The observation period is from 0 to 25 s. The framework was evaluated with respect to the following points:

1. correct edge termination (t_{start} and end of observation period),
2. omitting short contacts,
3. omitting contact in the past,
4. avoiding duplicated or transient edge
5. correct graph construction,
6. calculating the optimal path, and
7. terminating if no path exists.

Listing 4.1 shows the timed edge list that was calculated based on the contact trace. For visualization purposes, this list contains the time stamps related to the edge events from the contact trace besides the calculated contact duration. This result already fulfills the first point. The contacts represented by edges on lines 9, 11 and 12 end at 25 s which corresponds to the end of observation period.

Listing 4.1: Calculated TimedEdgeList used for validation

```
1  srcId destId  up[s]  down[s]  duration[s]  rate[kbit/s]
2      A      B    0.1      5.4          5.3          2000
3      D      F    2.0      8.1          6.1          2000
4      B      C    6.3      9.4          3.1          2000
5      B      E    7.5     15.2          7.7          2000
6      A      E    8.4     12.4          4.0          2000
7      A      F    8.5     13.6          5.1          2000
8      A      C    9.4     13.8          4.4          2000
9      B      D   10.3     25.0         14.7          2000
10     A      D   11.4     16.7          5.3          2000
11     C      D   11.5     25.0         13.5          2000
12     D      G   18.6     25.0          6.4          2000
```

Figure 4.3 presents a visualization of a derived forwarding graph and its construction process. This graph describes all forwarding opportunities of a message of size 500 kB that is created after 2 s at node A with node D as destination. In this figure, r represents t_{rcvd}, s stands for t_{start}, and w corresponds to t_{wait}.

The construction therefore starts with node A at 2 s. According to the list, node A has an active contact with node B at this point in time and the remaining time is sufficient to transfer the message. Since the contact is active already, t_{wait} is set to 0 s and t_{start} is therefore set to 2 s instead of 0.1 s as specified in the list.

Subsequently, all active contacts of node A are processed. This includes a direct connection to the destination node D that starts at 11.4 s and would result in a delay of 13.4 s. However, this is not the delay-optimal path even if it is optimal in terms of the minimum number of required transmissions.

After processing all outgoing edges of node A the next node with the smallest t_{rcvd} is selected (indicated by the blue circle). In this case, node B has the lowest value. When checking the active edges, it becomes obvious that no further nodes have to be added. But all edges update t_{rcvd} of the respective nodes. This is indicated by canceled values. Besides that, the edge pointing to node D already provides the delay-optimal path. However, at this point in the processing it is not clear that there are no other paths with lower values and thus the algorithm continues until node D is processed.

When processing the edge from $C \rightarrow D$, t_{rcvd} is not updated, as the edge does not provide a faster path. Finally, the edge from $F \rightarrow D$ is omitted, because the contact ended before F received a copy of the message.

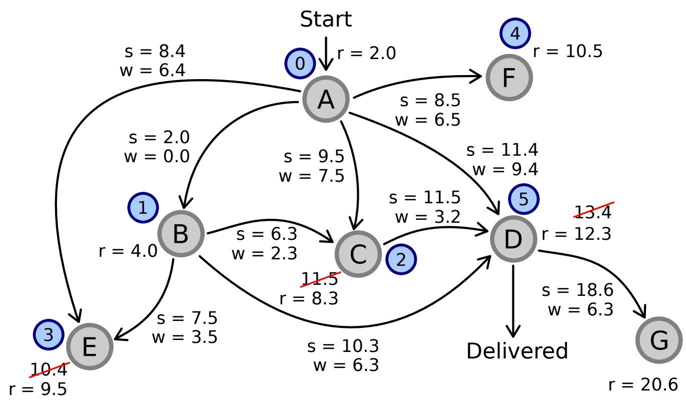


Figure 4.3: Visualization of the resulting forwarding graph for a message from $A \rightarrow D$ with details on each algorithm step

Based on $t_{rcvd}(A)$ and $t_{rcvd}(D)$ the delay is calculated at the end of the graph construction process. The corresponding path is then calculated using a variant of Dijkstra's algorithm. The required adaptation is the representation of the passed time or delay as an edge weight ($weight(e_{u \rightarrow v})$). To obtain the introduced delay of an edge Equation (4.4) is used.

$$weight(e_{u \rightarrow v}) = t_{start}(e_{u \rightarrow v}) - t_{rcvd}(u) + t_{trans}(e_{u \rightarrow v}) \tag{4.4}$$

In case of the example in Figure 4.3, the overall delay is 10.3 s achieved by the path $A \rightarrow B \rightarrow D$.

4.4 Extensions to ONE

ONE is the de facto standard tool for DTN-related protocol analyses and already provides several implementations of well-known protocols. However, it lacks some features that are discussed in the context DTNs applied to disaster scenarios in order to potentially enhance the overall network performance. In Section 3.3, an application providing realistic traffic patterns has been introduced. Beside that, two features are of special interest: one is related to message ferries with controlled mobility and the other one provides means of addressing nodes using EIDs as defined in the RFC. These features allow detailed analyses of multicast traffic that is required for group communication within rescue teams and the impact of additional dedicated nodes on the network including the interaction with routing protocols.

This section will provide details on the two additional features that were developed as student thesis projects [62, 135].

4.4.1 Correlated Ferry Movements Module

Message ferries and corresponding control algorithms that are able to adjust the traveling characteristics of the ferries to the current communication needs of other nodes in order to enhance the global network performance have been an active field of research for years (e. g. [59, 143, 176]). Especially if the approaches are related to UAVs, they are frequently presented as an option to enhance the connectivity [153] or communication opportunities in DTN-based communication systems for disaster scenarios. However, these approaches are evaluated either analytically based on *Traveling Salesman Problem* variants or using custom simulation tools [58, 59, 143, 145] without any link to the related networking aspects . These aspects have been studied experimentally in the UAV community, e. g. in [1, 5, 60].

The interplay between contact availability, routing decisions of dedicated DTN protocols and message ferry movement decisions has not been evaluated, because on the one hand *DirectDelivery* is usually assumed as the only routing option for the ferries. *DirectDelivery* routing in DTNs assumes that the nodes in question have to meet physically to deliver a message. Therefore, no additional intermediate relays are involved and thus in case of message ferries additional routing protocols on the ferry itself are not considered/required while still covering the characteristics of the *Traveling Salesman Problem*. On the other hand, network simulation tools do not support the required context-based dynamic movement model.

Such a movement model serves two purposes. Firstly, it allows the node to dynamically adjust its path based on the decisions from a message ferry algorithm and secondly, it can provide movement-related context-information required for the decision making of the message ferry algorithm. To consider these aspects in the analysis of first responder communication is interesting because in such scenarios controlled movement at least of a subset of nodes is available. Fire fighters in Germany can use for example human messages dispatchers. The task of any fire fighter in this dispatcher role is to move towards currently unreachable groups and collect/deliver messages to them once within communication range. Essentially, this is a message ferry dedicated to aid the communication within the network. Therefore, such concepts can play a vital role when analyzing first responder communications and should be available within the simulation. To enable this, ONE was extended by a *ContextualMovementModule* that supports both the context-based movement and in order to select the next destination based on that context the integration of message ferrying algorithms [62, 88].

Traditionally, there is only a unidirectional interaction between the simulation engine and the configured mobility model, in which the mobility information is fed into the simulation. This has to be changed, in order to allow context-based movement decisions. In this case, two types of information are needed from the simulation within the movement model. The first is related to messages that are currently stored within the message buffer of the node. This information is used to determine potential target nodes to visit next. Second, some information regarding the position and planned trajectory of other nodes in the network is required, in order to find a valid path towards them.

Based on this preliminary consideration, the question is how to obtain this information. This is simple for the messages within the node buffer, as this is local information and should be accessible in real-world systems as well. For movement-related information, there is an easy way to obtain the needed values for simulations. Since the simulation environment is aware of all nodes, it allows access to all properties of the nodes including the movement model. This allows an access to the current positions and optionally future way-points depending on the mobility model currently in use from within the simulation using the appropriate interfaces.

However, in a real-world scenario this will not be possible, as nodes might share their current position, speed, and direction upon contact only. In case of first responder scenarios, there is an exception that is relaxing this a bit and justifying the chosen simplification. The coordinators have ideally an almost complete knowledge of approximate positions of all teams as part of their situational awareness. This information could be provided to any kind of message ferry as well and represent the knowledge of the simulation engine.

The following steps are performed whenever the ferry has to select the next target [88]:

1. Collecting information on currently buffered messages from the routing module of the ferry
2. Selecting a target node based on the message ferry algorithm
3. Estimating the position of the target node
4. Calculating the path towards the target node

The first step is related to the locally collected buffer status information. This could include further information, if that is required for the chosen algorithm in step 2. Afterwards, a message ferry algorithm determines a set of possible target nodes and chooses one of them. Based on the available positioning and trajectory information, the target rendezvous position is calculated including a valid path to reach this position. These steps have some interdependencies but are designed as separate components. Especially the components to calculate the position as well as to determine the next node are designed in a modular way, allowing further extensions and easy integration of further algorithms. Figure 4.4 shows the components related and its interaction with other modules in ONE. The *ContextualMovementModule* itself is implemented based on the generic movement model templates in ONE and thus ensures that it can be configured like any other movement model.

It should be noted that the current implementation does not include any dedicated

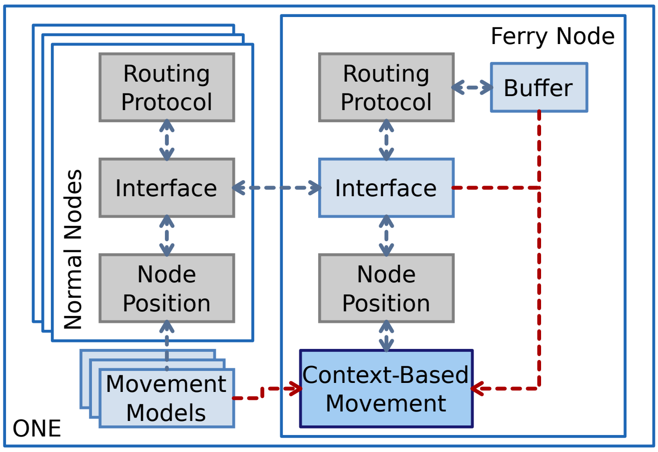


Figure 4.4: Components and Interactions of the ContextualMovementModule

ferry algorithms. Instead some simple rules are implemented to select the target node. The following options are currently supported:

Random selects a random target either based on message receivers or all known nodes.

Closest selects the closest node that is not within communication range.

Most messages selects the receiver with the highest number of messages for delivery.

While these rules are simple, they already cover several interesting use cases and thus allow first evaluations of message-correlated ferry movements. The selection from all known nodes is for example useful if the message buffer of the ferry is initially empty. The same is true for closest nodes. In addition to the initial state, this might also be useful to collect messages along the path.

Other options to select the target node could include a message priority or time critical messages that are likely to miss the deadline if not forwarded next. These variants are currently not supported in the implementation because ONE does not fully support the required message fields. Besides the simple selection rules, future work should include the integration of dedicated message ferry algorithms (e. g. as described in [143]).

Compared to other ferry algorithm evaluations, the movement model considers two additional parameters that can have a significant impact. The first one defines a threshold value to the target distance. This allows the ferry to move within communication distance of the target and already start to transmit messages as soon as the link comes up for better contact utilization. The second parameter indicates, whether the ferry stays at the target position or follows the target node until all transmissions are finished. Again, this helps to better utilize the contact. Traditional evaluations usually do not consider these parameters for simplicity reasons (e. g. [143]).

4.4.2 Host EID Addressing Module

Finally, ONE is extended with a module that enables simulations to use EIDs as addresses instead of simulation-internal node identifiers. This module was designed and implemented during a master project [135].

The goal was to support RFC-compliant addresses for DTN nodes in ONE because according to the RFC specifications [29, 142] there are multiple options to use an EID address. These are the description of a single node (singleton) and the description of a group of nodes. Besides that, each node can be part of multiple endpoints and thus react to multiple EIDs. Each node has to be identified by an EID of the singleton type [142] which corresponds to a unicast address and the internal node ID used so far to identify nodes. However, the multicast-like group communication as well as the assignment of multiple addresses to a single node is not supported in ONE.

To fully support these features, the Host EID Addressing Module was developed. It enables proper EID-based addressing schemes and supports different address-based communication schemes. For each scheme a specific prefix is defined for the EID identifying the address type. This is needed to allow an easy lookup at the routing protocol and is fully RFC compliant, as this specification allows arbitrary scheme-specific definitions after the initial „`dtn://`"notation. Table 4.1 shows the supported schemes and corresponding prefixes.

Table 4.1: Communication Schemes and Defined Prefixes

Type	Prefix
unicast	`dtn://uc.`
multicast	`dtn://mc.`
anycast	`dtn://ac.`
broadcast	`dtn://mc.ffff`

Except for the broadcast scheme, all other schemes are followed by further information in order to build a valid EID. In case of unicast, the internal node ID and a configurable number of preceding zeros is used to ensure unique addresses for each node. The remaining two schemes end with a freely configurable alphanumeric string identifying the group of receivers in question. This string has to be unique as well and is checked during the initialization of the simulation. Actual group assignments are currently done via manual configurations but could be extended to dynamic multicast group management approaches (e. g. as described in [13]), if required. All nodes are members of the broadcast scheme per default.

Figure 4.5 shows how this concept was integrated into ONE. In order to enable the usage of addresses, the nodes themselves as well as the message data structure were extended accordingly. To allow a configurable usage of the addressing module, a new version of the message class was derived featuring source and destination EIDs instead of internal node identifiers. Besides that, the required configuration options were added. To fully support the different address types, the routing protocols had to be adjusted as well. The available protocol-specific features of currently supported routing protocols in ONE are implemented in separate classes each derived from one common base class. This base class also handles all address-related features of the nodes and is therefore extended to handle EIDs.

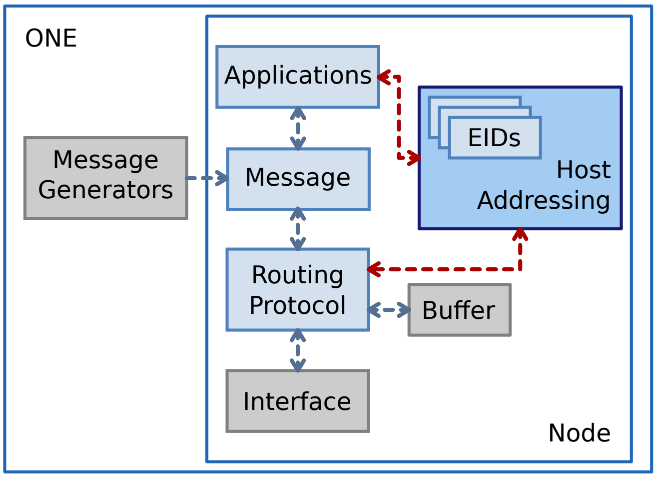


Figure 4.5: Components and interactions of the host EID addressing module

In case of pure unicast traffic between nodes in question, this module does not provide any advantage over the existing implementation. On the other hand, it does not introduce any disadvantages in this case either. The benefits become obvious when dealing with group or multicast communication.

Multicast communication requires that a message is delivered to multiple receivers belonging to the same group simultaneously. Using the existing addressing features of ONE this is not possible with a single copy of the message or requires custom protocols and applications (e.g. [17]). If custom protocols are not an option, the alternative is to create one separate copy of a multicast message for all receivers. Therefore, sender or message generator has to know all potential recipients beforehand. This has two major drawbacks. First, the number of recipients might not be known locally at a sending node, if the group memberships are dynamic. Second, the impact of other constraints of the simulation such as the available bandwidth or buffer size is more severe or has to be adjusted if copies are sent for each recipient in parallel instead of creating such copies only if required. Both aspects can lead to inaccurate simulation results. This is especially crucial if buffer management strategies are of interest [15, 16].

With the presented extension and the according routing protocols, it is possible to efficiently and realistically model multicast traffic.

4.5 OMNeT++ Extensions

In order to allow an interchangeable evaluation using two separate simulation tools that produce comparable results, two aspects should be considered. On the one hand, the setups and evaluations should be as similar as possible and on the other hand in cases when one tool allows more detailed results related to specific aspects these results should be available for further evaluations in the other tool to benefit from both. To ensure these aspects, externally stored files that contain the relevant trace information (e. g. movements, contacts, or messages) can be used to provide relevant information between the environments, if suitable import/export modules exist. This functionality was integrated into ONE by design [76], while OMNeT++ provides modules to import movement traces only.

In case of OMNeT++ simulations, the evaluations focus on more realistic underlying network characteristics and their impact on the overall network performance. Therefore, the resulting contacts are one essential trace that could enhance the level of detail in ONE. On the other hand, it is useful to run both simulations with the same message load. This can be achieved by providing an appropriate message trace to OMNeT++. Besides the import/export features, OMNeT++ was extended with a module that supports the simulation of realistic signal propagation characteristics based on 3D terrains. This allows to capture the effect that the terrain can act as an obstacle and thus causes irregular transmission ranges as well as contact durations.

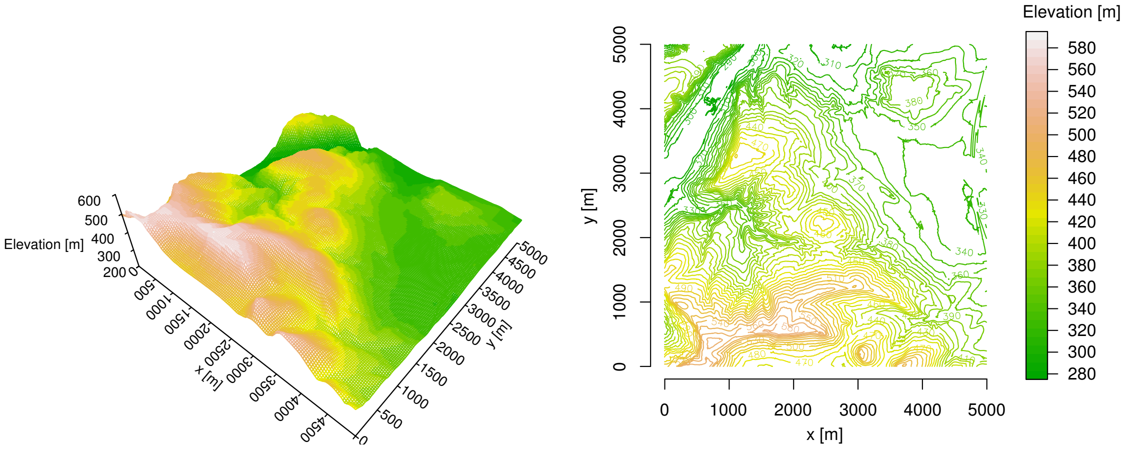
4.5.1 Terrain-Based 3D Signal Propagation Module

As the measurements in Section 2.3 showed, the terrain can have a significant impact on the actually achievable communication range of nodes. Especially in rough terrain with a variety of hills, mountains, and valleys this impact can result in more frequent disruptions and uncommonly short direct communication options. This is a crucial effect in any distributed scenario in rough terrain such as the SAR scenario (cf. Section 2.1.2) and where the communication to the central coordination can get blocked by the terrain features. If this happens, first responders have to relocate to find a suitable communication opportunity, which can consume too much time if human lives are at risk.

However, terrain impact on communication is usually neglected during simulative studies. Such simulations assume homogeneous propagation characteristics in all directions unless obstacles are specifically modeled. The propagation characteristics introduced by terrain features are, however, not regular or homogeneous. Besides that, these aspects are difficult to model via the existing options to specify obstacles. As a consequence, traditional simulations provide too optimistic results. Figure 4.6 compares the plot of an example 3D terrain and a 2D contour plot of the terrain used to describe the scenario in Section 2.1.2 in Wipfratal, Germany. These figures already show a high potential of blocking terrain features due to the variable terrain surface.

Other options to calculate the impact of 3D-terrains are to model the terrain and calculate the propagation characteristics offline for each possible position on the map [74] or analytically [161]. These approaches are useful for static scenarios and confirm the impact of realistic terrain features presented in Section 2.3. However, it is infeasible for scenarios with mobile nodes, as the maps would have to be calculated whenever a node is repositioned. To achieve this, the terrain should be integrated into the simulation tool and be considered during the calculation of propagation conditions. As mentioned before, one implementation of this feature was presented in [48, 49] for ns-2 based on Durkins propagation model [40]. This approach uses the calculation of Fresnel Zones under *knife edge* diffraction to the calculations of the signal strength at the receiver in case of 3D obstacles.

While this approach fulfills the given requirements for realistic terrain simulations its usefulness is limited because ns-2 is not under active development anymore



(a) 3D terrain plot of the complete area **(b)** 2D contour plot of the complete area

Figure 4.6: 3D terrain and 2D contour plots of the area used to describe the example SAR scenario

and thus lacks the support for recent protocols or standards. Therefore, a similar approach is needed for a current simulation tool, if the terrain features pose an essential challenge for communications in the given scenarios. The module published in [113–115] and presented here is based on the mathematics described in the existing papers but is a unique implementation of the concept in OMNeT++.

To integrate a realistic terrain, geo-spatial data representing the terrain surface is needed. Several file formats exist to do this. In [48, 49], the authors verify their approach with simple artificially generated landscapes but already mention the Digital Elevation Model (DEM) format. Later, they enhanced their approach using the Triangulated Irregular Network (TIN) format [37] that allows a better approximation of the terrain with less data points.

Terrain models in DEM format are available for free from the US Geological Survey (USGS). Conversions to other formats are possible but require specific GIS tools. To avoid this, the DEM format was chosen [115]. It represents the terrain surface of a selected area as regular grid structure of 3D data points [150, 151]. One file usually covers an area of 7.5 minutes or larger in Universal Transverse Mercator (UTM) projection. The grid spacing between data points varies depending on the area covered by the DEM file. In case of 7.5 minute DEM files, it is approximately $30 \times 30\,\text{m}$.

One challenge when using a complete DEM file as basis for simulations is the large number of data points contained in a single file. This can be efficiently mitigated by extracting only those points that are relevant for the scenario in question and storing the elevation information only. Due to the regular grid, the (x,y) coordinates can be coded into row and column numbers if a reference position is known.

In order to calculate the impact of the terrain, it is crucial to estimate the power of a received signal in the presence of additional terrain-based obstacles. Obstacles and their impact on the received power are already supported in OMNeT++. Therefore, the terrain is modeled with obstacle-like objects with irregular shape that can block communications effectively if located within the Line of Sight (LOS) of any direct communication partners. However, the existence and exact location of the blocking terrain surface is unknown. Therefore, the calculation of the received signal strength needs to check whether there are terrain-based obstacles and if there are any, their impact on the propagation has to be considered. The steps described in Algorithm 2 are needed to estimate the received power between all nodes when considering the terrain features as potential obstacles [115].

Algorithm 2 Calculation of 3D Propagation

Input: DEMData file; AreaSizeX n; AreaSizeY m; RefPos pos;

Initialization :
import $m \times n$ data points from *file* based on pos
Estimate current 3D positions :
position nodes on (x,y)-plane according to the mobility model
for all nodes **do**
    identify the orientation of the terrain surface based on DEM grid points
    estimate 3D node position based on simple plane equations and projection on the (x,y)-plane
end for
Propagation Calculation :
detect obstacles along the LOS between nodes
for each node pair **do**
    move along the LOS in discrete steps
    for each position **do**
        estimate the terrain elevation
        calculate the *knife edge diffraction*
    end for
    estimate received power using *max(diffraction)* along the LOS
end for

Figure 4.7 shows the integration of the developed 3D terrain simulation module into OMNeT++. The core logic is implemented in the *Durkin Model* module representing a specialized path loss model based on Durkin's signal propagation model [40]. This module uses a *TerrainGround* class to access the geo-spatial data. *TerrainGround* implements a physical environment and loads and stores the relevant terrain data points upon simulation startup as configured using the *DEM Data* import module and provides information on the terrain surface as needed to the propagation module.

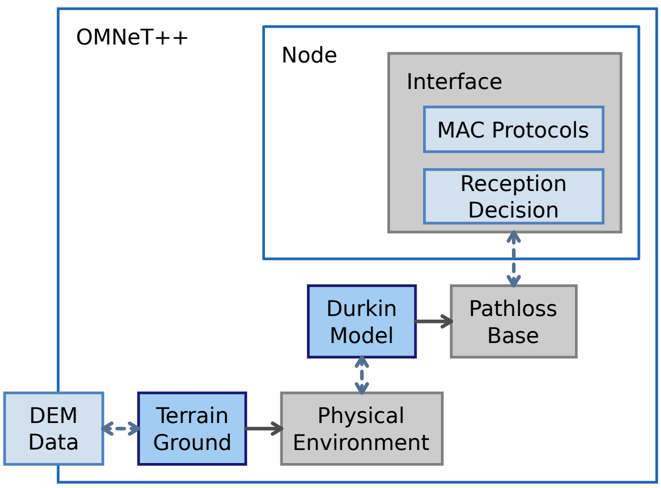
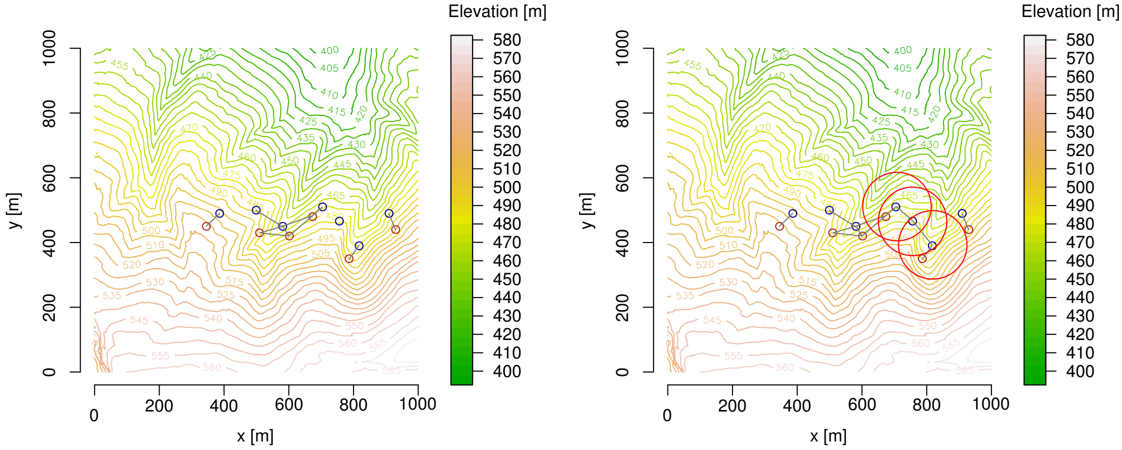


Figure 4.7: Structure of the 3D terrain simulation module in OMNeT++

The complete module was developed to capture the impact of a realistic 3D terrain surface on the communication. First results using DEM data from the United States of America showed that this impact can be significant if less direct communication opportunities are available due to the terrain features [112, 115]. Therefore, the results confirm the insights from the measurement campaign and the module now allows further analyses on the connectivity in rough terrain.

Figure 4.8 represents an zoomed detail area from Figure 4.6 including example node positions on the (x,y)-plane and a visualization of possible communication links that could be actively used in this case.



(a) 3D connectivity **(b)** 2D connectivity

Figure 4.8: Detailed contour plot with estimated node locations and available links based on 3D and 2D and highlighted difference due to the terrain

However, the module was not used so far to evaluate any of the presented realistic scenarios in more detail because the DEM data that is freely available for Germany from the USGS has a spatial resolution of 90×90 m, only. This grid allows a rather limited approximation of the envisioned terrain features and thus might limit the accuracy of the simulations. Besides that, the movement of the first responders is depending on the terrain features at the incident locations (cf. Section 2.1 and Section 3.2.2). Due to that, it is not reasonable to simply use movement traces created based on map data for a specific area in any other area as the correlation between the movement and the terrain would be lost.

In the first quarter of 2017 the government of the German Free State of Thuringia started to provide access to open geo-spatial data for public non-commercial use[1]. This also includes a detailed digital elevation model with a spatial resolution of 2 $\times$ 2 m and covers the whole state. Using this data would allow a corresponding analysis of the presented scenarios. Due to time constraints, this analysis will have to be part of future research and the provided data has so far only be used in R for plotting the diagrams in Figure 4.6 and Figure 4.8 to illustrate the relevance of terrain features.

1 http://www.geoportal-th.de/de-de/downloadbereiche/downloadoffenegeodatenthüringen.aspx

4.5.2 Contact Trace Export

From the DTN perspective, a contact is any communication opportunity between two nodes. Since traditional DTNs are overlay networks, the notation of a contact is not strictly bound to neighboring nodes within direct communication range. Instead, a contact could be any existing and potentially multi-hop communication path within the underlying network. Traditional DTN research often does not focus on this aspect and rather assumes that contacts have a point-to-point characteristic. This point of view results from the assumptions that the network is very sparse and that only few nodes meet at a time.

In disaster scenarios with the described team structure this traditional view does not hold. While one node can only communicate with one neighboring node at a time, multiple nodes can be within range or reachable via others. This multi-contact nature opens new possibilities and challenges [166] but has not been studied with respect to its impact on the DTN routing performance.

To allow a more detailed view on the actual contacts, two aspects of the underlying network are of special interest. The first is related to the actual point-to-point connectivity on the Medium Access Control (MAC) layer or L2. Here, the contacts mainly depend on the actual transmission characteristics of the chosen network access technology as well as the modeled channel characteristics. This can result in multi-contacts as well but on a rather local perspective and thus it provides a more realistic model than the default unit-disk model used in ONE. The second aspect that can be analyzed is the connectivity on the network layer or L3 which is not limited to the point-to-point connections, if a suitable L3 routing protocol is employed. In this case, direct DTN contacts between nodes with a valid route via multiple hops on the network layer become possible. While this is not surprising, it opens a new direction for routing research in DTNs as it enables a direct delivery between DTN neighbors even if there are multiple non-DTN nodes in between instead of requiring each hop to support DTN principles.

In order to evaluate both aspects, the corresponding connectivity events should be exported from simulations in OMNeT++ as a contact trace. This trace file could then be analyzed via the *OracleSolver* framework or used as input for simulations in ONE with all details available in OMNeT++. The INETMANET framework in OMNeT++ provides multiple implementations of well-known MANET routing protocols as well as IP-based ad hoc-capable WiFi nodes. The communication between different layers is modeled via messages and signals in OMNeT++. Messages can represent data or other protocol-internal events that trigger actions and signals are used either for logging/statistics or as cross-layer notifications. In case of possible contact traces, both versions to communicate are relevant. If contacts on the network layer shall be captured, all corresponding messages and signals that trigger a change in the routing table of a node are relevant. For layer 2 point-to-point contacts, this is not that easy. While the disruption of an ongoing communication is already signaled to the upper layer as *link break* signal, the detection of upcoming contacts is more difficult. To capture this, the successful reception of a frame from the physical layer is used as trigger to report a new contact. Figure 4.9 shows the resulting structure with the described options to capture the contact information on different layers as well as the modules that were extended to generate additional log messages (light blue).

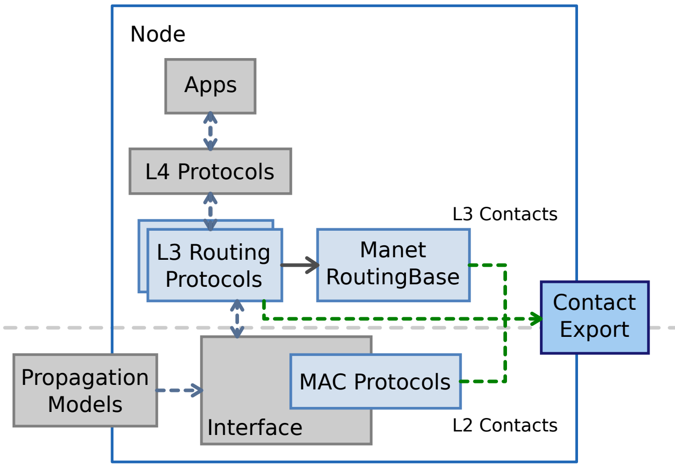


Figure 4.9: Integration of and interactions to provide a contact trace export feature in OMNeT++

The easiest way to generate a trace is to use the existing logging features. This feature provides an easy way to generate text-based trace reports of any structure with configurable log levels. The resulting event messages are then visible in the Graphical User Interface (GUI) or can be redirected to a file using the command line interface. Alternatively, the relevant event messages could be written to the console directly. The first option is chosen here because it also supports the GUI for easy verification.

Since the messages are generated via the logging features, the resulting log file will also include other messages. Therefore, the file is parsed afterwards using a *bash* script to extract the relevant contact-related messages with *grep* and *awk*. To enable this, an appropriate string was added to the log message. The result is a file that corresponds to the *contact trace* format described in Section 4.3.2.

It should be noted that the resulting contact trace in this case depends on the actual messages that are exchanged between different nodes due to the nature of the protocols employed and the decision to log successful receptions as initial contact information. Especially in case of reactive MANET protocols, an appropriate traffic generation is needed to trigger the route discovery process. The configuration of the traffic source has to ensure the required level of detail on contact information by selecting both sending intervals and destinations. Otherwise, the contact information gathered represents a snapshot of the actual underlying connectivity only, which can be misleading [168]. The same is true for chosen MAC protocols. If the protocol in question does not provide a default neighbor discovery mechanism, some traffic is required. One easy option to get a good representation of the overall connectivity is to use the available *ping* functionality between all nodes. If properly configured for any given scenario, this regularly triggers route requests and packet transfers between the participating node and thus fulfills the requirement to capture the contacts. On the other hand, this feature allows to capture rather local contact perspectives based on realistic traffic if the corresponding traffic is configured and reactive MANET routing is used.

4.5.3 Module to Import Message Traces

The previous module is used to export a more detailed and realistic view regarding available contacts in any scenario and thus allows further analyses in ONE or the *OracleSolver* framework. Instead of this, the goal of this module is to import messages generated externally (e. g. via ONE or recorded from the testbed) into OMNeT++ simulations in order to evaluate realistic traffic. Realistic first responder traffic could have been integrated by implementing the described first responder traffic model (cf. Section 3.3) into OMNeT++ as well. But since this module was already available including options to export the message trace, the additional effort seemed unnecessary. Besides that, an importing feature is not restricted to first responder communication. Instead, it allows to integrate any type of traffic.

Figure 4.10 shows the integration of the module into OMNeT++ simulations, again form the perspective of a single configured node. Similar to the implementation of the first responder traffic model, an application is used as the base for the implementation since it already provides the required functionality to send, receive and process messages and is able to handle node events such as the startup or shutdown. The main goal is to import the corresponding message trace file and send the messages at the appropriate points in time.

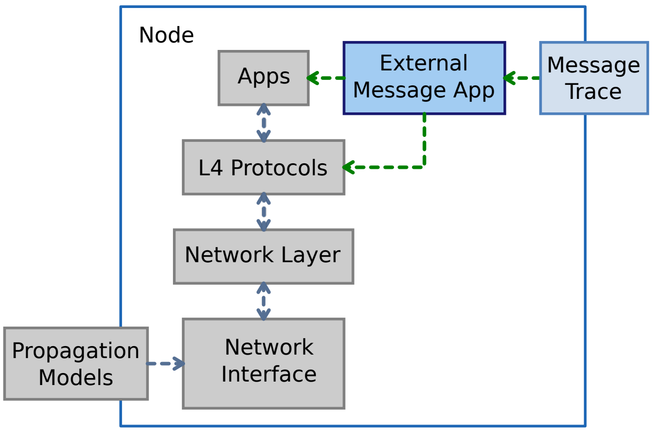


Figure 4.10: Integration of the message trace import application into nodes in OMNeT++

An externally provided message trace file is read from the file system during the initialization of any simulation run at each node that was configured with the application. It is possible to use only one trace file containing the messages of all nodes. To support this case, the initialization procedure at each node filters the messages for the corresponding node and stores them in a list and schedules the first message to be sent at the configured point in time. Once it is sent, the message is removed from the list and the next message is scheduled.

Besides the sending of messages according to the trace file, the application acts as sink for received messages. Upon the reception of a message, the delivery time stamp is written to the log and a corresponding signal is emitted. These values can be used for statistics collection.

Currently, the application messages are generated as UDP packets with the corresponding destination and message size. Further custom message header fields are possible, but not implemented in the current version. The same is true for other transport layer protocols and optional acknowledgements. While these features are interesting for further analyses or statistics, they are not required for a basic representation of the network traffic and corresponding load introduced by the trace file.

4.6 Outdoor Capable Testbed

All previously presented tools help to evaluate scenarios based on simulations or data generated via simulations. To capture realistic features, the tools as well as further models have to be configured appropriately. Even if this criteria is fulfilled, the models might still introduce simplifications to make the simulations more feasible and faster.

The first challenge here is to identify the relevant criteria affecting the performance of the communication system in the real-world environment. At this point, a real hardware test platform which can be used for measurements and evaluations of the envisioned scenario under real environmental conditions is a key tool to identify the mentioned criteria. In Section 2.3 such a measurement study was presented. It was carried out with a mobile test platform based on Raspberry Pi devices and embedded Linux as operating system as well as a notebook for control reasons. This section will introduce and discuss the developed platform in more detail.

4.6.1 Testbed Design Goals

In case of first responder ad hoc communication, the devices of such an envisioned system should be attached to existing equipment as far as possible [172]. Therefore, the device will be attached to the backpacks of rescuers or the harness of dogs in SAR scenarios. This requires that the nodes are portable and thus battery powered. The goal was therefore to develop a mobile outdoor-capable test platform that enables measurements and evaluations in outdoor settings as described in Section 2.3.

To achieve this, the test platform has to provide mobile nodes that are able to withstand harsh environmental conditions. Damage due to weather or shocks should be avoided by selecting a suitable case. Since the devices are carried by users, both the size and the weight of the equipment have to be considered as well. This also limits the size and thus the capacity of the battery. It should at least provide enough power for the complete search of one area. Especially, if the nodes are supposed to be carried by users and attached to other already present equipment, an option to mount the device is needed.

Besides these aspects related to the outdoor environment, the platform should provide means to analyze different communication options for a thorough evaluation. If heterogeneous and hybrid networking approaches are the focus of an analysis, both aspects should be supported by the chosen platform. In terms of heterogeneity, this means that multiple interfaces should be available, each providing connectivity via a different physical network specification. Ideally, such a platform is able to evaluate networks operating multiple access technologies at the same time and thus requires multi-homed nodes that are able to bridge the communication from the different networks. Besides that, different protocols required to setup MANETs and DTNs should be supported and ideally implementations of several well-known protocols should be available for comparison reasons. Finally, the platform should be designed to allow an easy extension of both hardware and software components.

Since the purpose is on evaluations and measurements, the platform has to provide tools that enable the observation of different relevant metrics. In terms of hybrid DTN-MANET approaches, interesting metrics are related to traditional protocol evaluation metrics like delay, packet loss ratio, throughput on higher layers, and contact/interrupt durations rather than received signal strength or other channel-related metrics that are commonly measured using testbeds. However, some metrics should be measured according to each protocol or mechanism currently under test. Besides that, details on communication ranges and movements that directly influence the contact durations are of interest.

4.6.2 Testbed Concept and Components

In order to fulfill the described requirements, popular Commercial Off-The-Shelf (COTS) hardware components were selected as base platform [81]. To build projects with embedded devices, different types of Raspberry Pi boards[1] are one promising option because there is an active community and many other components are either already supported or easy to integrate. A modular setup in terms of hardware components and software components is chosen to provide extendability and customization for different scenarios. Figure 4.11 shows a schematic view of all components. It should be noted that interfaces and sensors of the complete platform can be activated or deactivated as needed for a given test scenario.

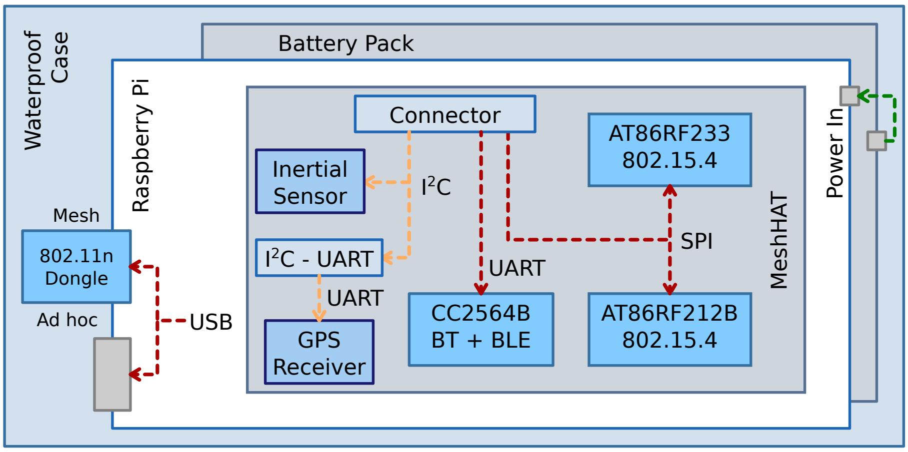


Figure 4.11: Schematic view of the designed plattform

There are however several additional points to consider in order to build the outdoor capable platform. Mobile devices require wireless communication and a battery as well as a suitable case. Raspberry Pi boards are typically powered by an external power supply. Fortunately, custom battery packs used to charge smartphones can provide the required power for the Pi boards, too. However, the size of such battery packs is usually suboptimal if it has to be placed into the case

1 https://www.raspberrypi.org/products/

together with the base board and possibly further extension boards. In this case, a flat version was selected.

The case poses another challenge besides the battery size. Since mirco Universal Serial Bus (USB) interfaces are used to connect the battery to the power supply of the board, additional space for the connector is required. Newer models (Pi 2, Pi 3 or Pi 1 A+) placed the power supply sideways and thus require additional space which could be avoided. Therefore, the basic platforms used here are Pi version 1 models B or A+ that come without any wireless networking interfaces. To attach such interfaces, USB dongles or dedicated chips with supporting circuitry can be used. Again both options require additional space. Finally, a dry box case was selected that is available in two sizes. In the smaller version, there is enough space for one Pi 1 model B board, the flat battery, a USB WiFi dongle as well as a GPS receiver. The bigger one provides enough space for multiple interfaces as well as one custom shield extension board and allows to fix all components securely and thus provide some shock protection.

Except the newer versions of the Raspberry Pi boards, these boards are not equipped with any wireless interfaces. To still enable wireless communication, external interfaces have to be attached. A USB dongle is used to provide IEEE 802.11 support. The driver for the dongle in question is capable to support both ad hoc and mesh operation modes. Especially, the mesh mode should allow robust MAC layer communication.

In order to enable the evaluation of further network access technologies, an extension board or Hardware Attached on Top (HAT) was designed to provide additional interfaces and sensors [22, 81]. This board is equipped with wireless transceivers for IEEE 802.14.5 and Bluetooth Low Energy (BLE) as well as corresponding jacks to connect external antennas for each transceiver. There are two transceivers for IEEE 802.14.5: one operating at 868 MHz and one operating at 2.4 GHz. The BLE transceiver was enabled by another student thesis [154]. With four different operational interfaces, the testbed provides a multi-purpose platform to evaluate outdoor applications for different network access technologies.

Besides the interfaces, the HAT is equipped with a GPS receiver and an inertial sensor to provide means for relative positioning [22]. Movement traces or tracks collected via the GPS receiver were used for the verification of assumptions in Section 3.2.3 and to evaluate the precision of GPS positions under various outdoor conditions. Regarding the inertial sensor, first tests showed that this positioning option is valid but needs to be combined with some cross validation [52]. Therefore, this option was not further exploited so far.

Besides the Raspberry Pis, a notebook is added to the testbed for control and measurement purposes. To achieve seamless communication with the Pis, the notebook is equipped with the same external USB dongle as the Pis with similar configuration. The relevant software tools for monitoring and measuring are described next.

Linux is used as operating system on all devices. In case of the Raspberry Pis, a customized embedded version of Debian 7.0 with Kernel version 3.18 (Raspbian Wheezy) is used. This operating system was extended with several drivers and kernel modules to provide support for all additional network interfaces. Each

Figure 4.12: Fully assembled Raspberry Pi node with casing

device has a default configuration enabling WiFi communication for configuration purposes via the notebook.

Currently, the platform supports measurements of transport layer throughput, network layer connectivity and delay as well as the capturing of on-the-air traffic via *Wireshark* on the notebook. These measurements are performed using built in Linux network monitoring tools such as *ping* and *iperf*. Wireshark allows to measure Received Signal Strength Indicator (RSSI) values of received frames as reported by the interface driver as well as contacts between the monitoring notebook node and other participating nodes within range if the traffic introduced via one of the other tools allows such an evaluation.

Besides that, the Raspberry Pis are configured to record their current positioning information and optionally live-transmit it to the notebook. Using these features, movement traces can be collected and live visualized as long as a connection between the two nodes is available. The transmission and visualization is done via remote *gpsd* access in *viking*[1], a tool to analyze and explore GPS data.

In addition to the described measurement and tracing options, the Raspberry Pis were enabled as DTN nodes [56]. To achieve this, the Raspberry Pi version of the existing DTN implementation IBR-DTN [38, 141] was deployed on the nodes. This enables the evaluation of DTN applications and protocols for realistic outdoor first responder scenarios using the different network interfaces of the platform.

4.7 Toolbox Discussion

This toolbox provides several extensions to existing well-known and accepted network simulators in order to combine their advantages and thus enable a thorough analysis of hybrid and heterogeneous networks. The simulators are complemented by additional tools that provide further insights in detailed aspects. The core of this concept is the exchange of different trace files characterizing the scenario under review that can be generated and used by the different tools of the toolbox. Such an interaction between different tools each with its own features

1 https://sourceforge.net/projects/viking/

and settings enables analyses on multiple levels of detail that were not available so far.

One example is the connectivity analysis in OMNeT++ which is now based on terrain features and tuned physical or MAC layer characteristics besides the pure node movement. The link characteristics, which are required to tune the interface properties, can be obtained from corresponding testbed measurements. These features directly impact the contact availability and allow more realistic representation of scenarios which has not been possible using only one simulator.

Besides these lower layer connectivity aspects, the possibility to capture contacts at layer 3 based on MANET routing information enables the analysis of hybrid DTN-MANET scenarios where nodes with and without DTN capabilities form a heterogeneous network. Especially the impact of present non-DTN nodes that provide connectivity on layer 3 over multiple hops and thus bridge communication between two DTN-enabled nodes can be analyzed using this feature.

These simulations in OMNeT++ with such a high level of detail are rather slow due to the high number of events to be processed. For typical DTN scenarios with a duration of at least several hours, the real-world runtime can be higher than the actual simulation time. However, the runs in question are needed only once per setup or configuration variant with respect to this lower layer interaction, in order to derive the corresponding traces. Once the traces are available, all other simulations and variations can be performed using ONE.

Simulations in ONE benefit from more details and the wide availability of well-known DTN routing protocols. Therefore, there is no need to re-implement these protocols as well as the bundle protocol [142] in other environments.

Besides that, the movement model extensions in ONE allow further analyses of strategies to enhance the connectivity for given scenarios. These strategies include additional nodes, utilizing any potential relay as well as dedicated message ferries. So far, analyses how the performance of routing protocols changes based on such strategies are open. Since any communication opportunity gets abstracted to contacts, heterogeneous networking technologies can be exploited as well.

The simulations are complemented by a more theoretical approach to derive the optimal forwarding decision offline. This tool does provide a lower bound on the delay and an upper bound on the delivery ratio. In addition to that, it also provides the intermediate forwarding graphs as well as details on the optimal path through the network. This enables further analyses on critical nodes or potential bottlenecks in the network.

Finally, a real-world testbed was developed which enables evaluations of various network access technologies as well as ad hoc communication protocols required for hybrid DTN-MANET approaches. First experiments with this platform showed the need for concepts handling intermittent connectivity and motivate the application of hybrid DTN-MANET approaches in first responder ad hoc networks.

CHAPTER 5

First Responder Scenario Analysis

After introducing realistic models for first responder scenarios and showing their feasibility as well as presenting the components of the developed analysis toolbox, these models and tools will be combined for further analyses of disaster scenarios in order to understand their characteristics as well as communication features. The base scenario for all analyses is the SAR scenario corresponding to the descriptions in Section 2.1.2 and Section 3.4.

In order to identify potential enhancements and future research directions for efficient communications in heterogeneous, hybrid first responder networks, existing protocols have to be evaluated. Therefore, the first part of this chapter will review existing MANET and DTN routing approaches and compare them with respect to their applicability to disaster scenarios. This includes a discussion of various protocol mechanisms that can provide useful features to fulfill the communication requirements of first responders. Besides the traditional routing protocols, this discussion is also extended on other hybrid DTN-MANET approaches.

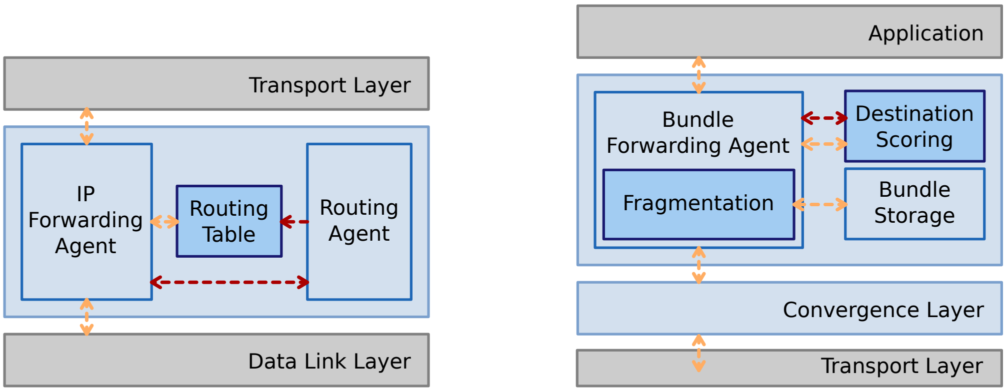
Afterwards, a subset of the discussed protocols is evaluated with respect to the requirements of first responders using the presented toolbox. The performed evaluations also include studies on the impact of several frequently discussed options to enhance the network connectivity. Such options are adding further nodes with different mobility characteristics or partially utilizing other network access technologies to enhance the coverage or data rates.

5.1 Protocol Review and Comparison

Before actually evaluating both the scenario itself and the protocols that could be applied in the scenario, these protocols have to be introduced, classified, and finally suitable protocols should be selected for the evaluation. This section briefly clarifies terms related to hybrid routing in the domain of hybrid DTN-MANET networks and then reviews protocols from each class. Based on a theoretical comparison considering specific aspects of first responder networks, candidates for the evaluation in the second part of this chapter are identified.

5.1.1 Definitions and Classification Options

First responders currently mainly use voice communication that is highly interactive. To some extend the interactiveness can be neglected if the communication system takes care of delivering the data in time to the destination without further interaction with the user. This process requires that the information gets recorded and stored at the source node and then the used routing protocol ensures a fast and reliable delivery through the network. In hybrid DTN-MANET environments, there are two sets of routing protocols that have to be considered in this case. Figure 5.1 illustrates the two traditional concepts, with the data plane in orange and the control plane in red. In both figures, the protocol stack is applicable to nodes that are end devices and routers at the same time and thus can generate and receive data at the application layer and act as relay for traffic from other nodes. This behavior is the traditional approach in MANETs and is useful in case of disasters as well because it allows to exploit any other device within the network as potential relay.



(a) MANET routing

(b) DTN routing

Figure 5.1: Comparison of routing principles employed in different network types for nodes that are end devices and routers at the same time

While MANET routing is Internet Protocol (IP)-based and operates on the network layer, DTN routing in conjunction with the Bundle Protocol traditionally operates between the transport and application layer based on names instead of IP addresses. One exception from this scheme is opportunistic routing. Protocols of this class operate at the network layer and are realized either as a hybrid approach that uses DTN-like principles or as a pure MANET approach exploiting broadcasting schemes.

To be hybrid, the routing approach in question combines two routing schemes in order to provide a better performance resulting from the advantages of the two basic schemes. This definition can lead to some confusion when applied to hybrid DTN-MANET environments as required for first responder networks. Figure 5.2 introduces a classification scheme for routing protocols in combined DTN-MANET environments.

According to this scheme, there are pure MANET routing schemes that already include hybrid MANET routing protocols as well as approaches to provide adaptive routing. The latter allows a node to dynamically select and switch the used routing scheme based on the current network conditions. In addition to these schemes, there are pure DTN routing schemes, again including hybrid routing protocols as a combination of several DTN protocols. Finally, there are protocols that combine DTN principles with MANET routing protocols. These schemes are

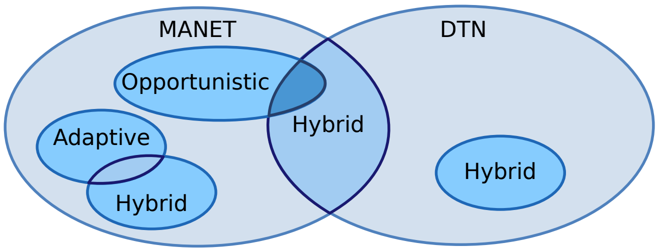


Figure 5.2: Classification of routing protocols in hybrid DTN-MANET settings

hybrid in the sense that they combine protocols or their mechanisms from both domains. According to the introduction above and the principles in Figure 5.1, these protocols require some cross-layer functionality and are of special interest for hybrid DTN-MANET environments.

Several routing protocols and frameworks have been introduced and discussed for each category. After discussing aspects that might help to build protocols for first responder communication, a selection of existing protocols from each category is reviewed and discussed in more details, before comparing them according to their applicability to first responder networks.

5.1.2 Specific Protocol Design Aspects in First Responder Ad hoc Networks

This section introduces several characteristics of first responder scenarios that might be useful for or should be considered by routing protocols applied to first responder ad hoc networks. Afterwards, the state of the art protocols are reviewed with respect to these aspects. Based on the communication requirements described in Section 2.2 and the scenario descriptions, the following points were identified:

- Movement patterns
- Traffic patterns
- Overhearing support
- Relay types
- Autonomous retransmission
- Multi path forwarding
- Partial delivery support
- Reliability-aware buffer management
- Message priority support

Especially in first responder missions, nodes move according to patterns (e. g. search formations), usually in teams consisting of several users as described in Section 3.2. The patterns are repeated throughout the whole mission and even if the nodes follow different movement types the pattern is followed by others. This in combination with the mission structure allows to exploit the underlying node movement characteristics of the first responders. Doing so, it can be avoided to forward messages to suboptimal relay nodes. Therefore, a forwarding mechanism that has to be able to recognize these movement patterns and take forwarding decisions based on knowledge about them, has to be developed.

Similarly, the traffic introduced by the first responders shows unique patterns like the parent-child relationship between team members and their commanders (cf. Section 3.3) or the merge of information into new packets at each hierarchical level. All messages are highly correlated to the underlying movement, because first responders will constantly report their findings during the active mission phases. In other phases (e. g. when resting or returning in Figure 2.3), they will generate less traffic. Forwarding strategies should be able to exploit irregular traffic distribution. Especially if message ferries are used, knowledge on expected traffic might be useful to select the most promising target positions according to this. In addition to these traffic-related aspects, nodes that currently do not introduce further traffic due to their current mission phase should be exploited as relay or mobile ferry.

Another feature that was described as a requirement in Section 2.2 is the capability to overhear communication from neighboring groups. While this is a security issue if unauthorized nodes are able to access the information, it is useful to reduce delay of the information spread in case of information that is relevant for all nodes in a certain area, independently of their location in the logical tree. Therefore, given that the required authorization and encryption procedures are applied to ensure the confidentiality of the information itself, a flooding or replication scheme that allows neighboring nodes to receive a copy of the message directly, would also be interesting.

The envisioned heterogeneous communication system described in Section 2.4 consists of multiple devices each supporting potentially different network access technologies that are either carried by the users or mounted on other equipment that could be mobile. This also results in a variation of the characteristics of the device in terms of relaying capabilities. Different relay types can be classified based on their movement characteristics, the available buffer space, or the power supply. Interesting movement characteristics are for example the speed (how fast can messages be delivered) and the question whether the movement can be influenced by current communication needs or the situation within the network. The latter point is crucial, because if the communication needs can be considered when moving, the node in question is actually a dedicated message ferry with controlled movement. Such nodes can actively aid the communication and thus effectively limit the delay. Forwarding schemes should therefore consider such differences and select the appropriate relay type.

To achieve the reliability requirements, the communication system has to ensure the delivery of the messages. This should be done ideally without any further interactions for the user, such as active relocation to gain connectivity or manually triggered retransmissions. Usually this requires an efficient buffer management that ensures that messages stay available within the buffer as long as needed. But even if messages have to be dropped due to limited buffer resources, an independent partial delivery of fragments (e. g. if a message had to be split into several packets at the convergence layer) potentially using multiple different paths will aid the overall mission success. Therefore, the forwarding approach should try to maximize the delivery ratio and thus support multi path as well as partial delivery schemes. The last option is especially interesting in environments with short contacts or error-prone links.

5.1.3 Review of Existing Protocols

After introducing the classification and discussing the design aspects that could be exploited to enhance first responder communication, this section will review several existing state of the art protocols from each classification category in Figure 5.2. The selection is exemplary and the discussion focuses on approaches either directly related/applicable to the given research question of this project or protocols that are well-known and thus used for evaluations later on.

MANET Protocols

Traditional MANET routing protocols get classified as reactive or proactive as well as a hybrid combination of these two schemes. This classification distinguishes protocols based on how the routing information is collected. Reactive routing searches for potential routes only, when an application requests a data transfer to a given node. Therefore, the routing schemes *react* to a given request on demand. The alternative is proactive routing, where all participating nodes periodically exchange routing information independently of any ongoing transmissions.

Ad hoc On-Demand Distance Vector (AODV) [121] routing protocol is a popular example of reactive routing. Once an applications asks for a data transfer to a node and there is no valid route in the routing table of that node, it sends a broadcast Route Request (RREQ) message in order to find a path to the destination of the message. This RREQ gets rebroadcasted by other nodes until it reaches the destination or another intermediate node that has a valid route to the destination. If a route is found, the corresponding node replies with a unicast Route Reply (RREP) message to the originator of the RREQ along the discovered path. All intermediate nodes are thus enabled to learn the route to this destination as well. One drawback of this approach is a larger initial delay that is required to setup a route upon the first usage.

AODV was enhanced and extended to fit several other specialized use cases. One extension developed by the Internet Engineering Task Force (IETF) MANET routing group is *Dynamic MANET On-demand (DYMO)* routing or AODVv2 [122]. It uses the same mechanisms as AODV and additionally allows nodes to learn routes to all intermediate nodes of a newly discovered path in addition to the destination. However, the message format is different [122], because DYMO uses the generalized MANET message format specified in [30].

In contrast to these two protocols, the *Optimized Link State Routing (OLSR)* [31] protocol is an example of a proactive routing scheme. Here, nodes periodically exchange information on available routes with their neighbors. The goal is to first discover all nodes within the two-hop set of a node and then select few Multi Point Relays (MPRs) that can cover the whole two-hop neighborhood. Later on, the MPRs distribute the topology information to the relevant neighbors. This scheme usually can provide a route immediately when requested by an application at the cost of higher control traffic overhead. Another issue is a slow convergence, when routes become unavailable due to link failures or node mobility.

The *Better Approach To Mobile Ad-hoc Networking (BATMAN)* [73, 110] is another protocol that collects its routing information periodically. In contrast to OLSR, BATMAN does not try to gather complete routes. Instead, it determines which single hop neighbor is best suited as gateway for another node in the network. To perform this selection, each node periodically sends a message that it exists which is flooded throughout the network, ideally to reach all nodes. The gateway selection is based on how many such messages from the potential destination node are received by a single hop neighbor.

Examples of opportunistic routing protocols that exploit the broadcast nature of the wireless medium and additional context information are *Context-aware Adaptive Opportunistic Routing (CAOR)* [179] and *Sensor Context-aware Adaptive Duty-cycled (SCAD)* [178] routing. These protocols were developed at the same group and are very similar except for the context selection and the application use case. While CAOR focuses on MANETs, SCAD was designed for sensor networks. Both operate without beacons by exploiting actual data transmissions and the broadcast nature of the wireless medium. Based on multiple context information (e. g. location information, link quality estimations, and energy levels) both select the best forwarding node that rebroadcasts the message. CAOR uses mobility information in addition and an analytical hierarchical process to weight the context information. This allows the sender to receive a notification that the message was forwarded successfully and thus later use the relay for unicast transmissions. To limit the flooding, each node starts a random timer and stops it in conjunction with overhearing the transmissions from neighbors of the same message or sends the message if the node did not overhear another transmission. As a result, only the first successful transmission is considered for the forwarding.

Besides these specific protocols, there are also adaptive routing frameworks that allow the dynamic switching between different protocols. One such framework was developed as part of preliminary work to this thesis [50]. Here a simple switching algorithm was presented that allows to select either OLSR or AODV and does not require changes to the base protocol operation.

For all MANET routing categories, multiple other protocols were proposed, each with some specialization to one or the other scenario. These protocols are not discussed here, as they will not be part of the further analyses performed in this project. There, the focus is on exemplary evaluations of hybrid DTN-MANET approaches and implementations for the presented protocols are available in OMNeT++ and widely tested by the research community.

DTN Protocols

DTN routing protocols are designed to handle intermittent connectivity or large delays and thus do not assume a given end-to-end path between sender and receiver. To achieve this, DTN protocols employ different mechanisms compared to routing approaches in traditional MANETs that are designed for scenarios with continuous connectivity between the participating nodes or only short term disruptions due to failures [149]. In DTNs, the routing has to handle a certain amount of uncertainty when taking routing decisions. This is due to rather slow information propagation through the network thanks to the extreme operational conditions.

Typical mechanisms are therefore either flooding messages to all nodes, forwarding messages based on a utility function describing the likeliness of a potential delivery, or the prediction of future contacts. Figure 5.3 gives an overview of the three mechanisms, some subcategories, and example protocols for each.

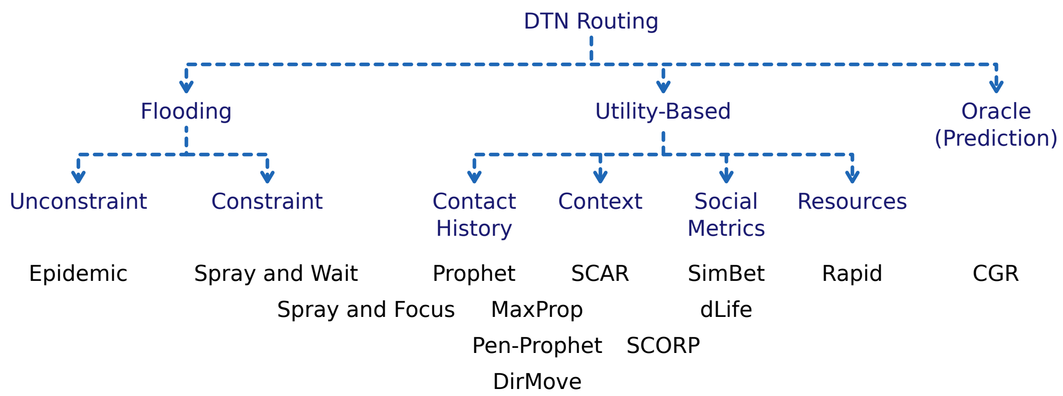


Figure 5.3: Classification of DTN routing protocols

Flooding is the simplest forwarding approach, where each node forwards the messages to any other node that does not have a copy already. The most prominent example is *Epidemic* routing [158]. Such a scheme consumes many resources, because all nodes have to store a copy of the message. This is problematic, because the buffer space is typically limited and thus requires a good buffer management in order to free buffer space without affecting the delivery performance. On the other hand, it allows the overhearing of messages by neighboring nodes that are not the intended recipients.

In order to limit the resource consumption, schemes to restrict the number of copies were introduced. *Spray and Wait* [148] is one example. The limit is enforced by configuring a maximum number of allowed copies. Once all copies are distributed, the message is delivered only if a direct contact with the destination is available. This distribution follows the *Direct Delivery* scheme. In disaster scenarios with sparse networks and groups of nodes (e. g. one search unit) with good connectivity, the number of copies has to be selected carefully to ensure that some copies can be forwarded to different groups.

To relax the need to meet the destination directly, *Spray and Focus* [147] was developed. It allows further forwarding of the messages, once all copies have been distributed. The message is forwarded only if the other node has a higher utility value. This scheme therefore combines flooding and utility function-based mechanisms. The authors in [147] argue that this scheme is better suited for sparse scenarios. However, the problem with nodes moving in groups persists even if the modified forwarding mechanism is able to mitigate it to some extend.

In case of utility function-based routing decisions, there are several options to build this function, each requiring a different set of additional information or metrics. The most common options are: contact history, available resources, context-based metrics, and social metrics.

Protocols using the contact history try to estimate the likeliness of future contacts based on observed historical contact information. Examples are Prophet [95, 96] and MaxProp [23]. The *Probabilistic Routing Protocol using History of Encounters* *and Transitivity (PROPHET)* or *Prophet* uses the history of previous contacts and a transitivity property to calculate the delivery probability for each node. If another node has a higher probability to meet the destination, the message is forwarded to that node.

MaxProp follows a similar approach, but here the messages are ordered according to a delivery likelihood metric. This metric represents weights assigned to a directed graph of contacts between nodes. Besides that, MaxProp uses acknowledgments to free buffer space, adaptive priorities for new messages and lists of traversed nodes in order to prevent flooding. MaxProp estimates the mobility characteristics of the nodes and tries to exploit them in forwarding decisions. This feature is interesting for first responder scenarios where the mobility shows distinct patterns that should be captureable.

The last two protocols of this category were specifically designed for disaster scenarios. *Priority Enhanced Prophet (Pen-Prophet)* [19] extends the traditional Prophet protocol by first classifying messages based on their content and assigning priorities according to predefined classes. Later, the messages are forwarded based on a utility value representing the traditional delivery probability of Prophet and this priority. The goal is to enhance the delivery of important messages by giving them more forwarding opportunities if the correct priority is selected. Priorities are one interesting feature in first responder communication, but the time constraints apply to all messages.

Finally, the *Direction of Movement based routing in DTN (DirMove)* [57] follows a similar approach as MaxProp. Here, the locally observed movement characteristics of neighboring nodes are integrated into the utility function. By integrating the direction of the movement, the authors try to avoid transmissions to nodes moving away from the destination. To achieve this in an effective way, the authors assume a given network setup with rescuers with movements constraint to specific areas, shelters with message stores places at fixed positions, a mobile backbone connecting the shelters, and a central gateway to the Internet. The goal of the routing is to deliver the messages to the known locations of the throw boxes and via the backbone to the gateway, if needed. While this is interesting in terms of identifying nodes moving away from the destination, the restriction on previously known locations that are not dynamic makes this protocol too specific to cover a wide range of first responder scenarios.

The *Resource Allocation Protocol for Intentional DTN (RAPID)* or *Rapid* [10] treats the forwarding decision as a resource allocation problem. It will forward the message only if the decision whether a gain in the utility value between two nodes is worth to spend the required resources is positive. The utility function used for the decision making can be designed to optimize a configurable metric (e. g. average delay, maximum delay, or missed deadlines). This protocol is interesting due to the resource management and the delay optimization.

A different class of routing protocols is based on social interactions and daily routines between the participating nodes. This is interesting because it reflects and exploits group structures similar to the team structure of the first responders. However, the time frame is usually completely different. Social-based approaches typically observe and exploit long term behavior, while in disaster scenarios the individual patterns might last a few hours or a week at most and individual nodes might be replaced by others with similar behavior at short term notice.

SimBet [32] tries to evaluate the utility value based on the similarity and the betweenness of nodes. Both metrics are inspired by social interaction of the nodes defining how similar nodes are (e. g. members of the same group) and which nodes are likely to move between different groups (betweenness). The metrics are calculated locally based on historic contact information that is also exchanged when two nodes meet. The utility function allows to tune the importance of the metrics using configurable parameters. SimBet uses a single copy of the message that is exchanged only if the other node has a higher utility score.

Another approach exploiting the social interactions of nodes based on their daily behavior is *dLife* [103]. The forwarding decision is based on two utility functions. If no information is available, the importance of a node in its social context is used. Otherwise, a score based on averaged contact durations between two nodes in certain time intervals over multiple days is used. This allows to exploit the social relationships during different times of a day. Such an approach might be useful in first responder scenarios if the duration of the time intervals can be adjusted to shorter periods of time in order to reflect different mission phases.

The context-aware protocol *Sensor Context-Aware Routing (SCAR)* [99] is designed to deliver sensor data gathered by mobile nodes efficiently to sink nodes, similar to SCAD. To do that, the nodes decide to forward a message based on an estimate of their neighborhood, the relationship to the sink and their battery level. This integration of multiple criteria is also interesting in disaster scenarios. However, due to the focus on sensor data offloading this protocol is not directly applicable to first responder communications.

The same authors as in [103] enhanced their scheme by adding content-awareness in the *Social-aware Content-based Opportunistic Routing Protocol (SCORP)* [104]. Besides the social metrics, additional nodes can be selected if they share the same interests. This feature might be useful for the overhearing capability. But predefined and static interests are not sufficient in dynamic scenarios.

The *Contact Graph Routing (CGR)* [24] is a protocol that was developed for space communications. Due to this setting, information about upcoming contacts and their duration is predictable based on the path of the satellites in orbit. Therefore, CGR has an oracle-like knowledge about contacts and exploits them by calculating appropriate graphs and forwarding messages along the best path based on the graphs. However, for most terrestrial settings, the assumption that all contacts are predictable does not hold and thus the approach is not applicable as is, due to the uncertainty in the contact information of a specific node.

Hybrid DTN-MANET Protocols

The last category that will be reviewed in more detail are existing routing schemes which are hybrid in terms of a combination of DTN features and a traditional MANET routing protocol. A classification of such approaches is presented in [127] where three categories are defined. However, due to partially overlapping schemes only two approaches are considered in the following:

- the integration of DTN mechanisms into existing MANET protocols and

- the combination of a specific DTN routing scheme and MANET protocols where the nodes can choose the current mode of operation.

The first class corresponds to the hybrid DTN-MANET protocols that can be classified as opportunistic protocols as well according to Figure 5.2. Such MANET protocols try to leverage the intermittent connectivity by adding the store-carry-and-forward principle and optionally features to generate multiple copies of a message as well as to select forwarders based on contact predictions [127]. The nodes store messages if no suitable DTN relay is currently reachable based on routing information collected by the MANET routing protocol in question. If such a relay is discovered, the message is forwarded according to the known route. This usually requires some changes to the route discovery and maintenance procedures of the MANET protocols.

One of the first hybrid approaches is presented in [118]. This approach combines DTN principles with AODV routing [121] for IP-based communication. The information required for DTN neighbor discovery and DTN routing metric exchange is piggy-backed to the normal AODV route discovery messages to save overhead. There is one exception to this if no route is discovered by AODV. In that case, DTN-enabled nodes create DTN-only replies to notify the source about potential DTN nodes that are reachable within the MANET partition. Depending on the availability of an end-to-end path to the destination, applications can choose between MANET or DTN operation or drop the message.

Delay-tolerant Dynamic MANET On-demand Routing (DT-DYMO) [78] uses DYMO as base protocol and identifies DTN relays based on the contact history using a similar approach as Prophet [95]. The DTN-related routing information is piggy-backed to beacons in order to limit the overhead and reduce the time required to identify suitable relays.

Hybrid DTN-MANET routing (HYMAD) [167] uses a distance vector algorithm to calculate routes in the connected case and Spray and Wait if there is no end-to-end connectivity. The distance vector algorithm relies on a periodic exchange of routing information which also includes information about DTN nodes. Spray and Wait is used for inter-partition communication between border nodes that act as gateway for one connected group.

BATMAN Store-and-Forward (BATMAN-SF) [33] combines a store-carry-and-forward scheme with BATMAN and was designed for communication in disaster scenarios. Here the authors try to stay compliant with the single copy scheme of BATMAN by using all mechanisms of BATMAN to forward messages and add an option to store messages if no suitable relay is within reach. Whether messages that are stored can be forwarded is checked whenever a new message or control packet arrives. This approach assumes the contact durations are longer than the interval for the periodic message exchanges of BATMAN.

In [126], an approach is described that can be integrated into any proactive MANET routing protocol. The authors discuss the integration of DTN and OLSR [31] or BATMAN, respectively. In terms of buffer management, a first-in, first-out scheme is applied that in addition deletes the oldest message if the buffer is full. This scheme has been evaluated using a dense first responder scenario modeled via the disaster area model [7]. The results show that hybrid schemes are able to enhance the delivery ratio for nodes in areas with frequent disruptions without degrading the performance of nodes in dense regions.

Hybrid Social Based Routing (HSBR) [100] finally combines the Dynamic Source Routing (DSR) protocol [72], a reactive MANET protocol similar to AODV, and a DTN protocol based on social metrics. To enable DTN-based forwarding, DSR is extended to collect the required information on the social relationship between nodes. If no end-to-end path is available, the last connected node of a path towards the destination is selected as DTN relay.

The second class of hybrid routing protocols combines both domains by forming a DTN overlay network at the application layer, where relays are selected based on a specialized DTN routing protocol if no end-to-end path can be found on the network layer. In some cases, the DTN routing protocols are also placed into the network layer as an alternative to traditional TCP/IP-based communication. This on the one hand allows the mitigation of intermittent connectivity and on the other hand mitigate congestion effects that can be introduced to lower layers by simple multi-copy DTN routing schemes. Approaches of this class also extend or utilize discovery mechanisms of MANET routing protocols in order to detect the presence of further DTN-enabled nodes within the given subnetwork. However, depending on a set of predefined metrics, the nodes are enabled to switch between both modes.

Such an approach was described in [92] where to authors present an adaptive routing scheme combining AODV and a DTN routing scheme. The nodes in this case are allowed to select the active routing scheme based on observed node density and speed of movements. This approach places the DTN routing as an alternative next to the MANET routing protocol on the network layer.

In [119], the authors present an overlay DTN network and use OLSR [31] on the network layer. This approach *Delay Tolerant Structured Overlay Link State Routing (DTS-OLSR)* corresponds to a combination of the two stack variants described in Figure 5.1. The routing table of DTN is used to identify potential DTN-enabled nodes and build a mesh network among the peer nodes. Similar to BATMAN-SF, a proactive routing scheme is chosen in order to provide information on possible DTN contacts a priori. The authors argue that this is essential to limit the initial delay required to check for active contacts in schemes based on reactive routing protocols.

A similar hybrid approach was introduced in [71]. Instead of a simulation-based protocol development, the authors present an implementation on hardware that enables smartphones to select between DTN and MANET operational modes. To perform the selection, the authors introduced a simple algorithm to switch the operational mode based on the current acceleration, battery level, and the number of neighboring nodes. However, they do not detail whether heterogeneous or non-DTN nodes are supported because their main focus is on the implementation of a switching mechanism on a device based on OLSR as MANET routing protocol and IBR-DTN [38] as DTN implementation.

All hybrid approaches presented so far support the participation of non-DTN nodes, at least within the given subnetwork. Whether they are able to benefit from DTN-based inter partition communication is often not described in detail.

Finally, the *Hybrid Routing System (HRS)* [102] represents a hybrid approach that actually provides means to dynamically access remaining infrastructure-based networks by forming a DTN overlay. Therefore, this approach handles heterogeneous network access technologies and allows to exploit all available communication options opportunistically. The authors combine efficient overlay-based routing and different DTN routing approaches. According to the classification in Figure 5.2, this approach is therefore a hybrid DTN-only variant.

Most of the presented hybrid DTN-MANET protocols are evaluated against the two base concepts only and not against other hybrid approaches. This makes a comparison with respect to the actual performance rather difficult. The result of a comparison against the base protocols provides only limited insights as the hybrid scheme should outperform both basic approaches under given circumstances, e. g. the pure DTN approach in case of dense scenarios and the pure MANET approach in terms of sparse setups. However, to fully understand the benefits from hybrid approaches they have to be evaluated in complex realistic scenarios and compared against each other.

5.1.4 Theoretical Protocol Comparison

Most of the protocols discussed in the previous section were designed for non-disaster scenarios and thus do not consider the special requirements of first responder communication. Therefore, applying them to disaster scenarios with the specific characteristics might not show the expected results. In Table 5.1, the discussed protocols are compared with respect to the design aspects introduced in Section 5.1.2. The table indicates which criteria and mechanisms are supported or considered by the protocols. Besides that, it also indicates whether implementations of the approaches are available for simulative evaluations and if so, which tool is supported. Part of this table was already presented in [85] when evaluating the applicability of pure DTN routing protocols for disaster scenarios. The current version was extended with the hybrid approaches.

While the pure DTN approaches already consider several aspects that are relevant for first responder communication, this is not the case for most hybrid protocols. This difference results from the design focus of most hybrid approaches which targets the mitigation of intermittent connectivity by adding the store-carry-and-forward mechanism. Only if a specific DTN routing protocol is integrated into the hybrid solution, this solution inherits the properties of the DTN protocol. However, these properties are only applicable to the DTN-enabled nodes. Due to the IP-based communication, these protocols can support partial delivery of fragments and utilize multiple different paths, if such paths are available.

Amongst the pure DTN protocols, none of the discussed protocols considers all aspects. The context-aware variants SCAR and SCORP consider most aspects followed by dLife. However, there are also some drawbacks of these protocols that limit their application to first responder scenarios. Due to its design as a protocols for wireless sensor networks, SCAR requires a distinct assignment of a role (sink, source, or relays) for each node. This is not applicable in the case of bidirectional first responder communication, especially for intermediate hierarchical layers. In case of SCORP, the interest assignment and the resulting multicast-like communication between all nodes sharing that interest contradict

Table 5.1: Theoretical protocol comparison based on considered design aspects in forwarding decisions

Protocol	Criteria: Movement Patterns	Traffic Patterns	Overhearing Support	Message Priorities	Multi Path Forwarding	Partial Delivery	Reliability-Aware Buffer Management	Relay Types	Autonomous Retransmission	Implementation
Opportunistic Protocols										
SCAD	X		(X)							N/A
CAOR	X		(X)							N/A
DTN Protocols										
Epidemic			X		X			(X)	(X)	ONE
Spray and Wait			(X)		X					ONE
Spray and Focus			X		X					ONE
Prophet	X		X		X					ONE
MaxProp	X		X	(x)	X		(X)			ONE
Pen-Prophet	X		X	X	X					N/A
DirMove	X		(X)		(X)					N/A
Rapid	X		X		(X)			(X)		ONE
SimBet	X									ONE
dLife	X		X		X					ONE
SCAR	X	X	X		(X)			X		ONE
SCORP	X	X	X		X			X		ONE
Hybrid Protocols										
DTN + AODV					(X)	(X)				N/A
DT-DYMO	X		(X)		(X)	(X)				OMNeT++
HYMAD			(X)		(X)	(X)				N/A
BATMAN-SF					(X)	(X)				N/A
DTN + OLSR					(X)	(X)				N/A
HSBR					(X)	(X)				N/A
Adaptive DTN + AODV					(X)	(X)				N/A
DTS-OLSR					(X)	(X)				N/A
HRS	X		(X)					X		N/A

the traffic patterns of first responders even though this might be useful in terms of overhearing. In addition to that, the duration of the reference periods is too large if first responder missions are considered, which typically do not last for several weeks. This is an issue for both dLife and SCORP.

Therefore, the DTN approaches considering most aspects are not applicable as is to first responder networks. None of the reviewed protocols considers all aspects and especially the hybrid approaches do not focus on delay minimization in case of intermittent connectivity. This leaves a potential for further enhancements of hybrid approaches that are able to provide both efficient routing in dense MANET-like scenarios with good connectivity and at the same time disruption-tolerance with acceptable delay based on the available resources.

The remainder of this chapter will present results from different studies to experimentally confirm this comparison and identify potential base mechanisms that are useful for the DTN part of a hybrid approach.

5.2 Comparison of Estimated Contact Durations

Since the availability of communication opportunities has a major impact on any routing protocol [64], this metric is evaluated first for different scenarios. In [133], the authors described several factors that influence the performance of heterogeneous networks. These are the network technology available as NIC on the devices, the employed routing protocols, and the link directionality or asymmetry. The last point is often neglected in simulative evaluations even though it could have an significant impact on real-world contact availability [77] in addition to different heterogeneous technologies.

Whether a contact is actually exploited to forward a message, is defined by the employed routing protocol. However, the protocols usually do not distinguish or have any information about the duration of the contact at hand. This can result in aborted transmissions if the contact was too short to complete the successful one-hop transfer. In Figure 3.6, the different contact distributions for different movement models were compared and first insights on the usefulness of contacts were introduced in Section 3.2.3.

In this section, the previously presented analysis will be enhanced by studying a combination of possible transmission ranges and corresponding data rates in order to identify the impact of different network access technologies on the contact availability in sparse first responder scenarios.

5.2.1 Contact Characterization Based on ONE Simulations

The values for the combination of transmission range and data rate usually correlate as the results of the outdoor measurement campaign (cf. Section 2.3.3) showed. At close range, the data rates can be higher while it is reduced in case of larger distances. To perform this analysis, the same simulation setup for the SAR scenario as in Section 3.4 is used in ONE with variations of the transmission range and data rate according to Table 5.2. The movement of the nodes is keep constant for all variations.

Table 5.2: Settings

Category	Range	Data Rate
Short Range	50 m	5 Mbit/s
Medium Range	150 m	2 Mbit/s
Long Range	200 m	500 kbit/s

This variation is needed because the evaluated version of ONE does not provide models to simulate varying data rates depending on the distance of two nodes. Figure 5.4 shows the contact distribution for all three configurations, again with red highlights indicating the range of contacts that are required to transfer between one data message and the total amount of data corresponding to the complete buffer size (relevant contacts). The tail of the distribution is cut at 250 s for better visibility. Table 5.3 gives the detailed values for the different contact categories and the corresponding time limits based on the buffer size, the message size, and the data rate for each type. The contact types are: *short* for communication opportunities that cannot be utilized because they are too short to transfer a single message, *long* for those opportunities that last longer than the time required to transfer the complete message buffer, and *relevant* for the remaining contacts in between.

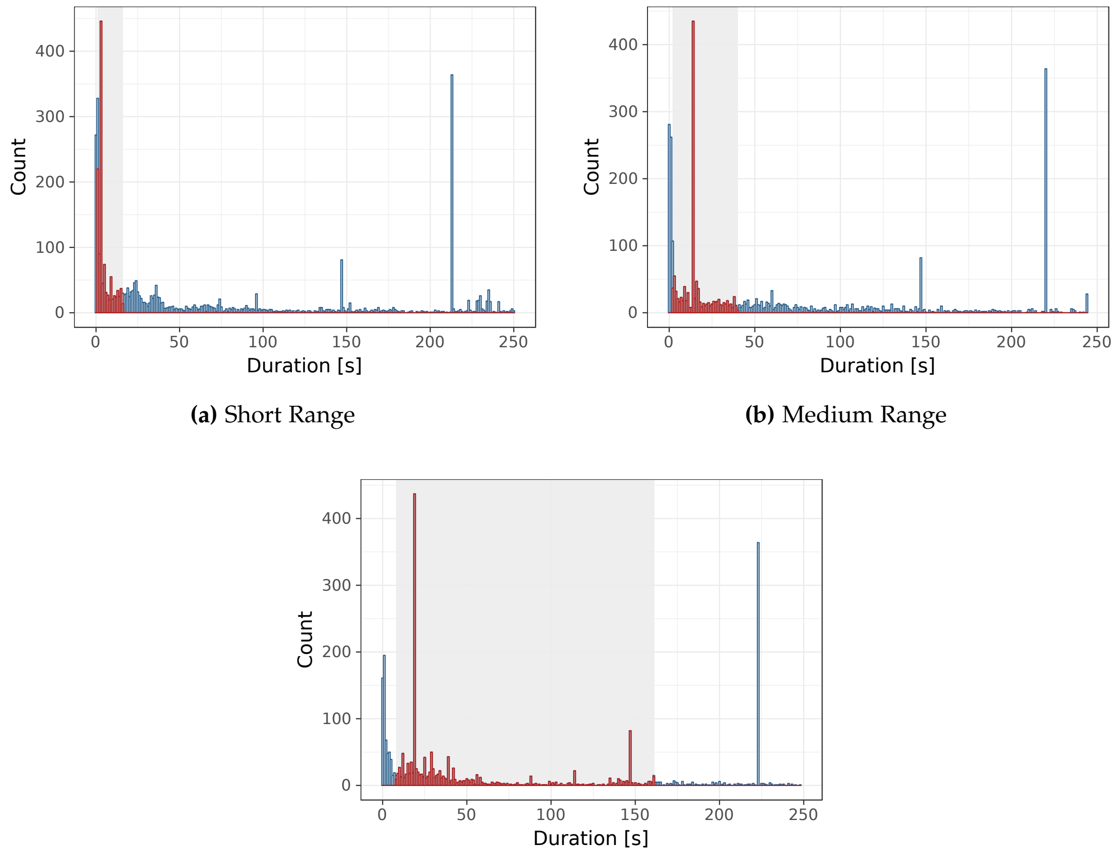
Table 5.3: Detailed Results of Contact Evaluation

Category	Contact Type				Time Limits		Duration
	Total	Short	Relevant	Long	Min	Max	Median
Short Range	8110	380	1189	6538	0.8 s	16.0 s	446.35 s
Medium Range	8356	608	1155	6588	2.0 s	40.0 s	642.5 s
Long Range	7889	601	1607	5681	8.7 s	161.3 s	714.4 s

As expected, the data rate has an impact on the duration of each contact type. The durations for relevant contacts follow this (red highlights) since for lower data rates more time is needed to transfer both a single message and the complete buffer. Rather unexpected is that this does not have a significant impact on the number of contacts in each category. The total number of contacts stays around 8000 for each case and the same is true for the number of relevant or long contacts. This results from reduced/increased communication ranges that again limit or enhance the time available for communication based on the underlying movements.

Using the simplified interface configuration that ONE provides, the presented results are rather optimistic. However, they already give a good insight on the correlation between contacts, communication range, and data rate. The medium setup achieves the most contacts, in total but cannot improve the number of relevant or long contacts significantly. In case of the long range setup the total number of contacts is somewhat reduced because individual otherwise shorter contacts remain stable for a longer period of time as indicated by the increased median value.

While short contacts are useless for the communication, the remaining two contact



(a) Short Range

(b) Medium Range

(c) Long Range

Figure 5.4: Distribution of contact opportunities based on different transmission ranges

types are the ones to be exploited by any hybrid DTN-MANET scheme. Long term contacts are of special interest for the MANET-based part as they remain stable for a longer period of time. The relevant contacts on the other hand should be exploited by the DTN part as these contacts represent scenarios with rather intermittent connectivity.

Similar contact evaluations are reported in [39] where the authors evaluated and modeled contact durations based on the communication range and movement directions of vehicular nodes. Their experimental results where obtained from a DTN testbed mounted on public transportation buses. The presented distributions also show a peak for short contacts and a long tail. Based on these results, the authors developed a model to predict contact durations for better message scheduling and priority management. Such a mechanism is required for hybrid approaches as well.

Based on the distribution of the contacts for the different modeled technologies, another fact becomes obvious. If all devices use the same technology and thus for a homogeneous network, a longer communication range is favorable over higher data rates that are only available at short ranges. Therefore, heterogeneous setups that provide long range, high data rate links as in infrastructure-based networks should be integrated whenever possible. These and other technologies with higher data rate should ensure that the contact duration is enhanced in order to benefit from the higher data rate. This could be done by integration additional nodes as described in Figure 2.9.

5.2.2 Impact of Detailed Layer 3 Contact Information

If hybrid approaches are employed, the simplified point-to-point contact information as provided by ONE does not capture any possible multi-hop contacts. These contacts are however relevant if non-DTN nodes are part of the network and can provide shortcuts to other DTN-enabled nodes and thus allow to mitigate delays. This depends on the MANET routing performance.

To evaluate this more detailed behavior at the lower layers, an additional study was performed in OMNeT++ with more realistic models for WiFi interfaces. The propagation conditions were fine tuned [131] to reproduce characteristics obtained via the measurements presented in Section 2.3.3. Besides that, the same external mobility traces as well as a suitable application that generates periodic traffic to trigger the route discovery process were configured. The route discovery had to be triggered, because the reactive DYMO protocol was used as network layer routing protocol. Proactive protocols would be better suited for this purpose but the simulations in OMNeT++ for a simulation of 3.3 hours are very slow. This is an essential problem of any more detailed simulation tool for opportunistic network simulations.

Finally, the developed contact trace export feature (cf. Section 4.5.2) was applied to capture the contacts. Figure 5.5 shows the resulting contact distribution. This version does not show any highlights for the contact classification because the data rate is now depending on the distance and propagation conditions.

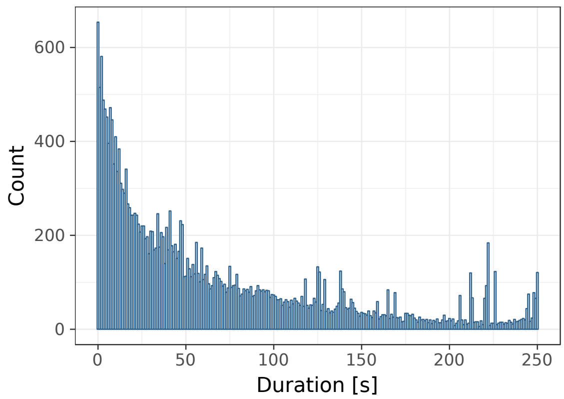


Figure 5.5: Contact Distribution considering direct and multi-hop contacts based on network layer information

Compared to the contacts obtained using the simple interface representation in ONE, these results show that there are actually much more communication opportunities in the underlying MANET. Such contact traces add therefore more realism to simulations in ONE.

The derived contacts now represent both point-to-point and point-to-multi-point communication opportunities that exist in parallel and capture efficiently the underlying MANET structure. This information has not been available for simulative evaluations even though the impact of this structure has been shown before, e. g. in [123]. These contacts represent the knowledge that a MANET routing scheme can provide as context information to the DTN routing approach as described in

Section 5.1.3. Therefore, the contact trace represents the base information on the underlying network and allows to integrate this information into simulations in ONE and thus some insights on hybrid approaches that are based on an existing MANET protocol and an existing DTN protocol in order to minimize the delay in the DTN part.

Besides that, the additional information also includes cases where one DTN node is in contact with multiple DTN neighbors at the same time. This aspect can have a significant impact on the routing protocol performance if it is considered by the protocols. In [166], the aouthors presented a first study regarding n to m contacts. The only protocol that should be capable of exploiting this aspect is HRS [102] due to its overlay structure.

5.3 Protocol Performance Evaluation and Comparison

After reviewing different protocols in theory, this section will present results from evaluations of the DTN routing protocols using simulation runs and the OracleSolver framework. This evaluation is limited to the DTN routing protocols because they have the most significant impact on the delay featured by messages that are exchanged between partitions. For connected subnetworks, it is assumed that the underlying MANET routing protocol is able to provide the corresponding routes within the connected zone and thus ensures a timely delivery of any message within the partition.

5.3.1 Evaluation Setup

To evaluate the impact of dedicated DTN routing protocols, the focus is again on sparse scenarios represented by the SAR scenario. The overall evaluation uses several parts of the presented toolbox despite the fact the simulations are performed in ONE. The scenario is build by combining a realistic mobility trace obtained via the pattern based movement model for a SAR scenario and the traffic is generated via the application according to the description in Section B.1. Besides that, the theoretical bounds for the performance in the defined scenario are evaluated using the OracleSolver framework.

ONE was chosen for this task, because it provides implementations for most of the protocols presented in Table 5.1. Out of the listed protocols in that table, the following protocols were considered for the evaluations: Epidemic, Spray and Wait, Spray and Focus, Prophet, MaxProp, Rapid, SimBet, and dLife. This selection covers the range of categories introduced in the previous section. In case of dLife, both the default version as well as a customized version with shorter time intervals were evaluated. Besides the discussed protocols, *Direct Delivery* was added as a benchmark protocol because it shows the worst case delay requiring the source and destination nodes to meet directly.

The first evaluation uses the contact traces reported for the previous evaluation in order to determine the impact of different technologies and thus contact times on the actual protocol performance. Later, only the medium range setup is used for more detailed evaluations as this provides still somewhat optimistic in terms of terrain and weather yet realistic setup as compared to the measurements in Section 2.3.3.

5.3.2 Routing Protocol Performance Evaluation in ONE

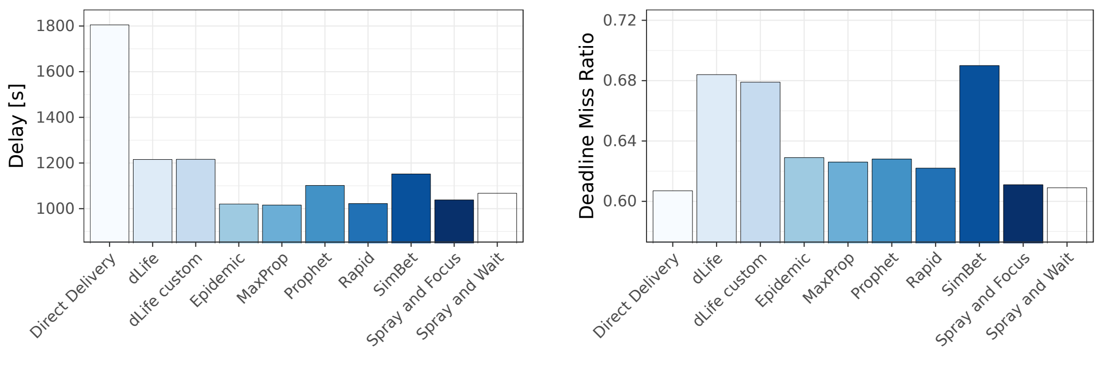
The first evaluations are related to the performance that is achievable using different protocols and how this depends on the communication opportunities discussed in Section 5.2.1. Throughout the evaluations, the deadline miss ratio ($ratio_{\ deadline\_misses}$) and total error ratio ($ratio_{\ errors}$) are calculated as metric to indicate the performance of the given protocols. This was done due to the distribution of delay values as presented in Figure 3.11. The long-tailed distribution with smaller peaks representing current mission areas at different distances requires different metrics than the common mean value. The deadline miss ratio is related to messages, that are delivered successfully but miss a given deadline and is calculated according to Equation (5.1). According to Section 2.2, 90 s are used for this evaluation.

$$ratio_{\ deadline\_misses} = \frac{num_{missed(90s)}}{num_{sent}} \tag{5.1}$$

Since the deadline miss ratio depends on the number of actually delivered messages, it is not representative without considering the messages that could not be delivered to their destination. Therefore, a second metric the overall error ratio considers both aspects. It is calculated as follows:

$$ratio_{\ errors} = \frac{num_{lost} + num_{missed(90s)}}{num_{sent}} \tag{5.2}$$

The mean value, even if it is misleading, is presented here to give an impression on the delays in the given scenario. Figure 5.6 shows the corresponding results of the average delay and the deadline miss ratio in the medium range setup for the SAR scenario.



(a) Average delay (cf. [85]) **(b)** Deadline miss ratio

Figure 5.6: Comparison of the performance achieved by different protocols in SAR scenarios

When checking the protocol performance using the medium range setup, it is obvious that Direct Delivery shows the worst delay as expected. Surprisingly, it shows the least deadline misses, which indicates that several messages can be delivered locally and the remaining ones experience a larger delay which should be mitigated. From the dedicated protocols, Epidemic and MaxProp show the best average delay. MaxProp is able to outperform Epidemic to some extend which indicates that the ability of MaxProp to predict and exploit mobility patterns which exist in the scenarios is useful for first responder scenarios.

The social based protocols show a significantly larger delay and deadline miss ratio than the other versions. This results partially from the metrics and the interaction patterns of the nodes in the scenarios. Since the teams move together and meet other nodes together, all nodes have similar social metrics and nodes with significantly different properties, that are able to interconnect multiple groups, are missing. In case of the customized version of dLife, the reduced timing intervals did not have a significant impact.

Based on these results, the following evaluations were performed with a subset of protocols (Epidemic, MaxProp, Rapid, Spray and Wait), only. Therefore, Figure 5.7 shows the impact of the combination of communication range and data rate for the subset.

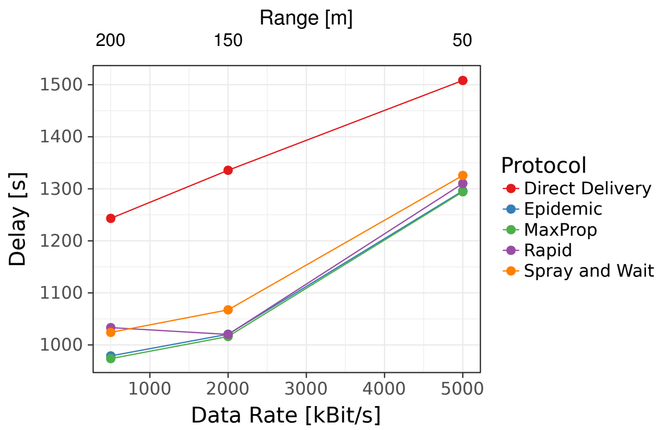
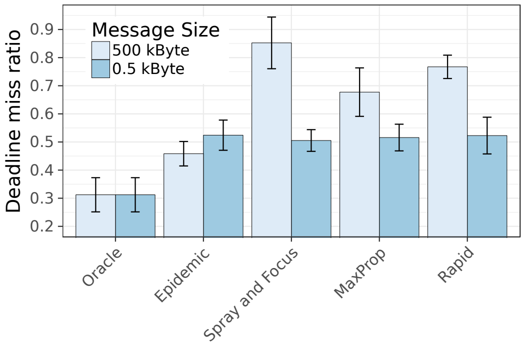


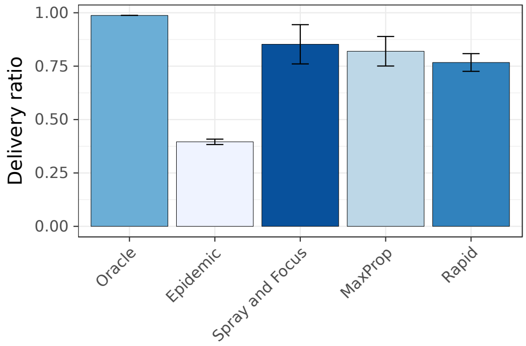
Figure 5.7: Impact of different access technologies and contact utilization [85]

When comparing the performance of the protocols under different contact distributions resulting from an approximation of different network access technologies, this result of the initial comparison is confirmed as all protocols show a similar trend. However, the resulting delays for the different technologies were rather unexpected. Surprisingly, the short range setup with higher data rates is not able to provide lower delays while the long range setup with a significantly smaller data rate is able to reduce the delay. This results from longer contact durations especially for rather short contacts that remain stable for a longer period of time while the high data rate in the first setup is not able to compensate for the shorter contacts. According to this result, the technology for first responder ad hoc networks should focus on long ranges and thus large coverage rather then high data rates at shorter ranges.

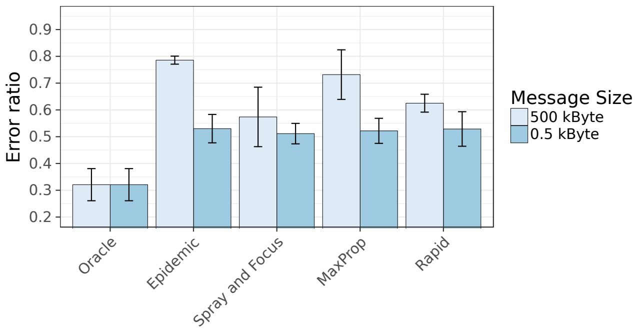
The selected protocols showed an average delay that is quite similar for the given message size with the same delivery ratio. This raises the question about lower bounds for the delay in order to verify further potentials to enhance the performance. Based on the reported messages and the corresponding Contact Trace, the OracleSolver framework was used to calculate this bound. Figure 5.8 shows the results comparing the protocol performance and the optimal solution



(a) Ratio of Missed Deadlines



(b) Delivery Ratio (500 kByte)



(c) Error Ratio

Figure 5.8: Comparison of the perfomance from existing protocols and the theoretically possible bounds (cf. [84])

for two different message sizes. Spray and Focus replaced Spray and Wait for the remaining evaluations because of the option to select further relay nodes once the initial copies have been distributed.

For all cases, the results obtained using the OracleSolver framework show a significantly lower deadline miss ratio and lower error ratio than any of the other protocols. This is surprising because the delivery ratio for the setup with small messages is the same for all evaluations. Even though, the optimal solution results in an reduced deadline miss ratio of 20 %. Mechanisms related to the buffer management cannot cause this behavior with the given constraints (10 MB buffer size and in total around 1000 messages of 500 Byte). This indicates that there is a potential to further enhance the routing decisions taken by the protocols. The error ratio of about 30 % for the optimal solution results from the number of messages missing the deadline that are considered as errors according to Equation (5.2).

In case of larger messages, this becomes even more clear. This time, the delivery ratio is quite different for all protocols, with Epidemic showing the worst performance. Based on this analysis, all evaluated protocols show a limited suitability for first responder networks and this does not result from the pure contact availability but rather from the capability to exploit the existing contacts.

5.3.3 Evaluation of MANET Protocol Contribution

Since the distribution of the delay shows a large number of messages that can be delivered quite fast, the next evaluation gathers insights on the MANET protocol performance. To do this, the movement traces as well as the message traces derived from the application in ONE were integrated into an OMNeT++ simulation of the same scenario. Besides that, OMNeT++ was configured once with the default WiFi-based ad hoc interface and once with a fine-tuned path loss model based on the measurements according to [131]. Similar to the contact evaluation, DYMO was used as example routing protocol.

Figure 5.9 shows a comparison of the number of received messages of the same scenario in OMNeT++ and the number of messages that can be delivered within 1 second in ONE or according to the OracleSolver framework.

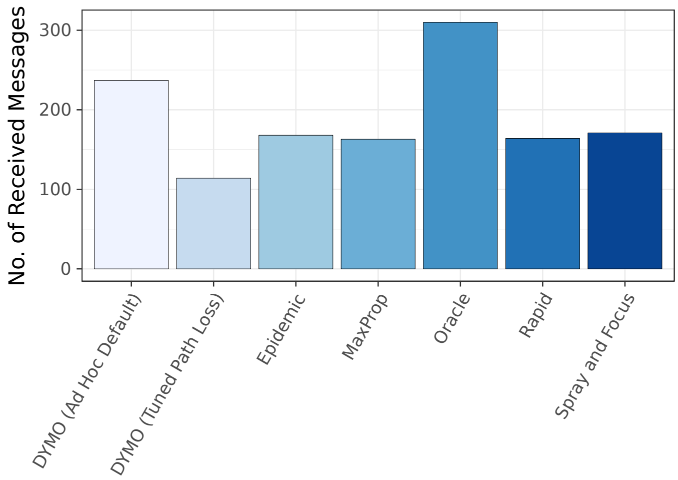


Figure 5.9: Comparison of messages deliverable via DYMO and in time deliverable via DTN protocols

The reduced number of messages in case of more realistic propagation conditions again indicates the importance of realistic scenario modeling, even if the more detailed tool is used. By adding a tuned path loss model the number of messages that can be received is reduced by 50 %. All messages in OMNeT++ are delivered within a maximum of 15 ms.

Compared to the pure DTN protocols, it becomes obvious that, many of the messages delivered within the first second are most likely messages, that could be delivered without any DTN features. However, the numbers are slightly higher than those of the pure MANET protocol and thus indicate that even these messages benefit from additional handling of intermittent connectivity. Since DYMO is a reactive protocol, some messages might be dropped because the contacts do not last long enough to establish a route on demand.

5.3.4 Discussion

The presented results so far strongly suggest to develop a hybrid DTN-MANET routing protocol for first responder ad hoc networks. Such a scheme is able to provide fast routing for areas with rather good and stable connectivity and still is able to handle intermittent connectivity. However, the results also show that simply adding a store-carry-and-forward mechanism to an existing MANET protocol will most likely not fulfill the timing requirements of first responders.

The same is true for approaches that switch between the two operational modes because these hybrid approaches relay on efficient route discovery on layer 3 and appropriate switching mechanisms. This leaves a scheme, where the DTN forms an overlay network on top of an underlying MANET. In this case, the overall network performance depends on efficient MANET routing providing routes to reachable DTN neighbors and on an efficient DTN protocol, that is able to select the best neighbor.

However, the analyses also show that pure DTN protocols are not able to perform well in SAR scenarios, representing a rather sparse version of the abstract model presented in Figure 1.1. This performance results partially from missing communication opportunities between different groups in the network. Therefore, the next set of evaluations targets common options to enhance the connectivity or provide further communication opportunities.

5.4 Impact of Additional Nodes

After evaluating the base scenario, it is clear that none of the evaluated DTN protocols is able to ensure a timely delivery due to missing communication opportunities. One solution to this is the addition of further relay nodes, that enhance the connectivity between the participating nodes. This section will first review different options to do this and then evaluate the impact of such nodes on the overall network performance.

5.4.1 Possible Types of Additional Nodes

There are in general two options to deploy additional nodes: to place *static* nodes at fixed positions or to employ mobile nodes. The first option applies to any equipment that is dropped at given locations. In the second case, the node is usually mounted or carried to some extend.

If equipment is dropped at given locations some difficulties arise. One problem are limited resources in terms of equipment and staff members to guard or place it. If any deployment has to take place, this has to be integrated into the normal operation processes of the first responders and cannot be an extra requiring careful node positioning [171]. Any equipment placed within the area cannot stay unattended as it might be stolen otherwise. This again requires valuable staff resources that might not be available or have to fulfill other more important tasks.

Besides that, the equipment has to be re-collected after the mission or during the mission if relocations of the teams in question occur. This again causes additional effort to the first responder tasks that should be avoided, ideally. Therefore, this option is mainly interesting for small scale events like burning buildings. However, even for other incidents the placement of a few nodes can be helpful.

In contrast to this static deployment, there are two options to integrate mobile nodes. Any mobile node that is enabled with DTN capabilities is able to act as a message ferry, by collecting and physically transporting (carrying) messages. These nodes act as message ferries.

The first option are nodes which are able to control their movement to actively enhance the communication. Such nodes can relocate and move based on the communication requirements and thus provide a *dynamic* service. One motivation for this is related to a concept in the German fire fighter work principles. If a team cannot be reached otherwise, one dedicated fire fighter will try to get into contact with the team in question by moving towards their presumed location. The task of this fire fighter is therefore dedicated to aid the communication between teams in the field and the central incident command. For modern networks UAVs could serve this purpose as well.

The seconds option is to integrate additional devices into the network, that are mobile but are not aware of the communication needs or have different tasks to fulfill that overrule the communication task. This is the case for any communication device carried for example by volunteers and also for UAVs if they are assigned to other non-communication-related missions such as surveillance.

5.4.2 Evaluation Setup

Based on the previously evaluated SAR scenario, all three kinds of additional nodes were added and the combinations are analyzed using ONE and the OracleSolver framework.

First, additional nodes that are placed at fixed positions are evaluated. To do this, up to 35 nodes are added to the simulation in seven steps of five additional nodes each. All nodes are carefully positioned to gain maximum coverage enhancement of the network. Therefore, they are placed along the main hiking paths (cf. black paths in Figure 2.2) and positioned so that each node has two neighbors at almost maximum communication range. In this case, 150 m are used as range and the distance between two neighboring nodes is approximately 140 m. Due to this setup the nodes create a fixed backbone (cf. proposed network architecture in Figure 2.9) into the search area and should provide shortcuts to the DTN nodes of the first responders.

The second evaluation targets nodes that are added to the scenario but have to fulfill their own mission. A node representing an UAV was added for this purpose. This node follows a surveillance mission in the same area as the first responders and thus could provide additional contacts. However, these are not tuned to any communication need of the ground based nodes.

Finally, a third evaluation uses the Contextual Movement Module (cf. Section 4.4.1) to add one or two node with controlled mobility. These nodes represent UAVs that actively aid the communication by acting as dedicated message ferry. In this case, each ferry was configured to randomly select the next target based on the messages in its buffer and wait until ongoing transmissions are finished. The second point was chosen to allow an optimal utilization of the current contact while the first one avoids any assumptions on the ferrying algorithm used. This was needed since no specialized algorithm is currently implemented in the Contextual Movement Module.

The second and third evaluation are performed for the base scenario without fixed nodes and all fixed backbone variants. Both variants represent options for mobile backbone nodes (cf. Figure 2.9). The combination of two UAVs and 35 fixed backbone nodes should provide a network that is almost fully connected.

The general simulation setup is the same as before and the evaluations are performed for the identified subset of DTN routing protocols. For both the movement of the nodes of the base scenario as well as the traffic introduced by the first responders, corresponding traces are used for better comparison. In case of traffic, two trace versions are used: one with approximately 500 messages for the first two evaluations and another one with around 1000 messages for the third evaluation. This increase was required because the movement of the controlled ferry depends on the number messages stored in the buffer of the ferry. More messages therefore provide better options to choose the next destination. All nodes in the different evaluations use the same communication range.

The additional nodes act as relay only and do not introduce any traffic themselves in the current evaluation. This assumption was taken in order to evaluate the ability of DTN routing protocols to exploit the additional communication opportunities without introducing further load to the network. In real-world applications, this assumption would only apply to the fixed backbone nodes as the UAVs would most likely report their status and in case of uncontrolled nodes their findings.

5.4.3 Fixed Backbone Nodes

If nodes are added to the scenario at fixed positions along the hiking path, they provide stable connections towards the central coordinators. These nodes are able to provide shortcuts, once another node comes into the coverage are of the backbone. The stepwise addition of further nodes represents the progress of first responders when searching the area. Figure 5.10 shows the results of all four protocols and the OracleSolver framework.

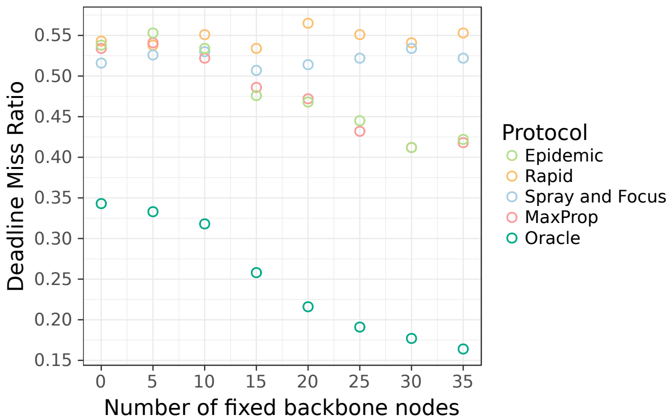


Figure 5.10: Impact of additionally deployed nodes at fixed positions (cf. [88])

While the optimal solution shows the expected reduction of the number of messages missing the 90 s-deadline, this is only the case for Epidemic and MaxProp, even though the gap to the optimal solution stays large and the enhancement is not as strong. The other two protocols are not able to benefit from the enhanced connectivity at all and the number of messages missing the deadline stays more or less constant.

The reason for this seems to be an unawareness of stable contacts that last for a longer period of time. As a result, the delivery probability stays on a low lever or even decreases over time since there are no new connectivity events, which are however not required if the connection is up and stable. Due to this, the active connection is not considered during the selection of the next relay.

This is a severe issue, since hybrid approaches that provide a stable connectivity in the underlying MANET would also suffer from this if the DTN protocol does not decide to forward the message even if a suitable connection is available. In such a case, the message would not be handed to the lower layer protocols for transmission.

5.4.4 Communication-Unaware Message Ferries

If special message ferries such as UAVs are used, they will most likely operate as multi-purpose sensing platform and thus their ability to support communication is limited to times when other tasks are not required. This evaluation shows the impact of such a node. The movement of the node was generated using the presented Pattern-based Movement Model (cf. Section 3.2).

Based on its movement path, the UAV is able to communicate with various other nodes in the scenarios. The surveillance missions are modeled in a way the reflect the current requirement to recharge the UAV after a certain operational time [36]. Therefore, it regularly returns to the central staging area to replace batteries or recharge [35]. This behavior should allow the node to collect and deliver at least some messages from nodes at different areas when moving in the same area. Figure 5.11 shows the corresponding results in comparison with the results from the previous evaluation.

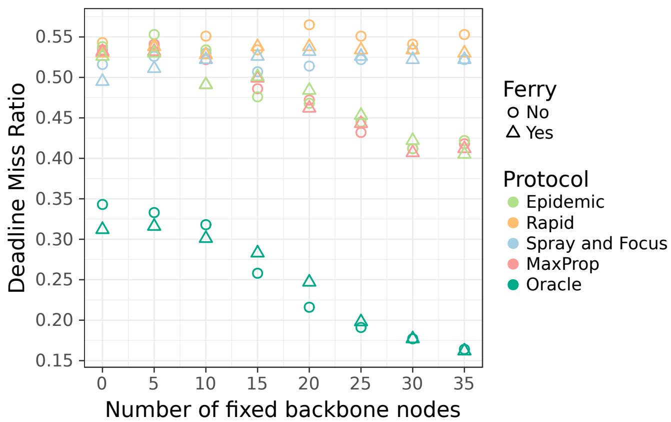


Figure 5.11: Impact of ferry node without communication-aware mobility (cf. [88])

In this case, the additional nodes does not provide any significant improvement for the protocol performance. This result was quite surprising, because at least some benefits should have been possible.

The main reason for this is that the UAV moves without being aware of ongoing transmissions and thus the contacts could be to short to finish transmissions. This leads to aborted transfers and is less efficient in exploiting the available contacts. . Besides that, this node does not adjust its movement based on messages it could deliver because this is overruled by the actual mission task.

These characteristics of the node are difficult to handle by the routing protocols.

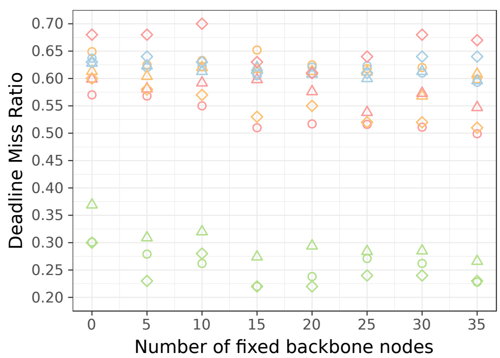
Epidemic should be able to exploit the ferry to some extend, if the contacts are long enough to transfer a message due to the flooding mechanism. Any other protocol will see a node with a good utility score but contacts that cannot be exploited efficiently and thus waste resources by trying to forward messages to the UAV.

These observations were also confirmed in two student projects related to the efficiency of selecting suitable ferries [20, 21]. Both projects showed an improved overall network performance if ferries are available that provide long enough contacts as well as are equipped with enough buffer space. However, since small messages and sufficient buffer sizes are used for this evaluation the uncontrolled ferry seems to generate only low quality contact opportunities.

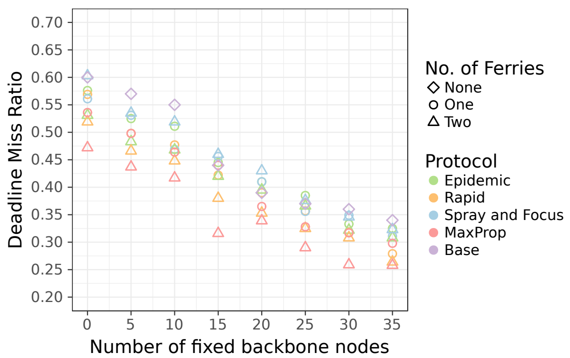
5.4.5 Communication-Aware Message Ferries

Dedicated message ferries are aware of the traffic and movement of other nodes and are able to generate good quality contacts required for an efficient message exchange with other participants. Therefore, the final evaluation of potentially added nodes targets such message ferries. In contrast to most message ferrying approaches, the ferries are equipped with the same DTN routing protocol as the other nodes. Traditionally, message ferrying approaches assume a direct delivery scheme for the ferry node [143]. Besides the traffic generation rate, also the message size was increased.

This evaluation should show an enhancement of the network performance due to the active support of message ferries. Figure 5.12 presents the results for the protocols and for each protocol in addition the optimal solutions in Figure 5.12(b). The optimal solution was calculated per protocol this time because the messages within the buffer of the ferry affect the movement. Therefore, each ferry can take different decisions based on the employed routing protocol. This results in different contacts that are captured via the OracleSolver framework.



(a) Protocols



(b) Optimal solution

Figure 5.12: Impact of ferry nodes with communication-aware mobility (cf. [88])

At first glance Epidemic seems to show the best performance of all protocols. However, the results are misleading because Epidemic has the worst delivery ratio of all protocols with around 50 %. This becomes clear when comparing th delivery ratios in Figure 5.13 and when comparing the deadline misses against the optimal solution. Actually, Epidemic show the worst performance with an error ratio ($ratio_{errors}$) of approximately 70 % in total over all combinations.

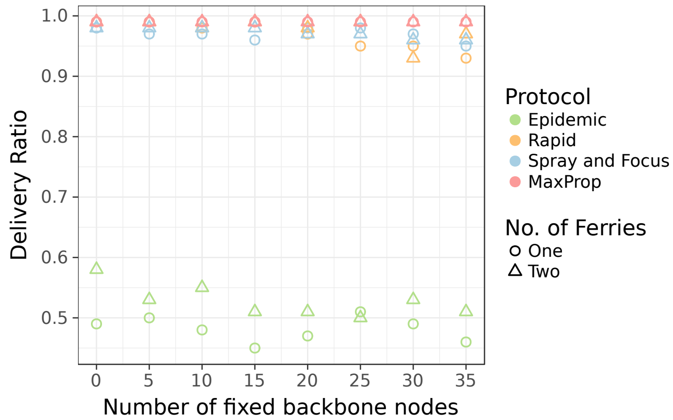


Figure 5.13: Delivery ratio of of DTN protocols with dedicated message ferries (cf. [88])

The remaining protocols show almost the same delivery ratio as the theoretical bound obtained via the OracleSolver framework. However, this time none of the protocols is able to benefit from the enhanced connectivity. That the connectivity is improved, can be seen in the curves of the optimal solutions that show the expected behavior.

Besides that, there are differences in the quality of the introduced contacts. With respect to this metric, a ferry running MaxProp is able to generate the most efficient contacts as shown by the reduced number of deadline misses for the optimal solution. Therefore, it is strongly recommended to add dedicated routing protocols to the ferries and allow an interaction between the path planning that defines the movement and the routing [85].

5.4.6 Discussion

All evaluations in this section showed that the connectivity gets enhanced by any type of additional nodes, even if the contribution is smaller for uncontrolled ferries. However, this effect can be mitigated by integrating more nodes even if they are unaware of the communication needs. This has been confirmed by the results of a student project [20]. As a result, the coverage of the MANET is increased and thus there are more nodes that can communicate directly with each other without relying on DTN principles. The links in the corresponding parts of the network are rather stable and result in long-lasting contacts.

Mobile nodes that are aware of ongoing transmissions and able to actively change their behavior to aid the communication provide the best connectivity. To achieve this, the traffic patterns of the simulated users has to reflect the corresponding inter-group communication. This is required in order to trigger the appropriate ferry movements and is given in first responder scenarios since movement and traffic generation of the first responders are strongly correlated. Using the first responder traffic model (cf. Section 3.3), this correlation can be ensured. Even though the Contextual Movement Module provides only simplistic decisions for target nodes, it is still able to demonstrate the benefit of message ferrying approaches for the overall network performance. The results further suggest a better connectivity if the ferry is aware of the routing decisions within the network. Therefore, message ferries should employ the same routing protocol as the other participants in order to utilize the ferry resources more efficiently. Besides this, such an approach allows the ferry to actively switch between different operational modes and potentially offload data if it has to take over a different non-communication mission [85].

Unfortunately, none of the protocols under evaluation was able to efficiently exploit the enhanced connectivity because DTN protocols seem to be unaware of stable contacts. The only exceptions are Epidemic and to some extend MaxProp when only fixed backbone nodes are used. In this case, Epidemics simple flooding scheme is able to exploit the hop-by-hop opportunities. This is an issue for hybrid DTN-MANET approaches, because the MANET approach provides routes to all currently connected neighbors that remain stable for a certain time.

In that case, the overall performance of the hybrid DTN-MANET approach can only benefit in two cases. The first is to take the right switching decision and thus change the network to MANET mode if stable connections are detected. Here it is crucial to select the operational mode based on the available contacts for each message as soon as a node comes into contact with another part of the network. The challenge is to limit the time overhead required to identify the route to DTN neighbors and to classify the messages accordingly. If this process takes to much time, the communication opportunity might have passed before exchanging any messages.

The second case requires that the DTN part decides to forward the data to the underlying MANET protocol accordingly. For this situation, the unawareness of existing long-lasting contacts or multiple simultaneous contacts [166] of the DTN protocols is critical. If a stable link exists, it is treated as one contacts and thus the utility score values related to this ongoing connection are not properly updated. This leads to a low probability of forwarding messages along this path.

Therefore, it is not sufficient to merely integrate existing DTN protocols or principles into a MANET protocol if the goal is to provide robust and timely delivery of messages in first responder scenarios. The same is true for a combination with switching options.

5.5 Impact of Addressing Schemes

The final scenario evaluation targets the impact of different message types and the corresponding addressing schemes. As described in Section 4.4.2, a module that supports EID-based addressing has been added to ONE. This module was evaluated using to messages traces. The first one was recorded by ONE and contains several multicast-style messages that are realized as unicast by creating one copy per intended receiver. The second one uses the presented multicast addresses instead. Due to this, the number of messages can be reduced by 81 messages in total from 931 in the trace to 850.

Both traces were simulated with the modified version of ONE that is able to handle the EIDs. The message size was set to 100 KByte. The remaining parameters are set again to configure the SAR scenario. Figure 5.14 shows the results for both traces using Epidemic and in addition the multicast version using Prophet. Prophet was used in this case because it was adapted to handle messages with EID addresses during the student project [135].

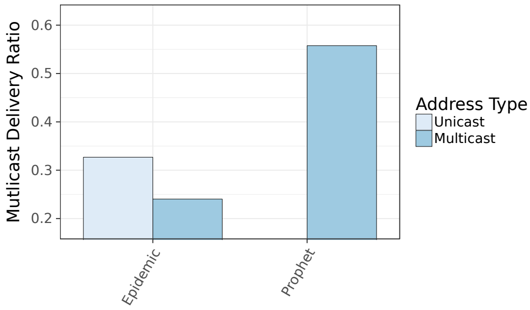


Figure 5.14: Comparison of different addressing schemes

Surprisingly, the delivery ratio is reduced for the multicast messages, even if the total number of messages within the scenario is reduced. These values also include partial deliveries to a subset of the envisioned receivers.

The main reason for this is most likely that none of the protocols evaluated in this case, was actually designed for the application to multicast traffic. Therefore, the benefit of reducing the number of required messages in the network and thus save resources cannot be exploited. A multicast protocol with a focus on first responder communication was developed as previous work [13, 16]. This protocol does focus on efficient buffer management to enhance the delivery ratio of group communication and thus should benefit from dedicated multicast messages. The evaluations were done in ONE, but without an EID support.

The results of this simple validation, however, show that the Host EID Addressing Module is operational and enables address-based simulations. Based on this work, it is now possible to efficiently evaluate multicast routing approaches for hybrid scenarios as well.

CHAPTER 6

Discussion and Lessons Learned

Based on the results of the previous chapters, this chapter will review and discuss on one hand the goals and contributions of this project in terms of developed tools and enabled analyses and on the other hand provide insights on lessons learned for the protocol design for efficient robust and reliable first responder networks.

6.1 Discussion

The base motivation for this project was to build a robust and reliable communication system for first responders. Such systems have to provide robust and reliable services to the users. In case of first responder networks, the requirement to cover potentially large geographical areas with limited available resources results in a network architecture featuring hybrid DTN-MANET routing over heterogeneous components. This structure is required to allow the first responders to adaptively exploit whatever communication technology is available [86] without any additional effort for the users that should concentrate on their humanitarian tasks.

To develop such systems, simulations and testbed evaluations are needed. However, suitable tools usually cover only single aspects of the overall interactions due to the hybrid and at the same time heterogeneous nature of the network in question. Besides that, there are only few very specific models that are able to describe the characteristic properties of first responder scenarios. Realistic models that are capable to reproduce various scenarios were not available.

Therefore, this project had four objectives: the modeling of first responder scenarios in terms of traffic and node movement, the development of a toolbox providing means to analyze the resulting scenarios with a focus on hybrid and heterogeneous networks, the analysis of different protocols based on the toolbox, and finally suggestions to design a better routing approach. So far, results related to the first three contributions have been presented and discussed. The scenario analysis in Chapter 5 was only possible in that level of detail because both the developed models and the developed tools were integrated into a toolbox. However, even if the models and tools were developed with a focus on first responder networks, most of the tools are applicable to other scenarios as well.

Regarding the results of the scenario analysis, it becomes clear that none of the described approaches in Table 5.1 is able to cover all requirements of first responder communication. While this was expected to some extend for the

MANET and DTN-specific protocols, adding knowledge available through hybrid approaches that combine principles from both should have shown an enhanced performance. This was not the case. Instead, especially the results on the impact of additional nodes show that the DTN part cannot exploit the enhanced knowledge on the underlying MANET structure. Due to sub-optimal decisions, the messages either remain buffered or are forwarded to relays moving in opposite directions. Therefore, the decision quality has to be enhanced.

This is crucial for the overall performance, if an overlay approach is chosen to combine MANET and DTN routing into a hybrid solution. Using an overlay, however, provides some advantages. The DTN part can take care of any communication coming from the application and thus handle potential disruptions or retransmissions independently from any user interaction. Such an approach requires routing on two layers as a combination of the sub-figures in Figure 5.1: a traditional MANET routing protocol at the network layer and a DTN routing protocol between application and transport layer. In this case, the DTN protocol relies on the MANET protocol to provide routes to any connected neighbor and notify the DTN agent about changes in the connectivity.

Based on this information, the DTN routing protocol decides whether to forward data or not. If that decision is negative, the data remains buffered at the current node even if a suitable connection to forward it is available. This is the reason for the poor performance of the existing DTN protocols and one point that should be evaluated further in order to enhance the routing protocol performance.

Therefore, the next section will review several options to build such hybrid protocols that exploit additional information available in first responder scenarios. The goal should be to generate approaches that fulfill most of the specific design criteria identified in Section 5.1.4 and listed in Table 5.1.

6.2 Lessons Learned and Proposed Design Considerations

Based on the observations in Chapter 5 and the performed measurements using the testbed (cf. Section 2.3), several points were identified that could help to enhance the overall network performance. These are presented in this section.

6.2.1 Lessons Learned on Routing Protocols in First Responder Ad hoc Networks

As discussed in the previous section, the analysis of routing options for first responder networks under realistic scenarios revealed several drawbacks of the existing approaches. However, based on the results it is possible to propose mechanisms to mitigate these drawbacks.

The first point is related to the chosen devices and access technologies as well as protocol stack design and the need to utilize even short contacts as efficiently as possible while providing larger communication ranges. To achieve this, the access technology should provide rather long range communication opportunities even at lower data rates. In addition, UDP should be used as transport layer protocol because it showed a higher throughput even if the connection is highly intermittent towards the maximum communication range of the given technology. By using UDP, it is still possible to transfer individual messages under these conditions and thus exploit the contact opportunity due to the reduced overhead of UDP compared to TCP. If UDP is used, some additional mechanisms are required at the DTN layer in order to provide the required reliability. At the same time, an adaptive fragmentation mechanism is needed, in order to adaptively define a message size that can be transferred via short contacts as well [21]. Besides that, such a fragmentation mechanism would allow different parts of a message to take different paths and thus enhance the probability that at least part of the information is received.

The next point is related to the structure of the network. If a deployment is possible and integrated into other first responder routines, the placement of additional nodes is a good option to enhance the connectivity between different parts of the network and provide backbone-like short cuts. The results showed that already a few nodes can enhance the situation. However, the exploitation of such nodes has to be enhanced independently of which type of additional node is added to the network.

This requires another point related to the operation of the DTN protocol. Currently the decisions consider one or a few criteria only to estimate upcoming contacts and this does not perform well for long-lasting stable contacts. Therefore, more intelligent decisions are required. One option, to enable such decisions, is the integration of additional context information. First responders are coordinated based on situational awareness information that is collected by the central coordinators. The required mission-related context information is available in the network and could be exploited to enhance the decision quality.

Besides that, the support of dedicated multicast messages is another point. If multicast messages are used, the number of copies as well as the number of required transmissions can be reduced. This would further enhance the utilization of the available contacts and resources. Hybrid DTN-MANET approaches so far do not consider this aspect.

Finally, the underlying MANET protocols have to provide the required route information and efficient forwarding if suitable paths are available. Besides that, services like name resolution for EIDs and DTN neighbor discovery are needed. The challenge here is to provide a solution that is able to perform well under changing network conditions. Adaptive MANET routing could be an interesting option in this case.

6.2.2 Conceptual Design Considerations to Improve Routing Performance

Based on these considerations, the following structure for a hybrid routing approach that is able to handle heterogeneous setups is proposed in Figure 6.1. This proposal is based on the results presented above as well as several contributions by other members of the groups whose work complemented this project (blue boxes). Red lines indicate the control flow, orange ones the data flow, and green ones the context collection.

The envisioned approach consists of the following components to manage the points mentioned in Section 6.2.1. All components are mentioned from the bottom of the stack upwards.

Name Resolution over Routing (NOR) – Name Resolution over Routing (NOR) provides two features to the node: it is able to resolve the name-style EID

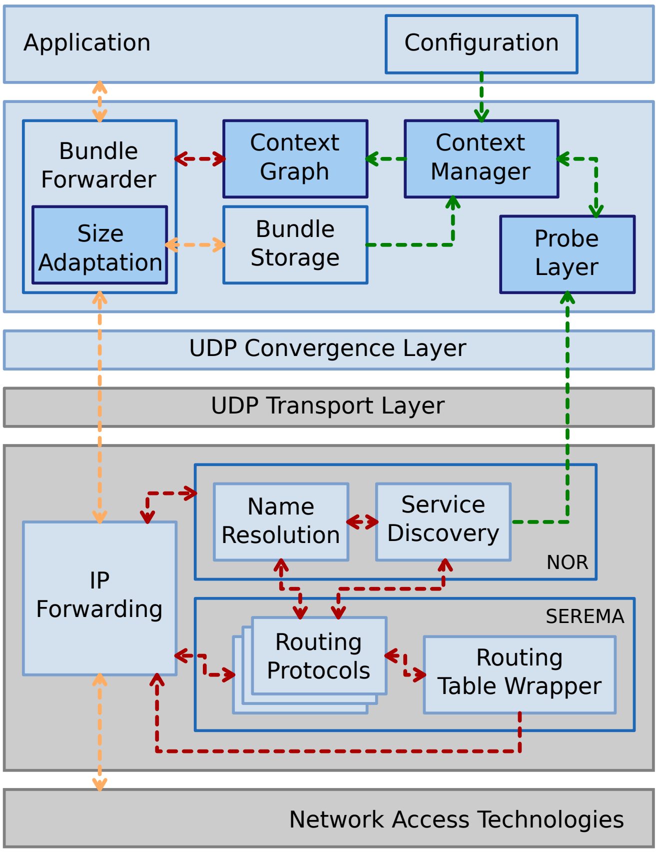


Figure 6.1: Protocol Concept embedded into the communication stack of a node

addresses to IP addresses and provides efficient service discovery [136]. The latter mechanism also allows to search for other network-based services such as DTN-enabled gateways or possible border nodes [140]. Since NOR operates based on MANET routing, any successful request to NOR also retrieves the corresponding route.

Adaptive MANET Routing – Finally, an adaptive routing approach is proposed as MANET routing protocol. This enables a more flexible utilization of network layer connectivity and thus adds robustness there. In this case, Self-organized Routing in heterogeneous MANETs (SEREMA) [50] is chosen because it supports legacy nodes running only one specific routing protocol and is compliant to the RFC definitions for both AODV and OLSR.

UDP Convergence Layer – Based on the insights from the measurements UDP, is suggested as transport layer protocol. This requires the configuration of an appropriate convergence layer. Such a layer has already been described [90] and is available in DTN implementations as well [38].

Graph Based Forwarding – The central idea is to represent the local knowledge of a node on the utility score of potential destinations as a local *Context Graph* which is then used by the *Bundle Forwarder* to take forwarding decisions. This graph representation allows the exploitation of multiple paths as well as the detection of possible transitive contacts. The goal is to select one or more options out of multiple already active or upcoming contacts. Besides that, the forwarding scheme should be able to handle multicast addresses and take the appropriate forwarding decisions depending on the address type used.

Graph Construction – To enable good forwarding decisions in the DTN overlay, the utility score assigned to the edges of the context graph and the structure of the context graph are essential. Based on the experience with the OracleSolver framework, the graph should be constructed using a Breadth First Search variant similar to the one in the OracleSolver graph construction. However, instead of using perfect knowledge, the approach will have to handle uncertainty and local knowledge only. The uncertainty on the network state has to be handled in a way that ensures a preferred forwarding using stable long-lasting contacts if they are available and no updates occur. The calculation of the assigned utility score plays a crucial role here. It should be based on multiple criteria and integrate various context information that is available at the application or device level. Therefore, a multi-criteria decision making algorithm could be used. Other options include more simple rule-based approaches for this. This graph construction is a subtask of the *Content Manager*.

Context Management – If the decisions are based on context information, this information has to be collected and stored. Several sources of such information are available ranging from specific scenario or mission [44] details, user specific values, such as its role, and device specific information, such as available interfaces or status information on battery and storage capacity, to traditional message related details such as priorities. Besides that, information on groups and thus the base for multicast addressing is also available. In general, this information is available and accessible via different paths. The mission and user related information as well as details on the device could be accessed via configuration options of the device and the deployed application. Besides that, information on neighboring nodes as well as changes in the connectivity is available at the MANET routing approach. Therefore, a probe layer is used to collect this information.

Probe Layer – The probe layer serves several purposes in this concept. It enables a neighbor discovery scheme similar to the one described in RFC5050 [142] based on network layer information collected by SEREMA and the discovery of nodes providing various services within the connected subnet. This is achieved by contacting the service discovery mechanism in NOR [136]. Alternatives are a combination of the neighbor discovery mechanisms described in [116, 117] and the service discovery mechanism described in [124]. However, the existing work on NOR provides both features in one solution.

Adaptive Bundle Fragmentation – In RFC 5050 [142], a simple fragmentation mechanism is described, that allows the bundles to be split into two smaller bundles if there are no suitable contacts and repeat this process at subsequent nodes. Since the bundle size is not fixed, this is rather infeasible, especially if short contacts have to be exploited. The impact of fragmentation has been shown in [125], where static schemes are evaluated. However, the authors conclude that the benefit of fragmentation depends on the current conditions in the network and thus an adaptive scheme is required. These results were confirmed by an evaluation of different messages sizes in heterogeneous mobility scenarios [21]. Fragmented bundles are treated as separate messages and are only reassembled at the final destination. This results in possibly partial deliveries that were one criteria in first responder networks, which is another benefit.

This combination of a context-aware overlay DTN routing approach and an adaptive MANET routing framework that integrates service discovery and name resolution should be able to handle and mitigate the identified drawbacks. Based on the criteria presented in Table 5.1, this approach should be able to cover the following aspects: The movement and traffic patterns of the nodes as well as message priorities and different relay types are available via the context information. The same is partially true for the overhearing support that can be enhanced further by using multicast addresses for neighboring groups. Due to the integration of adaptive routing, the fragmentation and an exploitation of multiple paths based on the context graph, partial delivery and multi path forwarding are also possible. Finally, the DTN principles allow the required robustness against disruptions by persistently buffering messages and notifications from the probe layer can trigger autonomous retransmissions. Therefore, eight out of nine criteria could be fulfilled using the approach.

6.2.3 Open Points

To implement the proposed concept, the toolbox requires further extensions. As the concept relies on a direct interaction between the MANET and DTN components, this combination has to be enabled in one of the simulation tools. The current version would only allow static offline evaluations with multiple manual reruns to tune the parameters. This is inefficient in the long term as the dynamics have to be considered as well.

To realize this, either the detailed MANET approach has to be ported to ONE or the DTN concepts have to be implemented in OMNeT++. The proposal here is to integrate an implementation of the bundle protocol into OMNeT++ and build the novel routing concept in addition. Due to time constraints, the port and the implementation were out of scope of this project.

CHAPTER 7

Conclusions and Perspectives

After introducing various first responder scenarios and developing a set of tools that enable detailed analyses of these scenarios, the performance of existing state of the art routing schemes in such scenarios was evaluated. The results show that the tools are functional and provide useful features for the evaluations and at the same time show several rather unexpected drawbacks of the existing approaches if applied to realistic first responder scenarios. While this is expected for the delay performance in general, it is rather surprising that additionally deployed nodes that enhance the connectivity cannot be exploited by the DTN protocols.

This is surprising because the communication in disaster scenarios is one research field that is in the focus of DTN research groups and remains an active field even if other technologies are added [156]. The latter should be exploited to limit the delay. However, if they provide more stable connectivity and still require the disruption tolerance of a hybrid scheme, the overall performance of the solution might not be improved.

Based on these results, several options to build a novel hybrid approach have been discussed that promise a better utilization of the available contacts and thus should provide a better overall performance. The implementation of this concept was however out of scope for this project.

The potential future work can be classified into two categories. Firstly, there are several enhancements to the toolbox as well as further experiments using the toolbox to get a more detailed understanding of the scenario and how different mechanisms interact. Secondly, the proposed concept or similar approaches should be refined and implemented in order to provide better communication services to first responders.

Several points are related to the first category. First of all, the integration of the bundle protocol into OMNeT++ is required to analyze hybrid approaches and the required interactions between the different components directly. Hybrid approaches both existing and novel should be integrated as well to enable comparison studies based on simulations. If real-world experiments are planned, the testbed can be extended with the envisioned routing schemes, too. In addition to the presented measurement results, a more detailed study on the impact of vegetation is planned that will also include RSSI measurements to better understand the propagation conditions. Besides that, dedicated message ferrying algorithms should be integrated into the Contextual Movement Module to further evaluate the interactions and interdependencies between path planning of the ferry and the routing schemes of both the ferry and the other participants. The OracleSolver framework can be extended with further shortest path algorithms as well as further criteria or parameters to define the graph structure. This allows more detailed evaluations of the decision quality under the given constraints. Independently of these enhancements, it is planned to make the developed tools available as Open Source Software to the research community.

Similarly, there are also multiple points related to the evaluation of first responder networks. In this case, the toolbox as it is described here can be used to further analyze the environmental impact on the communication performance. This includes the terrain, but also further studies on the impact of vegetation using the testbed. Beside that, the proposed conceptual approach should be implemented, refined, and finally compared and evaluated using the toolbox, once the required extensions are available for this.

APPENDIX A

Outdoor Measurement Campaign

This chapter presents more details on the performed measurement campaign to assess the impact of environmental conditions on an example technology that could be applied to build first responder ad hoc networks.

A.1 Measurement Setup

This section gives details on the setup and the equipment.

A.1.1 Hardware Components

To perform the outdoor measurements, the following hardware components were employed:

Mobile control node Asus Zenbook notebook equipped with Edimax WiFi dongle in mesh mode

Fixed node DogBox (Raspberry Pi) equipped with GPS receiver, and two WiFi dongles: TP-Link (infrastructure mode) and XyZel (mesh mode)

The DogBox node is based on our outdoor testbed (cf. Section 4.6 and [81]) with some modifications. This version is based on an Raspberry Pi Model B with two USB interfaces. Figure A.1 gives an overview of the added node components. In this setup, all non-Wifi components of the MeshHAT were disabled (gray) except for the GPS receiver. Besides that, an additional WiFi dongle was attached via the second USB interface. This dongle was operated in infrastructure mode and used for initial configurations, only.

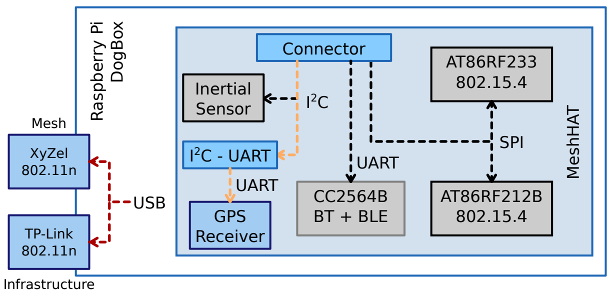


Figure A.1: Schematic components of DogBox outdoor nodes

A.1.2 Software

The goal of the measurements was not to capture the propagation conditions via RSSI values. Instead, these measurements show the impact of poor conditions on higher layer protocols and thus show to which extend these protocols are able to handle outdoor conditions. To achieve this, the following tools where used:

- *iperf* to measure TCP and UDP throughput
- *ping* to measure round trip delay and packet loss/errors

A.1.3 Configuration

The goal of the measurements is to capture the conditions in different outdoor environments and represent communication characteristics of a typical SAR scenario. Therefore, the following configuration was used:

- Positions

  fixed node – height: 30 cm

  mobile node – height: 100 cm

- Measurement duration

  30 s per application

- Application specific settings

  iperf maximum throughput 150 Mbit/s

  ping sending interval 1 packet per s

A.2 Measurement Conditions

The outdoor conditions of each individual measurement series are listed in Table A.1. The conditions captured cover the weather and the state of the leaves. In addition to this, the table lists the classification of the observed conditions with respect to their impact on the communication.

Table A.1: Overview and Classification of Outdoor Conditions for all Measurements

Measurement		Environmental Conditions							Class.	Impact of
No.	Date	Temp. °C	Rel. Humidity %	Wind	Clouds	Rainfall	Comment	Leaves	Weather	Leaves
1	09 Jan	5	75	none	cloudy	none		none	good	
2	10 Jan	5	77	none	cloudy	none		none	good	
3	30 Jan	4	60	storm	cloudy	snow		none	poor	
4	31 Jan	4	60	storm	cloudy	snow		none	poor	
5	21 Feb	11	75	breeze	cloudy	drizzle		none	poor	
6	28 Mar	10	50	breeze	none	none		none	good	
7	10 Apr	15	50	none	partly cloudy	none		buds	good	
8	17 Apr	10	85	none	cloudy	fog	after rain	few leaves	poor	none
9	01 May	18	40	breeze	partly cloudy	none		green shrubs	good	none
10	08 May	25	40	breeze	none	none		green trees	good	none
11	25 Jun	30	60	none	partly cloudy	none	humid	complete cover	good	yes
12	24 Jul	18	84	none	high fog	dew	humid	complete cover	good	yes
13	24 Jul	24	51	none	cloudy	dew	humid	complete cover	good	yes
14	10 Sep	30	39	none	partly cloudy	none		complete cover	good	yes
15	29 Oct	10	50	breeze	cloudy	none		autumn colors	good	yes
16	30 Oct	10	75	none	cloudy	none		autumn colors	good	yes
17	12 Nov	0	71	none	cloudy	fog		shrubs remain	poor	none
18	13 Nov	3	58	none	none	none	frost	shrubs remain	good	none
19	03 Jan	-2	70	breeze	cloudy	snow	5 cm snow	none	poor	

APPENDIX B

Model Comparison Simulation Details

This chapter provides additional details related to the verification of the developed mobility and traffic models. The described SAR scenario is used in further simulations later with the same basic parameters.

B.1 Simulation Setup

In order to evaluate the developed models and compare their impact on the routing protocol performance to that of existing and commonly used models, two disaster scenarios and three traffic generation options were simulated in ONE.

B.1.1 Common Parameters

Table B.1 shows the common parameters that were not varied for all eight combinations of models.

Table B.1: Common Simulation Parameters of the Model Evaluation

Parameter	Value
Network Interface	
Type	WiFi
Data Rate	2 Mbit/s
Message Related	
Size	500 kB
Time-To-Live (TTL)	300 min
Routing	
Protocol	Epidemic [158]
Buffer Size	5 MB
Random Traffic	
Generation	default MessageGenerator [76]
Message Generation Interval	10 to 30 s

B.1.2 SAR Scenario

The first scenario represents an SAR scenario as described in Section 2.1.2. It was modeled once with the presented trace based approach and once with random movement. For each movement type, three variants of traffic were simulated resulting in 6 combinations in total. Table B.2 gives an overview of the scenario-specific settings.

Table B.2: Simulation Parameters of the SAR Scenario

Parameter	Value
Network Interface	
Range	150 m
Area	
Size	6000 × 5000 m
Nodes	62
Random Movements	
Generation	Shortest Path Map Based Movement [76]
External Traffic	
Generation	manually matched to movements/mission phases
Messages	300, 600

B.1.3 Evacuation Scenario

The second scenario represents an evacuation scenario or any other mission that involves a large number of affected people in one location. This scenario was described and modeled by [7] and is available via the BonnMotion [6] tool. Here, the provided example script was used to generate the movement traces of the nodes. In this case, the traffic generation via manually generated messages was omitted. Therefore, only two additional combinations are simulated. Table B.3 gives an overview of the scenario specific settings.

Table B.3: Simulation Parameters of the Evacuation Scenario

Parameter	Value
Network Interface	
Range	50 m
Area	
Size	350 × 200 m
Nodes	150
Disaster Area Movements	
Generation	Example script provided in [6]

B.2 Detailed Results

Table B.4 provides the detailed results that build the base for Figure 3.12.

Table B.4: Detailed Simulation Results of Model Impact Evaluation

Mobility	Random			Disaster Area		Pattern		
Traffic	Random	Appl.	Events	Random	Appl.	Random	Appl.	Events
Delivery Ratio [%]								
mean	16.000	63.600	87.100	39.300	94.500	32.200	88.400	99.600
variance	1.600	4.000	1.700	4.400	0.600	1.200	1.400	0.100
Delay [s]								
mean	1835.287	3087.710	1655.136	96.470	0.665	448.196	442.870	480.145
variance	179.333	196.524	143.250	8.503	0.006	55.548	0.733	337.932

APPENDIX C

Scenario Analysis Simulation Details

This chapter gives the detailed results of all simulations performed to analyze first responder scenarios in Chapter 5.

C.1 Comparison of Access Technologies

The following tables show the results for the evaluation of different network access technologies as far as these can be modeled in ONE. The collected statistics are the delay, delivery ratio, deadline miss ratio, and the error ratio of the different simulations. In this case, the message size was set to 500 Byte in order to eliminate an influence of buffer management strategies.

Table C.1: Protocol Performance of Short Range Setup

Metric	Protocol				
	Direct Delivery	Epidemic	Spray and Wait	MaxProp	Rapid
Short Range (50 m, 5 Mbit/s)					
avg [s]	1591.3	1296.0	1325.7	1294.3	1310.2
stdev [s]	1139.9	1134.6	1171.5	1136.1	1138.4
min [s]	0.1	0.1	0.1	0.1	0.1
median [s]	1454.0	1454.7	1462.3	1451.6	1466.3
max [s]	4881.2	4881.2	5532.9	4881.1	4880.8
deadline	369	379	368	373	376
ratio [%]	0.677	0.695	0.675	0.684	0.690
delivered	535	534	535	535	535
ratio [%]	0.982	0.980	0.982	0.982	0.982
error ratio [%]	0.695	0.716	0.694	0.703	0.708

Table C.2: Protocol Performance of Medium Range Setup

Metric	Protocol				
	Direct Delivery	Epidemic	Spray and Wait	MaxProp	Rapid
Medium Range (150 m, 2 Mbit/s)					
avg [s]	1804.8	1020.6	1067.4	1015.8	1022.3
stdev [s]	1259.2	1032.3	1091.3	1033.1	1039.0
min [s]	0.0	0.1	0.1	0.1	0.1
median [s]	1450.3	750.2	770.6	722.5	751.6
max [s]	5509.2	4165.0	4818.3	4165.0	4164.9
deadline	331	343	332	341	339
ratio [%]	0.607	0.629	0.609	0.626	0.622
delivered	543	543	543	543	543
ratio [%]	0.996	0.996	0.996	0.996	0.996
error ratio [%]	0.611	0.633	0.613	0.629	0.626

Table C.3: Protocol Performance of Long Range Setup

Metric	Protocol				
	Direct Delivery	Epidemic	Spray and Wait	MaxProp	Rapid
Long Range (200 m, 0.5 Mbit/s)					
avg [s]	1282.5	978.9	1024.1	973.7	1033.3
stdev [s]	1008.7	1002.3	1062.6	1004.8	992.9
min [s]	0.0	0.1	0.1	0.1	0.1
median [s]	659.6	680.2	680.5	665.6	862.3
max [s]	4144.4	4144.4	4780.2	4144.4	4144.4
deadline	335	345	333	339	353
ratio [%]	0.615	0.633	0.611	0.622	0.648
delivered	543	543	543	543	543
ratio [%]	0.996	0.996	0.996	0.996	0.996
error ratio [%]	0.618	0.637	0.615	0.626	0.651

C.2 Protocol Comparison Results

Table C.4 provides statistics on the delay, delivery ratio, deadline miss ratio, and the error ratio of the different simulations. In this case, the message size was set to 500 Byte in order to eliminate an influence of buffer management strategies.

Table C.4: Comparison of Different Routing Protocols

Metric	Protocol									
	Direct Delivery	Epidemic	Spray and Wait	Spray and Focus	Prophet	MaxProp	Rapid	SimBet	dLife	dLife customized
avg [s]	1804.8	1020.6	1067.4	1038.5	1101.7	1015.8	1022.3	1152.0	1215.4	1216.1
stdev [s]	1259.2	1032.3	1091.3	1074.2	1104.2	1033.1	1039.0	1064.0	1110.6	1112.3
min [s]	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	1450.3	750.2	770.6	771.4	873.9	722.5	751.6	1100.7	1273.5	1276.1
max [s]	5509.2	4165.0	4818.3	4814.7	4852.7	4165.0	4164.9	4170.5	5453.7	5449.5
deadline	331	343	332	333	342	341	339	376	373	370
ratio [%]	0.607	0.629	0.609	0.611	0.628	0.626	0.622	0.690	0.684	0.679
delivered	543	543	543	543	543	543	543	543	543	543
ratio [%]	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996
error ratio [%]	0.611	0.633	0.613	0.615	0.631	0.629	0.626	0.694	0.688	0.683

C.3 Comparison with Optimal Solution

Table C.5 provides the results for the comparison of the protocol performance with the theoretical solution calculated using the OracleSolver framework.

Table C.5: Protocol Performance for Small Messages

Metric	Protocol				
	Epidemic	MaxProp	Spray and Wait	Rapid	Oracle
Small messages (500 Byte)					
avg [s]	324.3	316.9	675.9	429.7	493.470
stdev [s]	533.2	502.2	874.7	583.1	798.797
min [s]	0.1	0.1	0.1	0.1	0.002
median [s]	7.0	18.0	166.4	168.4	0.002
max [s]	2856.5	2848.3	4818.3	3122.9	3564.202
deadline	195	198	251	255	165
ratio [%]	0.173	0.557	0.443	0.374	0.343
delivered	475	475	475	475	475
ratio [%]	0.383	0.746	0.746	0.746	0.988
error ratio [%]	0.790	0.811	0.696	0.628	0.356

Table C.6: Protocol Performance for Larger Messages

Metric	Protocol				
	Epidemic	MaxProp	Spray and Wait	Rapid	Oracle
Larger messages (500 kByte)					
avg [s]	588.886	1071.350	743.785	745.840	495.843
stdev [s]	1071.768	1080.952	979.264	1032.310	798.813
min [s]	2.0	2.0	2.0	2.0	2.0
median [s]	77.5	860.1	81.2	91.6	2.0
max [s]	5346.7	4699.6	4082.6	5429.0	3566.2
deadline	83	268	213	180	165
ratio [%]	0.173	0.557	0.443	0.374	0.343
delivered	184	359	359	359	475
ratio [%]	0.383	0.746	0.746	0.746	0.988
error ratio [%]	0.790	0.811	0.696	0.628	0.356

C.4 Comparison with MANET-only Protocols

Table C.7 presents a comparison of the number of received messages within different time intervals. In case of OMNeT++ simulations, the number represents the total number of messages delivered and the interval corresponds to the maximum delay observed for theses messages. In case of ONE, it should be noted that the minimal time resolution is 0.1 s. A finer evaluation is not possible and usually not required since typical delays are in the order of at least several seconds or even minutes in DTN simulations.

Table C.7: Comparison between MANET and DTN protocols

Protocol	Number of Received Messages			Tool
	< 0.02 s	< 1 s	< 0.3 s	
DYMO (Ad Hoc Default)	237			OMNeT++
DYMO (Tuned Path Loss)	114			OMNeT++
Oracle		306	310	OracleSolver
Rapid		142	164	ONE
Spray and Focus		148	171	ONE
MaxProp		137	163	ONE
Epidemic		147	168	ONE

C.5 Comparison of Fixed Backbone Node Utilization

This section provides the detailed results of the comparison of different protocols in scenarios with additional backbone nodes at fixed positions. All evaluations were performed with two message sizes: 500 Byte and 500 kByte, respectively.

C.5.1 Oracle Solution

Table C.8: Oracle performance for in case of additional backbone nodes (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	493.470	378.378	342.477	236.265	190.493	138.708	125.421	117.241
stdev [s]	795.688	634.863	587.122	471.163	418.394	320.936	301.866	294.120
min [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
median [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
max [s]	3564.202	3118.212	2968.216	2785.816	2623.52	2456.022	2302.93	2156.534
deadline	165	160	153	124	104	92	85	79
ratio [%]	0.343	0.333	0.318	0.258	0.216	0.191	0.177	0.164
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.356	0.345	0.331	0.270	0.229	0.204	0.189	0.177

Table C.9: Oracle performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	495.843	384.160	348.726	242.072	196.523	144.964	133.040	124.913
stdev [s]	798.813	638.512	591.816	475.102	421.858	323.967	304.592	296.453
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
max [s]	3566.2	3130.2	2984.2	2801.8	2643.5	2478	2332.9	2190.5
deadline	165	161	153	124	104	92	85	80
ratio [%]	0.343	0.335	0.318	0.258	0.216	0.191	0.177	0.166
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.356	0.347	0.331	0.270	0.229	0.204	0.189	0.179

C.5.2 Epidemic

Table C.10: Epidemic performance for in case of additional backbone nodes (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	834.144	675.038	644.053	520.133	445.002	391.398	381.046	377.663
stdev [s]	998.477	850.769	834.245	749.48	680.704	643.767	660.074	657.893
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	325.8	261.0	210.0	69.4	61.4	28.9	10.0	10.0
max [s]	4144.4	4118.3	4118.3	3976.0	3978.2	3977.5	4117.6	4117.6
deadline	259	266	257	229	225	214	198	203
ratio [%]	0.538	0.553	0.534	0.476	0.468	0.445	0.412	0.422
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.551	0.565	0.547	0.489	0.480	0.457	0.424	0.435

Table C.11: Epidemic performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	588.886	387.300	376.194	578.706	421.682	522.153	284.152	412.514
stdev [s]	1071.768	714.446	648.102	1218.638	786.660	992.771	521.501	927.190
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	75.2	53.3	55.7	48.0	66.3	46.0	47.9	65.1
max [s]	5346.7	3800.4	3054.8	8072.0	5597.4	6137.0	2445.9	8107.0
deadline	83	64	71	77	82	71	56	65
ratio [%]	0.173	0.133	0.148	0.160	0.170	0.148	0.116	0.135
delivered	184	172	180	189	190	193	164	164
ratio [%]	0.383	0.358	0.374	0.393	0.395	0.401	0.341	0.341
error ratio [%]	0.790	0.775	0.773	0.767	0.775	0.746	0.775	0.794

C.5.3 MaxProp

Table C.12: MaxProp performance in case of additional backbone nodes (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	827.190	678.838	647.913	537.409	459.765	397.062	380.722	379.276
stdev [s]	1005.224	852.932	837.872	751.485	684.180	649.505	660.619	660.511
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	237.0	268.0	196.6	70.0	67.9	20	17.5	12.1
max [s]	4144.4	4106.5	4107.8	3998.0	3998.6	3997.7	4113.0	4115.4
deadline	257	260	251	234	227	208	198	201
ratio [%]	0.534	0.541	0.522	0.486	0.472	0.432	0.412	0.418
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.547	0.553	0.534	0.499	0.484	0.445	0.424	0.430

Table C.13: MaxProp performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	1071.350	1052.657	1231.395	1163.740	957.625	1121.058	1037.007	1101.936
stdev [s]	1080.952	1162.704	1115.954	1233.389	1017.369	1259.093	1164.817	1130.404
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	876.4	618.9	1283.0	775.1	589.0	699.3	624.4	887.5
max [s]	4699.6	5860.3	4170.5	6728.2	4790.7	6654.4	7309.7	4719.9
deadline	268	264	297	276	269	267	278	285
ratio [%]	0.557	0.549	0.617	0.574	0.559	0.555	0.578	0.593
delivered	408	403	417	392	406	399	419	423
ratio [%]	0.848	0.838	0.867	0.815	0.844	0.83	0.871	0.879
error ratio [%]	0.709	0.711	0.751	0.759	0.715	0.726	0.707	0.713

C.5.4 Rapid

Table C.14: Rapid performance in case of additional backbone nodes (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	853.881	774.811	754.105	650.208	703.224	630.875	708.187	711.296
stdev [s]	1005.895	940.884	910.233	831.176	831.766	803.998	870.116	872.023
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	336.2	248.0	326.7	190.0	385.2	268.0	277.0	307.5
max [s]	4144.4	4105.6	4165	4058.1	4031.1	4066.8	4106.5	4106.7
deadline	261	259	265	257	272	265	260	266
ratio [s]	0.543	0.538	0.551	0.534	0.565	0.551	0.541	0.553
delivered	475	475	475	475	475	475	475	475
ratio [s]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [s]	0.555	0.551	0.563	0.547	0.578	0.563	0.553	0.565

Table C.15: Rapid performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	745.840	841.450	799.140	750.923	853.524	724.454	685.334	771.471
stdev [s]	1032.310	1098.990	1018.480	925.254	1046.420	877.648	890.460	981.576
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	91.6	120.2	141.3	174	282.2	203.5	123.2	154.5
max [s]	5429.0	7664.8	4915.8	4078.2	4790.5	4127.2	4135.3	5376.8
deadline	180	180	178	189	185	182	177	178
ratio [%]	0.374	0.374	0.370	0.393	0.385	0.378	0.368	0.370
delivered	359	343	335	342	318	322	324	325
ratio [%]	0.746	0.713	0.696	0.711	0.661	0.669	0.674	0.676
error ratio [%]	0.628	0.661	0.674	0.682	0.723	0.709	0.694	0.694

C.5.5 Spray and Focus

Table C.16: Spray and Focus performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	873.964	886.115	889.755	825.412	829.482	831.355	881.526	881.944
stdev [s]	1066.653	1078.874	1078.979	1054.601	1048.073	1046.721	1071.475	1074.944
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	215.5	205.0	240.0	120.0	130.0	140.0	205.1	205.1
max [s]	4780.0	4818.6	4818.3	4780,0	4780.1	4780.1	4818.3	4818.4
deadline	248	253	255	244	247	251	257	251
ratio [%]	0.516	0.526	0.530	0.507	0.514	0.522	0.534	0.522
delivered	472	475	475	475	475	475	475	475
ratio [%]	0.981	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.534	0.538	0.543	0.520	0.526	0.534	0.547	0.534

Table C.17: Spray and Focus performance in case of additional backbone nodes (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	743.785	769.487	748.607	707.854	786.808	793.451	849.131	833.383
stdev [s]	979.264	996.247	978.467	964.545	1017.093	1033.944	1047.431	1031.658
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	83.2	91.1	103.5	70.0	106.0	119.0	161.5	135.0
max [s]	4082.6	4071.0	4121.4	4787.6	4737.8	4840.5	4784.9	4840.3
deadline	213	219	221	213	231	238	249	241
ratio [%]	0.443	0.455	0.459	0.443	0.480	0.495	0.518	0.501
delivered	437	438	435	441	457	463	462	459
ratio [%]	0.909	0.911	0.904	0.917	0.950	0.963	0.960	0.954
error ratio [%]	0.534	0.545	0.555	0.526	0.530	0.532	0.557	0.547

C.6 Comparison of Uncontrolled Ferry Utilization

This section provides the detailed results of the comparison of different protocols in scenarios with one uncontrolled message ferry. All evaluations were performed with two message sizes: 500 Byte and 500 kByte, respectively.

C.6.1 Oracle Solution

Table C.18: Oracle performance in case of an additional uncontrolled ferry (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	214.262	197.297	178.447	162.699	140.106	122.479	111.86	99.344
stdev [s]	375.419	358.256	320.999	305.598	288.560	279.038	270.704	256.510
min [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
median [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
max [s]	1690.302	2155.502	1855.610	1813.512	1813.512	1813.512	1813.512	1813.512
deadline	150	152	145	136	119	95	85	78
ratio [%]	0.312	0.316	0.301	0.283	0.247	0.198	0.177	0.162
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.324	0.328	0.314	0.295	0.26	0.21	0.189	0.175

Table C.19: Oracle performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	224.326	206.723	188.155	169.2	146.434	128.953	118.884	106.951
stdev [s]	389.165	370.083	334.857	311.096	291.282	280.084	272.05	258.158
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
max [s]	1692.3	2157.5	1865.6	1825.5	1825.5	1825.5	1825.5	1825.5
deadline	151	152	145	136	120	96	85	80
ratio [%]	0.314	0.316	0.301	0.283	0.249	0.200	0.177	0.166
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.326	0.328	0.314	0.295	0.262	0.212	0.189	0.179

C.6.2 Epidemic

Table C.20: Epidemic performance in case of an additional uncontrolled ferry (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	453.852	451.427	394.118	409.814	360.977	354.752	343.929	324.272
stdev [s]	597.723	613.614	539.320	580.021	532.244	534.711	536.413	533.227
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median	153.8	141.9	90.0	104.1	75.0	50.0	25.0	7.0
max [s]	3118.4	2930.3	2856.8	2856.4	2856.5	2856.4	2856.8	2856.5
deadline	253	255	236	241	233	218	203	195
ratio [%]	0.526	0.530	0.491	0.501	0.484	0.453	0.422	0.405
delivered	475	475	474	475	475	475	475	475
ratio [%]	0.988	0.988	0.985	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.538	0.543	0.505	0.514	0.497	0.466	0.435	0.418

Table C.21: Epidemic performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	365.439	385.830	468.197	344.260	322.722	361.279	426.045	352.241
stdev [s]	605.811	583.847	738.147	670.789	591.583	797.399	842.122	623.718
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median	72.1	69.1	66.9	52.1	45.1	49.8	73	48.3
max [s]	3262.9	2140.4	3304.1	3518.3	3148.1	6384.7	6223.8	3127.3
deadline	84	76	85	67	61	64	78	70
ratio [%]	0.175	0.158	0.177	0.139	0.127	0.133	0.162	0.146
delivered	189	176	199	179	165	170	175	186
ratio [%]	0.393	0.366	0.414	0.372	0.343	0.353	0.364	0.387
error ratio [%]	0.782	0.792	0.763	0.767	0.784	0.78	0.798	0.759

C.6.3 MaxProp

Table C.22: MaxProp performance in case of an additional uncontrolled ferry (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	458.081	409.750	394.118	385.143	344.557	336.232	321.622	316.942
stdev [s]	599.225	549.312	539.320	526.146	502.919	504.039	505.742	502.174
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	130.0	150.0	90.0	109.3	65.1	40.0	16.9	18.0
max [s]	3118.3	2927.4	2856.8	2847.3	2846.4	2855.3	2848.2	2848.3
deadline	256	256	236	240	222	213	196	198
ratio [%]	0.532	0.532	0.491	0.499	0.462	0.443	0.407	0.412
delivered	475	475	474	475	475	475	475	475
ratio [%]	0.988	0.988	0.985	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.545	0.545	0.505	0.511	0.474	0.455	0.420	0.424

Table C.23: MaxProp performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	812.215	879.080	980.126	895.940	961.506	889.528	796.305	876.390
stdev [s]	962.430	993.748	985.531	903.352	1055.342	919.927	830.258	893.350
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	335.1	556.9	705.1	619.0	685.0	655.4	515.8	645.2
max [s]	5363.9	5594.6	4106.1	4101.5	5591.2	4820.2	3621.1	4046.4
deadline	284	292	313	308	285	303	294	305
ratio [%]	0.590	0.607	0.651	0.640	0.593	0.630	0.611	0.634
delivered	451	432	436	445	428	450	450	452
ratio [%]	0.938	0.898	0.906	0.925	0.890	0.936	0.936	0.940
error ratio [%]	0.653	0.709	0.744	0.715	0.703	0.694	0.676	0.694

C.6.4 Rapid

Table C.24: Rapid performance in case of an additional uncontrolled ferrys (I)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	476.374	473.671	441.495	450.667	435.955	436.116	433.258	429.733
stdev [s]	605.547	608.519	588.498	588.110	581.888	578.795	582.223	583.069
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	190.0	202.2	160.0	195.6	164.8	167.4	167	168.4
max [s]	3119.4	3125.2	2925.2	2865.1	2870.4	2881.5	3122.9	3122.9
deadline	255	259	254	259	259	257	257	255
ratio [%]	0.530	0.538	0.528	0.538	0.538	0.534	0.534	0.530
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.543	0.551	0.541	0.551	0.551	0.547	0.547	0.543

Table C.25: Rapid performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	594.805	637.570	651.021	649.267	607.200	604.995	561.834	552.477
stdev [s]	714.862	730.691	760.415	737.326	708.973	703.002	681.298	672.811
min [s]	2.0	2.0	2,0	2.0	2.0	2.0	2.0	2.0
median [s]	210.0	243.2	278.8	286.9	238.4	250.4	131	151.1
max [s]	3658.6	3142.6	3771.7	3140.8	3136.6	3147.5	3149.2	3157.2
deadline	230	227	219	223	208	207	192	202
ratio [%]	0.478	0.472	0.455	0.464	0.432	0.430	0.399	0.420
delivered	407	391	382	389	374	375	355	370
ratio [%]	0.846	0.813	0.794	0.809	0.778	0.780	0.738	0.769
error ratio [%]	0.632	0.659	0.661	0.655	0.655	0.651	0.661	0.651

C.6.5 Spray and Focus

Table C.26: Spray and Focus performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Small messages (500 Byte)								
avg [s]	587.634	664.928	675.084	661.789	660.029	659.773	652.082	675.927
stdev [s]	818.183	873.738	886.095	870.549	874.519	868.643	865.294	874.659
min [s]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
median [s]	95.6	150.9	166.4	175.5	162.8	162.7	152.7	166.4
max [s]	4780.0	4818.5	4818.5	4818.4	4818.4	4818.4	4818.5	4818.3
deadline	238	246	251	253	256	253	251	251
ratio [%]	0.495	0.511	0.522	0.526	0.532	0.526	0.522	0.522
delivered	475	475	475	475	475	475	475	475
ratio [%]	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
error ratio [%]	0.507	0.524	0.534	0.538	0.545	0.538	0.534	0.534

Table C.27: Spray and Focus performance in case of an additional uncontrolled ferry (II)

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
Larger messages (500 kByte)								
avg [s]	650.746	663.789	683.183	713.372	706.530	713.502	703.308	725.920
stdev [s]	913.364	911.267	928.321	965.470	961.844	959.117	940.951	968.714
min [s]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
median [s]	88.5	101.5	119.0	139.3	145	154.0	156.1	158.2
max [s]	4806.4	4841.3	4748.4	4781.5	4820.3	4841.3	5016.3	4840.0
deadline	229	228	236	246	250	251	250	253
ratio [%]	0.476	0.474	0.491	0.511	0.520	0.522	0.520	0.526
delivered	460	450	452	461	463	466	467	471
ratio [%]	0.956	0.936	0.94	0.958	0.963	0.969	0.971	0.979
error ratio [%]	0.520	0.538	0.551	0.553	0.557	0.553	0.549	0.547

C.7 Comparison of Controlled Ferry Utilization

This section provides the detailed results of the comparison of different protocols in scenarios with one or two controlled message ferries. All evaluations were performed with a message size of 100 kByte.

C.7.1 Single Ferry

Epidemic

Table C.28: Protocol performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	515.9	552.8	580.3	506.7	450.5	539.1	512.8	500.8
stdev [s]	673.2	703.5	810.7	798.7	664.6	753.3	771.8	822.2
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	170.3	131.1	110.5	86.9	90	112.8	104.8	83.7
max [s]	3428.7	3083.5	4397.2	4597.7	3000.1	5507.1	5541.8	6054.4
deadline	280	260	244	205	222	252	244	212
ratio [%]	0.301	0.279	0.262	0.220	0.238	0.271	0.262	0.228
delivered	454	466	452	422	445	476	460	432
ratio [%]	0.488	0.501	0.485	0.453	0.478	0.511	0.494	0.464
error ratio [%]	0.813	0.779	0.777	0.767	0.760	0.759	0.768	0.764

Table C.29: Oracle performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	342.029	380.748	330.653	287.682	239.701	272.952	214.602	211.621
stdev [s]	387.142	476.206	396.535	415.128	346.067	410.598	360.967	347.455
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	205.3	133.6	122.3	31.5	4.0	3.6	3.6	3.6
max [s]	1622.7	2075.1	1390.1	1909.9	1485.8	1839.0	1645.0	1485.8
deadline	536	489	476	414	382	358	310	303
ratio [%]	0.576	0.525	0.511	0.445	0.410	0.385	0.333	0.325
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.589	0.538	0.524	0.458	0.423	0.397	0.346	0.338

MaxProp

Table C.30: Protocol performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	245.7	268.3	262.2	292.9	264.6	214.8	245.4	209.1
stdev [s]	255.1	313.1	320.6	370.2	319.7	244.0	279.8	244.3
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	159.7	169.0	162.5	172.5	147.0	118.5	143.4	120.3
max [s]	1188.3	1525.6	1725	2272.6	1439.5	1090.9	1382.2	1229.6
deadline	558	541	551	557	536	501	533	509
ratio [%]	0.599	0.581	0.592	0.598	0.576	0.538	0.573	0.547
delivered	918	918	918	918	918	918	918	918
ratio [%]	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986
error ratio [%]	0.613	0.595	0.606	0.612	0.590	0.552	0.586	0.561

Table C.31: Oracle performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	209.153	257.021	199.263	196.844	185.942	128.362	147.173	97.519
stdev [s]	241.081	400.870	299.119	296.975	307.703	212.911	258.028	175.560
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	126.9	94.6	64.0	27.2	4.0	3.6	3.6	3.6
max [s]	1188.1	2055.2	1589.2	1585.2	1435.1	1004.8	1302.3	970.8
deadline	499	464	432	410	340	305	295	277
ratio [%]	0.536	0.498	0.464	0.440	0.365	0.328	0.317	0.298
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.549	0.511	0.477	0.453	0.378	0.340	0.330	0.310

Rapid

Table C.32: Protocol performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	402.0	359.7	406.7	368.3	271.7	335.0	302.8	315.9
stdev [s]	482.7	423.2	480.7	442.3	262.3	402.8	315.9	333.0
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	251.1	218.3	210.5	208.6	202.2	202.0	210.8	215.2
max [s]	2271.7	2090.7	2155.8	2197.1	1233.1	2168.9	1607.9	1752.3
deadline	604	582	589	607	582	575	577	558
ratio	0.649	0.625	0.633	0.652	0.625	0.618	0.620	0.599
delivered	919	919	918	919	904	890	887	870
ratio	0.987	0.987	0.986	0.987	0.971	0.956	0.953	0.934
error ratio	0.662	0.638	0.647	0.665	0.654	0.662	0.667	0.665

Table C.33: Oracle performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	320.854	257.021	301.776	251.143	148.187	212.652	138.056	127.775
stdev [s]	453.731	400.87	453.559	413.261	216.235	388.38	235.503	255.828
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	153.4	94.6	73.7	26.4	4	3.6	3.6	3.6
max [s]	2268.4	2055.2	2105.9	1985.8	1082.9	2158.8	1200.7	1535.6
deadline	530	464	444	393	363	332	296	260
ratio [%]	0.569	0.498	0.477	0.422	0.390	0.357	0.318	0.279
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.582	0.511	0.490	0.435	0.402	0.369	0.331	0.292

Spray and Focus

Table C.34: Protocol performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	836.8	698.1	756.3	686.8	845.9	860.1	748.7	745.1
stdev [s]	888.0	855.1	946.3	843.8	974.6	1004.0	1007.8	950.0
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	704.7	436.5	443.5	340.7	532	573.5	379.7	474.1
max [s]	5282.1	4804.3	5609.5	4777.3	5791.6	5447.4	5572.1	5573.8
deadline	593	577	579	563	578	580	568	552
ratio [%]	0.637	0.620	0.622	0.605	0.621	0.623	0.610	0.593
delivered	910	906	905	897	913	912	906	884
ratio [%]	0.977	0.973	0.972	0.963	0.981	0.98	0.973	0.950
error ratio [%]	0.66	0.647	0.650	0.641	0.640	0.643	0.637	0.643

Table C.35: Oracle performance in case of an additional controlled ferry

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	638.113	410.856	438.052	424.074	406.363	351.059	231.782	257.156
stdev [s]	686.170	522.900	608.213	640.099	560.740	549.715	398.478	435.145
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	506.8	154.0	143.6	34.7	4.0	3.6	3.6	3.6
max [s]	3073.5	2266.1	2613.1	2832.6	2136.5	2507.2	2016.2	2163.3
deadline	561	498	483	428	400	350	322	301
ratio [%]	0.603	0.535	0.519	0.460	0.430	0.376	0.346	0.323
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.615	0.548	0.532	0.473	0.443	0.389	0.359	0.336

C.7.2 Two Ferries

Epidemic

Table C.36: Protocol performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	503.2	518.1	454.1	512.3	490.1	486.8	430.5	459.1
stdev [s]	598.3	678.5	626.2	716.5	675.1	666.2	606.3	667.3
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	221.8	166.9	145.1	112.2	126.4	126.8	113.0	103.5
max [s]	3469.7	3436.1	3099.3	4331.0	3056.2	3474.1	3036.7	4383.3
deadline	344	288	298	255	274	264	265	248
ratio [%]	0.369	0.309	0.320	0.274	0.294	0.284	0.285	0.266
delivered	537	493	512	476	478	468	491	473
ratio [%]	0.577	0.530	0.550	0.511	0.513	0.503	0.527	0.508
error ratio [%]	0.793	0.780	0.770	0.763	0.781	0.781	0.757	0.758

Table C.37: Oracle performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	219.755	211.659	227.447	214.834	220.174	194.324	128.862	155.874
stdev [s]	268.983	285.326	346.007	351.761	321.727	313.028	220.666	280.162
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	122.1	80.6	73.6	22.9	4.0	3.6	3.6	3.6
max [s]	1181.7	1409.1	1915.5	1995.1	1366.5	1368.0	1097.0	1284.9
deadline	494	450	436	391	368	341	300	287
ratio [%]	0.531	0.483	0.468	0.420	0.395	0.366	0.322	0.308
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.544	0.496	0.481	0.433	0.408	0.379	0.335	0.321

MaxProp

Table C.38: Protocol performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	191.9	184.2	193.9	164.8	169.7	165.7	151.6	167.5
stdev [s]	224.7	198.0	219.8	214.9	219.1	201.2	174.4	207.8
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	112.8	128.4	120.1	97	95.5	98.5	98.1	94.0
max [s]	1236.2	992.3	1055.3	1342.0	1323.3	991.4	1044.6	1115.8
deadline	531	529	512	475	481	480	476	465
ratio [%]	0.570	0.568	0.550	0.510	0.517	0.516	0.511	0.499
delivered	918	918	918	918	918	918	918	918
ratio [%]	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986
error ratio [%]	0.584	0.582	0.564	0.524	0.531	0.530	0.525	0.513

Table C.39: Oracle performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	152.798	133.604	137.309	112.000	108.539	94.869	73.782	95.537
stdev [s]	209.837	176.029	195.248	201.839	191.356	173.120	134.783	186.684
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	80.4	58.6	41.6	12.2	3.6	3.6	3.6	3.6
max [s]	1049.4	958.9	941.7	1340.0	1206.8	989.1	909.6	951.9
deadline	439	407	388	294	316	270	241	240
ratio [%]	0.472	0.437	0.417	0.316	0.339	0.290	0.259	0.258
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.484	0.450	0.430	0.329	0.352	0.303	0.272	0.271

Rapid

Table C.40: Protocol performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	334.5	310.9	331.1	278.4	283.0	271.0	296.2	224.5
stdev [s]	427.4	410.7	423.0	381.7	378.0	325.8	394.1	237.9
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	185.9	172.5	190.1	161.2	158.4	154.2	149.6	147.6
max [s]	2154.5	2095.0	2216.0	2026.0	1947.6	1767.0	1984.9	1363.1
deadline	571	562	577	574	571	570	529	566
ratio [%]	0.613	0.604	0.620	0.617	0.613	0.612	0.568	0.608
delivered	919	919	918	919	916	919	871	907
ratio [%]	0.987	0.987	0.986	0.987	0.984	0.987	0.936	0.974
error ratio [%]	0.626	0.617	0.634	0.629	0.629	0.625	0.633	0.634

Table C.41: Oracle performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	270.123	243.115	246.321	198.895	187.145	158.174	179.265	93.141
stdev [s]	418.512	401.949	406.512	379.215	363.488	292.705	356.510	187.860
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	102.6	67.0	50.6	18.6	4.0	3.6	3.6	3.6
max [s]	2082.1	2067.2	2045.9	2009.6	1942.0	1582.2	1816.3	1362.3
deadline	483	434	417	354	329	303	287	246
ratio[%]	0.519	0.466	0.448	0.380	0.353	0.325	0.308	0.264
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.532	0.479	0.461	0.393	0.366	0.338	0.321	0.277

Spray and Focus

Table C.42: Protocol performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	673.1	665.5	578.6	751.1	723.1	759.2	702.7	721.2
stdev [s]	900.3	777.1	728.2	923.6	826.1	974.8	897.4	985.4
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	299.5	399.2	265.8	466.4	452.0	374.3	422.1	336.2
max [s]	4816.3	3587.5	3587.9	4938.0	4919.4	5314.0	5660.6	5401.4
deadline	585	580	571	577	566	559	571	555
ratio [%]	0.628	0.623	0.613	0.62	0.608	0.6	0.613	0.596
delivered	914	917	918	910	903	900	899	892
ratio [%]	0.982	0.985	0.986	0.977	0.97	0.967	0.966	0.958
error ratio [%]	0.647	0.638	0.627	0.642	0.638	0.634	0.648	0.638

Table C.43: Oracle performance in case of two additional controlled ferries

Metric	No. of Backbone Nodes							
	0	5	10	15	20	25	30	35
avg [s]	362.652	374.728	340.330	383.609	337.458	308.308	242.632	206.017
stdev [s]	468.213	493.647	511.205	558.621	513.516	495.057	416.353	380.562
min [s]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
median [s]	157	170.2	69.1	38.2	4	3.6	3.6	3.6
max [s]	2191.7	2152.2	2152.1	2443	2136.5	2063.2	2109.4	2090.6
deadline	522	494	437	425	382	331	325	290
ratio[%]	0.561	0.531	0.469	0.456	0.410	0.356	0.349	0.311
delivered	919	919	919	919	919	919	919	919
ratio [%]	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
error ratio [%]	0.574	0.544	0.482	0.469	0.423	0.368	0.362	0.324

C.8 Impact of Multicast Messages

Table C.44 provides the results of the evaluation of the Host EID Addressing Module using EIDs for both unicast and multicast messages. Besides that, several multicast messages were generated either as true multicast messages addressed to a group or by generating separate unicast messages for each recipient. The message size is set to 100 kB.

Table C.44: Evaluation of multicast addresses

Multicast generation	by Unicast	by Multicast	
Protocol	Epidemic	Epidemic	Prophet
total of messages	931	850	850
avg [s]	921.394	541.417	221.404
stdev [s]	1096.572	965.388	440.427
min [s]	0.400	0.400	0.400
median [s]	669.500	104.800	10.000
max [s]	5740.000	4852.600	1952.900
received messages	465	331	613
delivery ratio [%]	0.499	0.389	0.721
Metrics related to multicast messages			
no. of messages	104	104	104
reduction	0	81	81
received messages	34	25	58
delivery ratio [%]	0.327	0.240	0.558

Bibliography

[1] T. Andre, K. A. Hummel, A. P. Schoellig, E. Yanmaz, M. Asadpour, C. Bettstetter, P. Grippa, H. Hellwagner, S. Sand, and S. Zhang: 'Application-Driven Design of Aerial Communication Networks'. In: *Communications Magazine* (2014), vol. 52(5), pp. 129–137.

[2] G. Araniti, N. Bezirgiannidis, E. Birrane, I. Bisio, S. Burleigh, C. Caini, M. Feldmann, M. Marchese, J. Segui, and K. Suzuki: 'Contact graph routing in DTN space networks: overview, enhancements and performance'. In: *Communications Magazine* (2015), vol. 53(3), pp. 38–46.

[3] A. Ariza-Quintana, E. Casilari, and A. Triviño Cabrera: 'Implementation of MANET routing protocols on OMNeT++'. In: *1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops (SIMUTools)*. Article 80. Marseille, France: ICST, Mar. 2008.

[4] M. Asadpour, D. Giustiniano, and K. A. Hummel: 'From ground to aerial communication: dissecting WLAN 802.11 n for the drones'. In: *8th ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization (WiNTECH)*. Miami, FL, USA: ACM, Sept. 2013, pp. 25–32.

[5] M. Asadpour, K. A. Hummel, D. Giustiniano, and S. Draskovic: 'Route or carry: Motion-driven packet forwarding in micro aerial vehicle networks'. In: *IEEE Transactions on Mobile Computing* (2017), vol. 16(3), pp. 843–856.

[6] N. Aschenbruck, R. Ernst, E. Gerhards-Padilla, and M. Schwamborn: 'BonnMotion - A Mobility Scenario Generation and Analysis Tool'. In: *3rd International ICST Conference on Simulation Tools and Techniques (SIMUTools)*. Article No. 51. Torremolinos, Malaga, Spain: ICST, May 2010.

[7] N. Aschenbruck, E. Gerhards-Padilla, M. Gerharz, M. Frank, and P. Martini: 'Modelling Mobility in Disaster Area Scenarios'. In: *10th ACM-IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM)*. Chania, Crete Island, Greece: ACM, Oct. 2007, pp. 4–12.

[8] N. Aschenbruck, M. Gerharz, M. Frank, and P. Martini: 'Modelling Voice Communication in Disaster Area Scenarios'. In: *31st IEEE Conference on Local Computer Networks (LCN)*. Tampa, FL, USA: IEEE, Nov. 2006, pp. 211–220.

[9] M. Asplund, S. Nadjm-Tehrani, and J. Sigholm: 'Emerging Information Infrastructures: Cooperation in Disasters'. In: *3rd International Workshop Critical Information Infrastructure Security (CRITIS)*. Rome, Italy: Springer, Oct. 2008, pp. 258–270.

[10] A. Balasubramanian, B. Levine, and A. Venkataramani: 'DTN Routing as a Resource Allocation Problem'. In: *ACM SIGCOMM Computer Communication Review* (2007), vol. 37(4), pp. 373–384.

[11] G. Bayer, S. Schneider, and A. Schweigger: *Kommunikation im Einsatz: Planung, Organisation und Technik (Einsatzpraxis)*. Ed. by U. Cimolino. 2nd ed. (in German). ecomed Sicherheit, July 2008.

[12] S. Bayhan, E. Hyytia, J. Kangasharju, and J. Ott: 'Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs'. In: *International Conference on Communications (ICC)*. London, UK: IEEE, June 2015, pp. 3287–3292.

[13] P. Begerow: 'Zuverlässige Gruppenkommunikation in mobilen Ad-hoc-Netzen auf Basis eines verzögerungstoleranten Kommunikationsdienstes'. (in German). Dissertation. Technische Universität Ilmenau, 2016.

[14] P. Begerow, S. Krug, K. Renhak, A. Al Rubaye, and J. Seitz: 'Delay Tolerant Handover for Heterogeneous Networks'. In: *39th IEEE Conference on Local Computer Networks (LCN)*. Edmonton, Canada: IEEE, Sept. 2014, pp. 370–373.

[15] P. Begerow, S. Krug, S. Schellenberg, and J. Seitz: 'Buffer Management for Reliable Multicast over Delay Tolerant Networks'. In: *10th International Conference on Mobile Ad hoc and Sensor Networks (MSN)*. Maui, HI, USA: IEEE, Dec. 2014, pp. 171–178.

[16] P. Begerow, S. Krug, S. Schellenberg, and J. Seitz: 'Robust Reliability-aware Buffer Management for DTN Multicast in Disaster Scenarios'. In: *3rd International Workshop on Understanding the inter-play between Sustainability, Resilience, and Robustness in networks (USRR)*. Munich, Germany: IEEE, Oct. 2015, pp. 274–280.

[17] P. Begerow, S. Schellenberg, J. Seitz, T. Finke, and J. Schröder: 'Reliable Multicast in Heterogeneous Mobile Ad Hoc Networks'. In: *Combined Workshop on Self-organizing, Adaptive, and Context-Sensitive Distributed Systems and Self-organized Communication in Disaster Scenarios (SACS/SoCoDiS)*. Stuttgart, Germany, Mar. 2013.

[18] M. Betz and V. Wulf: 'EmergencyMessenger: A Text based Communication Concept for Indoor Firefighting'. In: *SIGCHI Conference on Human Factors in Computing Systems (CHI)*. Toronto, Canada: ACM, Apr. 2014, pp. 1515–1524.

[19] S. Bhattacharjee, S. Basu, S. Roy, and S. D. Bit: 'Best-effort Delivery of Emergency Messages in Post-disaster Scenario with Content-based Filtering and Priority-enhanced PRoPHET over DTN'. In: *8th International Conference on Communication Systems and Networks (COMSNETS)*. Bengaluru, India: IEEE, Jan. 2016, pp. 1–7.

[20] D. M. Bravo: 'Impact of Different Ferry Types on DTN Routing Protocols'. Basic Research Project. Technische Universität Ilmenau, July 2016.

[21] D. M. Bravo: 'Impact of Different Message Sizes on DTN Routing Protocol Performance'. Advanced Research Project. Technische Universität Ilmenau, Feb. 2017.

[22] A. Brychcy: 'Evaluation von Ad-hoc-fähigen Funklösungen für Demonstratoren im Innen- und Außenbereich'. (in German). Masterarbeit. Technische Universität Ilmenau, Nov. 2015.

[23] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine: 'MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks'. In: *25th IEEE International Conference on Computer Communications (INFOCOM)*. Barcelona, Spain: IEEE, Apr. 2006, pp. 1–11.

[24] S. Burleigh: *Contact Graph Routing*. Internet Draft (Experimental). Internet Engineering Task Force, July 2010.

[25] T. Camp, J. Boleng, and V. Davies: 'A Survey of Mobility Models for Ad Hoc Network Research'. In: *Wireless Communications and Mobile Computing* (Sept. 2002), vol. 2(5), pp. 483–502.

[26] A. Casteigts, P. Flocchini, B. Mans, and N. Santoro: 'Measuring Temporal Lags in Delay-Tolerant Networks'. In: *Transactions on Computers* (2014), vol. 63(2), pp. 397–410.

[27] A. Casteigts, P. Flocchini, W. Quattrociocchi, and N. Santoro: 'Time-Varying Graphs and Dynamic Networks'. In: *International Journal of Parallel, Emergent and Distributed Systems* (2012), vol. 27(5), pp. 387–408.

[28] A. Casteigts, R. Klasing, Y. M. Neggaz, and J. G. Peters: 'Efficiently Testing T-Interval Connectivity in Dynamic Graphs'. In: *9th International Conference on Algorithms and Complexity (CIAC)*. Paris, France: Springer, May 2015, pp. 89–100.

[29] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, and H. Weiss: *Delay-Tolerant Networking Architecture*. RFC 4838 (Informational). Internet Engineering Task Force, Apr. 2007.

[30] T. Clausen, C. Dearlove, J. Dean, and C. Adjih: *Generalized Mobile Ad Hoc Network (MANET) Packet/Message Format*. RFC 5444 (Standards Track). Internet Engineering Task Force, Feb. 2009.

[31] T. Clausen and P. Jacquet: *Optimized Link State Routing Protocol (OLSR)*. RFC 3626 (Experimental). Internet Engineering Task Force, Oct. 2003.

[32] E. M. Daly and M. Haahr: 'Social Network Analysis for Routing in Disconnected Delay-Tolerant MANETs'. In: *8th International Symposium on Mobile Ad hoc Networking and Computing (MobiHoc)*. Montreal, Canada: ACM, Sept. 2007, pp. 32–40.

[33] L. Delosieres and S. Nadjm-Tehrani: 'BATMAN Store-and-Forward: the Best of the Two Worlds'. In: *2nd International Workshop on Pervasive Networks for Emergency Management (PerNEM)*. Lugano, Switzerland: IEEE, Mar. 2012, pp. 721–727.

[34] M. D'Emidio and D. Frigioni: 'Engineering shortest-path algorithms for dynamic networks'. In: *15th Italian Conference on Theoretical Computer Science (ICTCS)*. Perugia, Italy, Sept. 2014, pp. 265–269.

[35] T. Dietrich, S. Krug, and A. Zimmermann: 'A Discrete Event Simulation and Optimization Framework for Multi UAV System Maintenance Processes'. In: *IEEE International Symposium on Systems Engineering (ISSE)*. (submitted). Vienna, Austria: IEEE, Oct. 2017.

[36] T. Dietrich, S. Krug, and A. Zimmermann: 'An Empirical Study on Generic Multicopter Energy Consumption Profiles'. In: *11th Annual IEEE International Systems Conference (SysCon)*. Montreal, Canada: IEEE, Apr. 2017.

[37] L. Djinevski, S. Stojanova, and D. Trajanov: 'Optimizing Durkins Propagation Model Based on TIN Terrain Structures'. In: *5th Conference for Information and Communication Technologies (ICT Innovations)*. Ohrid, Macedonia: Springer, Sept. 2013, pp. 263–272.

[38] M. Doering, S. Lahde, J. Morgenroth, and L. Wolf: 'IBR-DTN: An Efficient Implementation for Embedded Systems'. In: *3rd ACM Workshop on Challenged Networks (CHANTS)*. San Francisco, CA, USA: ACM, Sept. 2008, pp. 117–120.

[39] M. Doering, W.-B. Pöttner, T. Pögel, and L. Wolf: 'Impact of Radio Range on Contact Characteristics in Bus-based Delay Tolerant Networks'. In: *8th International Conference on Wireless On-Demand Network Systems and Services (WONS)*. Garmisch-Partenkirchen, Germany: IEEE, Jan. 2011, pp. 195–202.

[40] R. Edwards and J. Durkin: 'Computer prediction of service areas for vhf mobile radio networks'. In: *Proceedings of the Institution of Electrical Engineers* (1969), vol. 116(9), pp. 1493–1500.

[41] F. Ekman, A. Keränen, J. Karvo, and J. Ott: 'Working Day Movement Model'. In: *1st ACM SIGMOBILE International Workshop on Mobility Models for Networking Research (MobilityModels)*. Hong Kong, China: ACM, May 2008, pp. 33–40.

[42] A. Elsts, H. Wennerström, and C. Rohner: 'IEEE 802.15. 4 Channel Diversity in an Outdoor Environment'. In: *6th ACM Workshop on Real World Wireless Sensor Networks*. Seoul, South Korea: ACM, Nov. 2015, pp. 11–14.

[43] N. Eulig: *BOS-Sprechfunk*. Tech. rep. THW OV Northeim, Jan. 2010.

[44] J. B. Evans, B. J. Ewy, M. T. Swink, S. G. Pennington, D. J. Siquieros, and S. L. Earp: 'TIGR: The Tactical Ground Reporting System'. In: *Communications Magazine* (2013), vol. 51, pp. 42–49.

[45] K. Fall: 'A Delay-Tolerant Network Architecture for Challenged Internets'. In: *Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications (SIGCOMM)*. Karlsruhe, Germany: ACM, Aug. 2003, pp. 27–34.

[46] K. Fall, G. Iannaccone, J. Kannan, F. Silveira, and N. Taft: 'A Disruption-Tolerant Architecture for Secure and Efficient Disaster Response Communications'. In: *7th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. Seattle, WA, USA, May 2010.

[47] A. Ferreira, A. Goldman, and J. Monteiro: 'Performance evaluation of routing protocols for MANETs with known connectivity patterns using evolving graphs'. In: *Wireless Networks* (2010), vol. 16(3), pp. 627–640.

[48] S. Filiposka and D. Trajanov: 'Terrain-aware three-dimensional radio-propagation model extension for NS-2'. In: *Simulation* (2011), vol. 87(1-2), pp. 7–23.

[49] S. Filiposka, D. Trajanov, and M. Vuckovik: 'Performances of Clustered Ad Hoc Networks on 3D Terrains'. In: *2nd International Conference on Simulation Tools and Techniques (SIMUTools)*. Article 45. Rome, Italy: ICST, Mar. 2009.

[50] T. Finke: 'SEREMA – Self-Organized Routing in Heterogeneous Mobile Ad Hoc Networks'. Dissertation. Technische Universität Ilmenau, 2016.

[51] T. Finke, J. Schroeder, S. Schellenberg, M. Hager, and J. Seitz: 'Address Resolution in Mobile Ad Hoc Networks using Adaptive Routing'. In: *7th International Conference on Systems and Networks Communications (ICSNC)*. Lisbon, Portugal: IARIA, Nov. 2012, pp. 7–12.

[52] S. Golisch and C. Gerhardt: 'Anbindung von Lagesensoren an Raspberry Pi'. (in German). Projektseminar. Technische Universität Ilmenau, Feb. 2016.

[53] C. Grant, A. Hamins, N. Bryner, A. Jones, and G. Koepke: *Research Roadmap for Smart Fire Fighting – Summary Report*. Special Publication 1191. National Institute of Standards and Technology (NIST). May 2015.

[54] S. Grasic: 'Not-so-instant-messaging Service for the Delay Tolerant Networks'. In: *14th International Multiconference Information Society - IS*. Ljubljana, Slovenia, Oct. 2011, pp. 203–207.

[55] S. Grasic and A. Lindgren: 'An Analysis of Evaluation Practices for DTN Routing Protocols'. In: *7th ACM International Workshop on Challenged Networks (CHANTS)*. Istanbul, Turkey: ACM, Aug. 2012, pp. 57–64.

[56] D. Gumpricht: 'Konzeption eines Demonstrators für Delay-tolerante Netzwerke'. (in German). Diplomarbeit. Technische Universität Ilmenau, Sept. 2015.

[57] A. K. Gupta, I. Bhattacharya, P. S. Banerjee, J. K. Mandal, and A. Mukherjee: 'DirMove: direction of movement based routing in DTN architecture for post-disaster scenario'. In: *Wireless Networks* (2016), vol. 22(3), pp. 723–740.

[58] M. Harounabadi and A. Mitschele-Thiel: 'Stigmergic Communication for Self-Organized Multi Ferry Delay Tolerant Networks'. In: *Mobile Networks and Applications* (2017), vol., pp. 1–10.

[59] M. Harounabadi, A. Rubina, and A. Mitschele-Thiel: 'Cooperative On-the-Fly Decision Making in Mobility-Controlled Multi Ferry Delay Tolerant Networks'. In: *8th EAI International Conference on Ad Hoc Networks (AdHocNets)*. Ottawa, Canada: Springer, Sept. 2016, pp. 246–257.

[60] S. Hayat, E. Yanmaz, and C. Bettstetter: 'Experimental Analysis of Multipoint-to-Point UAV Communications with IEEE 802.11n and 802.11ac'. In: *26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. Hong Kong, China: IEEE, Aug. 30–Sept. 2, 2015, pp. 1991–1996.

[61] G. Heindl: 'Neue breitbandige Datendienste unter einsatztaktischen Gesichtspunkten mit Anwendungsbeispielen'. In: *Breitbandsymposium*. (in German). Professioneller Mobilfunk e.V. Berlin, Germany, Sept. 2014.

[62] M. Helbig: 'Konzeption eines dynamischen Mobilitätsmodells zur Simulation von Kontext-abhängigen Bewegungen in ONE'. (in German). Bachelorarbeit. Technische Universität Ilmenau, 2017.

[63] Ó. R. Helgason and K. V. Jónsson: 'Opportunistic Networking in OMNeT++'. In: *1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops (SIMUTools)*. Article 82. Marseille, France: ICST, Mar. 2008.

[64] Ó. R. Helgason, S. T. Kouyoumdjieva, and G. Karlsson: 'Does Mobility Matter?' In: *7th International Conference on Wireless On-demand Network Systems and Services (WONS)*. Kranjska Gora, Slovenia: IEEE, Feb. 2010, pp. 9–16.

[65] P. Holme and J. Saramäki: 'Temporal networks'. In: *Physics reports* (2012), vol. 519(3), pp. 97–125.

[66] T. Hossmann, F. Legendre, and T. Spyropoulos: 'From Contacts to Graphs: Pitfalls in Using Complex Network Analysis for DTN Routing'. In: *1st IEEE International Workshop on Network Science For Communication Networks (NetSciCom)*. Rio de Janeiro, Brazil: IEEE, Apr. 2009, pp. 260–265.

[67] T. Hossmann, T. Spyropoulos, and F. Legendre: 'Know Thy Neighbor: Towards Optimal Mapping of Contacts to Social Graphs for DTN Routing'. In: *29th Conference on Computer Communications (INFOCOM)*. San Diego, CA, USA: IEEE, Mar. 2010, pp. 866–874.

[68] *IEEE Standard for Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. IEEE, 2012.

[69] *IEEE Standard for Local and metropolitan area networks – Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*. IEEE, 2011.

[70] T. Islam, A. Turkulainen, and J. Ott: 'Voice Messaging for Mobile Delay-Tolerant Networks'. In: *3rd International Conference on Communication Systems and Networks (COMSNETS)*. Bangalore, India: IEEE, Jan. 2011, pp. 1–11.

[71] M. Ito, H. Nishiyama, and N. Kato: 'A Novel Communication Mode Selection Technique for DTN over MANET Architecture'. In: *International Conference on Computing, Networking and Communications (ICNC)*. Honolulu, HI, USA: IEEE, Feb. 2014, pp. 551–555.

[72] D. Johnson, Y. Hu, and D. Maltz: *The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4*. RFC 4728 (Experimental). Internet Engineering Task Force, Feb. 2007.

[73] D. Johnsson, N. Ntlatlapa, and C. Aichele: 'Simple pragmatic approach to mesh routing using BATMAN'. In: *2nd IFIP International Symposium on Wireless Communications and Information Technology in Developing Countries (CSIR)*. Pretoria, South Africa: IFIP, 2008.

[74] L. Joneckis, C. Kramer, D. Sparrow, and D. Tate: 'Modeling terrain impact on MANET connectivity'. In: *Military Communications Conference (MILCOM)*. Baltimore, MD, USA: IEEE, Oct. 2014, pp. 1382–1386.

[75] K. V. Jónsson, Ý. Vigfússon, and Ó. Helgason: 'Simulating Large-scale Dynamic Random Graphs in OMNeT++'. In: *5th International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops (SimuTools)*. Sirmione-Desenzano, Italy: ICST, Mar. 2012, pp. 311–318.

[76] A. Keränen, J. Ott, and T. Kärkkäinen: 'The ONE Simulator for DTN Protocol Evaluation'. In: *2nd International Conference on Simulation Tools and Techniques (SIMUTools)*. Article 55. Rome, Italy: ICST, Mar. 2009.

[77] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott: 'Experimental evaluation of wireless simulation assumptions'. In: *7th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*. Venice, Italy: ACM, Oct. 2004, pp. 78–82.

[78] C. Kretschmer, S. Rührup, and C. Schindelhauer: 'DT-DYMO: Delay-tolerant Dynamic MANET On-demand Routing'. In: *3rd International Workshop on Wireless Mesh and Ad Hoc Networks (WiMAN)*. Montreal, Canada: IEEE, June 2009, pp. 493–498.

[79] S. Krug: 'Analyse von Einflussgrößen auf die Kommunikation von Rettungskräften anhand verschiedener Einsatzszenarien'. In: *13. Ilmenauer TK-Manager-Workshop (Tagungsband)*. (in German). Ilmenau, Germany, Sept. 2014.

[80] S. Krug, P. Begerow, A. Al Rubaye, S. Schellenberg, and J. Seitz: 'A Realistic Underlay Concept for Delay Tolerant Networks in Disaster Scenarios'. In: *10th International Conference on Mobile Ad-hoc and Sensor Networks (MSN)*. Maui, HI, USA: IEEE, Dec. 2014, pp. 163–170.

[81] S. Krug, A. Brychcy, and J. Seitz: 'A Mobile Embedded-Linux-Based Testbed for Outdoor Ad Hoc Network Evaluation'. In: *International Conference Wireless for Space and Extreme Environments (WiSEE)*. Aachen, Germany: IEEE, Sept. 2016, pp. 164–166.

[82] S. Krug, M. Debes, and J. Seitz: 'Framework zur Simulation von realistischen Einsatzszenarien'. In: *44. Jahrestagung der Gesellschaft für Informatik (INFORMATIK) Big Data – Komplexität meistern*. (in German). Stuttgart, Germany: GI, Sept. 2014, pp. 953–964.

[83] S. Krug, S. Schellenberg, and J. Seitz: 'Impact of Traffic and Mobility Patterns on Network Performance in Disaster Scenarios'. In: *10th ACM MobiCom workshop on Challenged networks (CHANTS)*. Paris, France: ACM, Sept. 2015, pp. 9–12.

[84] S. Krug and J. Seitz: 'A Framework to Calculate Delay-Optimal Oracle Solutions based on DTN Contact Graphs'. In: *23rd European Wireless (EW)*. Dresden, Germany: VDE Verlag, May 2017, pp. 179–184.

[85] S. Krug and J. Seitz: 'Challenges of Applying DTN Routing Protocols in Realistic Disaster Scenarios'. In: *8th International Conference on Ubiquitous and Future Networks (ICUFN)*. Vienna, Austria: IEEE, July 4–8, 2016, pp. 784–789.

[86] S. Krug and J. Seitz: 'Exploiting Already Deployed Sensor Networks for Opportunistic Emergency Communication Services'. In: *14. GI/ITG KuVS Fachgespräch Sensornetze (FGSN 2015)*. Erlangen, Germany, Sept. 22–23, 2016.

[87] S. Krug and J. Seitz: 'Impact of Environmental Conditions on WiFi-based Outdoor Mesh Networks'. In: *15. GI/ITG KuVS Fachgespräch Sensornetze (FGSN 2016)*. Ed. by J. Scholz and A. von Bodisco. Technical Reports. Augsburg, Germany, Sept. 22–23, 2016, pp. 1–4.

[88] S. Krug and J. Seitz: 'Utilization of Additional Nodes in Hybrid DTN-MANET Scenarios'. In: *12th ACM MobiCom workshop on Challenged networks (CHANTS)*. (submitted). Snowbird, UT, USA: ACM, Oct. 2017.

[89] S. Krug, M. F. Siracusa, S. Schellenberg, P. Begerow, J. Seitz, T. Finke, and J. Schröder: 'Movement Patterns for Mobile Networks in Disaster Scenarios'. In: *8th IEEE WoWMoM workshop on Autonomic and Opportunistic Communications (AOC)*. Sydney, Australia: IEEE, June 2014, pp. 1–6.

[90] H. Kruse, S. Jero, and S. Ostermann: *Datagram Convergence Layers for the Delay- and Disruption-Tolerant Networking (DTN) Bundle Protocol and Licklider Transmission Protocol (LTP)*. RFC 7122 (Experimental). Internet Engineering Task Force, Mar. 2014.

[91] J. Lakkakorpi and P. Ginzboorg: 'ns-3 Module for Routing and Congestion Control Studies in Mobile Opportunistic DTNs'. In: *International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)*. Toronto, Canada: IEEE, July 2013, pp. 46–50.

[92] J. Lakkakorpi, M. Pitkänen, and J. Ott: 'Adaptive Routing in Mobile Opportunistic Networks'. In: *13th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM)*. Bodrum, Turkey: ACM, Oct. 2010, pp. 101–109.

[93] F. Legendre, V. Borrel, M. D. De Amorim, and S. Fdida: 'Reconsidering microscopic mobility modeling for self-organizing networks'. In: *IEEE Network* (2006), vol. 20(6).

[94] L. Lei and H. Li: 'A Routing Policy Based on Time-varying graph for Predictable Delay Tolerant Networks'. In: *7th International Conference on Wireless Communications and Signal Processing (WCSP)*. Nanjing, China: IEEE, Oct. 2015, pp. 1–6.

[95] A. Lindgren, E. Davies, S. Grasic, and A. Doria: *Probabilistic Routing Protocol for Intermittently Connected Networks*. RFC 6693 (Experimental). Internet Engineering Task Force, Aug. 2012.

[96] A. Lindgren, A. Doria, and O. Schelén: 'Probabilistic Routing in Intermittently Connected Networks'. In: *ACM SIGMOBILE Mobile Computing and Communications Review* (2003), vol. 7(3), pp. 19–20.

[97] J. Lundberg and M. Asplund: 'Communication Problems in Crisis Response'. In: *8th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. Lisbon, Portugal, May 2011.

[98] A. Markham, N. Trigoni, and S. Ellwood: 'Effect of rainfall on link quality in an outdoor forest deployment'. In: *International Conference on Wireless Information Networks and Systems (WINSYS)*. Athens, Greece: IEEE, July 2010, pp. 1–6.

[99] C. Mascolo and M. Musolesi: 'SCAR: Context-aware Adaptive Routing in Delay Tolerant Mobile Sensor Networks'. In: *International Conference on Wireless Communications and Mobile Computing (IWCMC)*. Vancouver, Canada: ACM, July 2006, pp. 533–538.

[100] M. Matis, L. Doboš, and J. Papaj: 'An Enhanced Hybrid Social Based Routing Algorithm for MANET-DTN'. In: *Mobile Information Systems* (2016), vol. Article ID 4803242.

[101] C. P. Mayer: *osm2wkt - OpenStreetMap to WKT Conversion*. http://www.chrismc.de/osm2wkt. 2010.

[102] C. P. Mayer and O. P. Waldhorst: 'Routing in hybrid delay tolerant networks'. In: *Computer Communications* (2014), vol. 48, pp. 44–55.

[103] W. Moreira, P. Mendes, and S. Sargento: 'Opportunistic Routing Based on Daily Routines'. In: *13th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. San Francisco, CA, USA: IEEE, June 2012, pp. 1–6.

[104] W. Moreira, P. Mendes, and S. Sargento: 'Social-Aware Opportunistic Routing Protocol Based on User's Interactions and Interests'. In: *5th International Conference on Ad Hoc Networks (ADHOCNETS)*. Barcelona, Spain: Springer, Oct. 2013, pp. 100–115.

[105] S. Mukherjee: 'Comparison of Opportunistic Routing Protocol Simulations in ONE and OMNeT++'. Basic Research Project. Technische Universität Ilmenau, Feb. 2016.

[106] P. Müller: 'Analyse von Kontakten in delaytoleranten Netzen mittels dynamische Graphen'. (in German). Bachelorarbeit. Technische Universität Ilmenau, Oct. 2015.

[107] G. Nannicini and L. Liberti: 'Shortest paths on dynamic graphs'. In: *International Transactions in Operational Research* (2008), vol. 15(5), pp. 551–563.

[108] S. C. Nelson, A. F. Harris III, and R. Kravets: 'Event-driven, Role-based Mobility in Disaster Recovery Networks'. In: *2nd ACM Workshop on Challenged Networks (CHANTS)*. Montreal, Quebec, Canada: ACM, Sept. 2007, pp. 27–34.

[109] M. Neteler, M. H. Bowman, M. Landa, and M. Metz: 'GRASS GIS: A multi-purpose open source GIS'. In: *Environmental Modelling & Software* (2012), vol. 31, pp. 124–130.

[110] A. Neumann, C. Aichele, M. Lindner, and S. Wunderlich: *Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.)* Internet Draft (Experimental). Internet Engineering Task Force, Mar. 2008.

[111] M. E. J. Newman: *Networks: An Introduction*. Oxford University Press, 2010.

[112] H. H. Nguyen: 'Evaluation of MANET- and Opportunistic Routing Protocols in 3D Terrains'. Masterarbeit. Technische Universität Ilmenau, Oct. 2016.

[113] H. H. Nguyen: 'Evaluation of Terrain Aware 3D Propagation for MANETs'. Basic Research Project. Technische Universität Ilmenau, Aug. 2015.

[114] H. H. Nguyen: 'Simulation of Signal Propagation in 3D Terrains'. Advanced Research Project. Technische Universität Ilmenau, Feb. 2016.

[115] H. H. Nguyen, S. Krug, and J. Seitz: 'Simulation of 3D Signal Propagation based on Real World Terrains for Ad-Hoc Network Evaluation'. In: *9th IFIP Wireless and Mobile Networking Conference (WMNC)*. IFIP. Colmar, France: IEEE, July 2016, pp. 131–137.

[116] M. Orlinski and N. Filer: 'Movement speed based inter-probe times for neighbour discovery in mobile ad-hoc networks'. In: *4th International Conference on Ad Hoc Networks (AdHocNets)*. Paris, France: Springer, Oct. 2012, pp. 316–331.

[117] M. Orlinski and N. Filer: 'Neighbour discovery in opportunistic networks'. In: *Ad Hoc Networks* (2015), vol. 25, pp. 383–392.

[118] J. Ott, D. Kutscher, and C. Dwertmann: 'Integrating DTN and MANET Routing'. In: *SIGCOMM Workshop on Challenged Networks (CHANTS)*. Pisa, Italy: ACM, Sept. 2006, pp. 221–228.

[119] R. Pant, A. Tunpan, P. Mekbungwan, R. Virochpoka, and K. Kanchanasut: 'DTN Overlay on OLSR Network'. In: *6th Asian Internet Engineering Conference (AINTEC)*. Bangkok, Thailand: ACM, Nov. 2010, pp. 56–63.

[120] P. S. Paul, S. Nandi, S. K. Dey, K. De, P. Pramanik, and S. Saha: 'Challenges in Designing Testbed for Evaluating Delay-Tolerant Hybrid Networks'. In: *International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*. St. Louis, MO, USA: IEEE, Mar. 2015, pp. 280–283.

[121] C. Perkins, E. Belding-Royer, and S. Das: *Ad hoc On-Demand Distance Vector (AODV) Routing*. RFC 3561 (Experimental). Internet Engineering Task Force, July 2003.

[122] C. Perkins, S. Ratliff, J. Dowdell, L. Steenbrink, and V. Mercieca: *Ad Hoc On-demand Distance Vector Version 2 (AODVv2) Routing*. Internet Draft. Internet Engineering Task Force, May 2016.

[123] T. Phe-Neau, M. D. de Amorim, and V. Conan: 'Fine-Grained Intercontact Characterization in Disruption-Tolerant Networks'. In: *IEEE Symposium on Computers and Communications (ISCC)*. Kerkyra, Greece: IEEE, June 2011, pp. 271–276.

[124] M. Pitkänen, T. Kärkkäinen, and J. Ott: 'Mobility and Service Discovery in Opportunistic Networks'. In: *International Workshop on the Impact of Human Mobility in Pervasive Systems and Applications (PerMoby)*. Lugano, Switzerland: IEEE, Mar. 2012, pp. 204–210.

[125] M. Pitkänen, A. Keränen, and J. Ott: 'Message Fragmentation in Opportunistic DTNs'. In: *2nd IEEE WoWMoM Workshop on Autonomic and Opportunistic Communications (AOC)*. Newport Beach, CA, USA: IEEE, June 2008, pp. 1–7.

[126] C. Raffelsberger and H. Hellwagner: 'A Hybrid MANET-DTN Routing Scheme for Emergency Response Scenarios'. In: *3rd International Workshop on Pervasive Networks for Emergency Management (PerNEM)*. San Diego, CA, USA: IEEE, Mar. 2013, pp. 505–510.

[127] C. Raffelsberger and H. Hellwagner: 'Overview of Hybrid MANET-DTN Networking and its Potential for Emergency Response Operations'. In: *Combined Workshop on Self-organizing, Adaptive, and Context-Sensitive Distributed Systems and Self-organized Communication in Disaster Scenarios (SACS/SoCoDiS)*. Stuttgart, Germany, Mar. 2013.

[128] L. Ramirez, T. Dyrks, J. Gerwinski, M. Betz, M. Scholz, and V. Wulf: 'Landmarke: an ad hoc deployable ubicomp infrastructure to support indoor navigation of firefighters'. In: *Personal and Ubiquitous Computing* (2012), vol. 16(8), pp. 1025–1038.

[129] D. G. Reina, M. Askalani, S. L. Toral, F. Barrero, E. Asimakopoulou, and N. Bessis: 'A Survey on Multihop Ad Hoc Networks for Disaster Response Scenarios'. In: *International Journal of Distributed Sensor Networks* (2015), vol. 11(10).

[130] C. W. Reynolds: 'Steering Behaviors For Autonomous Characters'. In: *Game Developers Conference*. Mar. 1999, pp. 763–782.

[131] P. Rönsch: 'Evaluation von Signalausbreitungsmodellen in OMNeT++ im Vergleich zu Messungen mit 802.11s-Knoten'. (in German). Masterarbeit. Technische Universität Ilmenau, Mar. 2017.

[132] G. Saake and K.-U. Sattler: *Algorithmen und Datenstrukturen: Eine Einführung mit Java*. 5th ed. (in German). dPunkt.verlag, Nov. 2013.

[133] B. K. Saha and S. Misra: 'Effects of heterogeneity on the performance of pocket switched networks'. In: *IET Networks* (2014), vol. 3(2), pp. 110–118.

[134] S. Saha, S. Nandi, P. S. Paul, V. K Shah, A. Roy, and S. K. Das: 'Designing delay constrained hybrid ad hoc network infrastructure for post-disaster communication'. In: *Ad Hoc Networks* (2015), vol. 25, pp. 406–429.

[135] S. Scheibe: 'Entwicklung eines Mechanismus zur Namensauflösung in ONE'. (in German). Masterarbeit. Technische Universität Ilmenau, Mar. 2017.

[136] S. Schellenberg: 'Naming and Address Resolution in Heterogeneous Mobile Ad hoc Networks'. Dissertation. Technische Universität Ilmenau, 2015.

[137] S. Schellenberg, P. Begerow, M. Hager, J. Seitz, T. Finke, and J. Schroeder: 'Implementation and Validation of an Address Resolution Mechanism using Adaptive Routing'. In: *27th International Conference on Information Networking (ICOIN)*. Bangkok, Thailand: IEEE, Jan. 2013, pp. 95–100.

[138] S. Schellenberg, S. Krug, J. Eckert, and J. Seitz: 'Comparison of Application and Network Layer Name Resolution in Mobile Ad hoc Networks'. In: *12th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks (PE-WASUN)*. Cancun, Mexico: ACM, Nov. 2015, pp. 71–76.

[139] S. Schellenberg, S. Krug, T. Finke, P. Begerow, and J. Seitz: 'Inter-Domain Routing and Name Resolution using Border Nodes'. In: *International Conference on Computing, Networking and Communications (ICNC)*. Anaheim, CA, USA: IEEE, Feb. 2015, pp. 950–956.

[140] S. Schellenberg, A. Saliminia, S. Krug, J. Seitz, T. Finke, and J. Schroeder: 'Routing-based and Location-aware Service Discovery in Mobile Ad-hoc Networks'. In: *28th International Conference on Information Networking (ICOIN)*. Phuket, Thailand: IEEE, Feb. 2014, pp. 7–12.

[141] S. Schildt, J. Morgenroth, W.-B. Pöttner, and L. Wolf: 'IBR-DTN: A Lightweight, Modular and Highly Portable Bundle Protocol Implementation'. In: *Workshop on Architectures, Services and Applications for the Next Generation Internet: Global Sensing (WASA-NGI)*. Kiel, Germany: GI, Mar. 2011.

[142] K. Scott and S. Burleigh: *Bundle Protocol Specification*. RFC 5050 (Experimental). Internet Engineering Task Force, Nov. 2007.

[143] T. Simon and A. Mitschele-Thiel: 'A Self-Organized Message Ferrying Algorithm'. In: *7th IEEE WoWMoM workshop on Autonomic and Opportunistic Communications (AOC)*. Madrid, Spain: IEEE, June 2013, pp. 1–6.

[144] T. Simon and A. Mitschele-Thiel: 'Micro Aerial Disaster Communication Systems'. In: *42. Jahrestagung der Gesellschaft für Informatik (INFORMATIK)*. Braunschweig, Germany: GI, Sept. 2012, pp. 165–174.

[145] T. Simon and A. Mitschele-Thiel: 'Next-Hop Decision-Making in Mobility-Controlled Message Ferrying Networks'. In: *1st Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use (DroNet)*. Florence, Italy: ACM, May 2015, pp. 9–14.

[146] C. Sommer, I. Dietrich, and F. Dressler: 'Simulation of Ad Hoc Routing Protocols using OMNeT++'. In: *Mobile Networks and Applications* (2010), vol. 15(6), pp. 786–801.

[147] T. Spyropoulos, K. Psounis, and C. S. Raghavendra: 'Spray and Focus: Efficient Mobility-Assisted Routing for Heterogeneous and Correlated Mobility'. In: *International Workshop on Intermittently Connected Mobile Ad hoc Networks (ICMAN)*. White Plains, NY, USA: IEEE, Mar. 2007, pp. 79–85.

[148] T. Spyropoulos, K. Psounis, and C. S. Raghavendra: 'Spray and Wait: An Efficient Routing Scheme for Intermittently Connected Mobile Networks'. In: *ACM SIGCOMM workshop on Delay Tolerant Networking (WDTN)*. Philadelphia, PA, USA: ACM, Aug. 2005, pp. 252–259.

[149] T. Spyropoulos, R. N. Rais, T. Turletti, K. Obraczka, and A. Vasilakos: 'Routing for disruption tolerant networks: taxonomy and design'. In: *Wireless Networks* (2010), vol. 16(8), pp. 2349–2370.

[150] *Standards for Digital Elevation Models - Part 1: General*. U.S. Geological Survey - National Mapping Division. 1997.

[151] *Standards for Digital Elevation Models - Part 2: Specifications*. U.S. Geological Survey - National Mapping Division. 1998.

[152] *Statement of Requirements for Public Safety Wireless Communications & Interoperablilty*. 1.1. Departement of Homeland Security. 2006.

[153] M. Tarasov, J. Seitz, and O. Artemenko: 'A Network Partitioning Recovery Process in Mobile Ad-Hoc Networks'. In: *7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. Shanghai, China: IEEE, Oct. 2011, pp. 32–36.

[154] T. Tausch: 'Evaluation von Ad-hoc-Kommunikation auf Basis eines Raspberry-Pi-Testbeds mit Bluetooth Low Energy Modulen'. (in German). Bachelorarbeit. Technische Universität Ilmenau, May 2017.

[155] T. Tomic, K. Schmid, P. Lutz, A. Domel, M. Kassecker, E. Mair, I. L. Grixa, F. Ruess, M. Suppa, and D. Burschka: 'Toward a Fully Autonomous UAV: Research Platform for Indoor and Outdoor Urban Search and Rescue'. In: *Robotics & Automation Magazine* (2012), vol. 19(3), pp. 46–56.

[156] S. Trifunovic, S. T. Kouyoumdjieva, B. Distl, L. Pajevic, G. Karlsson, and B. Plattner: 'A Decade of Research in Opportunistic Networks: Challenges, Relevance, and Future Directions'. In: *IEEE Communications Magazine* (2017), vol. 55(1), pp. 168–173.

[157] M. Y. S Uddin, D. M. Nicol, T. F. Abdelzaher, and R. Kravets: 'A Post-Disaster Mobility Model for Delay Tolerant Networking'. In: *Winter Simulation Conference (WSC)*. Austin, Texas: ACM, Dec. 2009, pp. 2785–2796.

[158] A. Vahdat and D. Becker: *Epidemic Routing for Partially-Connected Ad Hoc Networks*. Tech. rep. CS-200006. Duke University, Apr. 2000.

[159] A. Varga and R. Hornig: 'An Overview of the OMNeT++ Simulation Environment'. In: *1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops (SIMUTools)*. Article 60. Marseille, France: ICST, Mar. 2008.

[160] N. Vastardis, K. Yang, and S. Leng: 'Socially-Aware Multi-phase Opportunistic Routing for Distributed Mobile Social Networks'. In: *Wireless Personal Communications* (2014), vol. 79(2), pp. 1343–1368.

[161] L. F. M. Vieira, M. G. Almiron, and A. A. F. Loureiro: '3D MANETs: Link Probability, Node Degree, Network Coverage and Applications'. In: *Wireless Communications and Networking Conference (WCNC)*. Cancun, Mexico: IEEE, Mar. 2011, pp. 2042–2047.

[162] *Wegehandbuch der Alpenvereine*. Deutscher Alpenverein e.V and Oesterreichischer Alpenverein. Aug. 2011.

[163] K. Wehrle, M. Günes, and J. Gross, eds.: *Modeling and Tools for Network Simulation*. 1st ed. Springer, Feb. 2010.

[164] E. Weingärtner, H. vom Lehn, and K. Wehrle: 'A Performance Comparison of Recent Network Simulators'. In: *International Conference on Communications (ICC)*. Dresden, Germany: IEEE, June 2009, pp. 1287–1291.

[165] H. Wennerström, F. Hermans, O. Rensfelt, C. Rohner, and L. Norden: 'A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance'. In: *10th International Conference on Sensing, Communication and Networking (SECON)*. New Orleans, LA, USA: IEEE, June 2013, pp. 221–229.

[166] H. Wennerström, C. Rohner, and D. Smith: 'Considering Multi-Contact Encounters in Opportunistic Networks'. In: *10th ACM MobiCom workshop on Challenged networks (CHANTS)*. Paris, France: ACM, Sept. 2015, pp. 13–18.

[167] J. Whitbeck and V. Conan: 'HYMAD: Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks'. In: *Computer Communications* (2010), vol. 33(13), pp. 1483–1492.

[168] J. Whitbeck, V. Conan, and M. Dias de Amorim: 'Critical Analysis of Encounter Traces'. In: *2nd Workshop on Wireless of the Students, by the Students, for the Students (S3)*. Chicago, IL, USA: ACM, Sept. 2010, pp. 29–32.

[169] J. Whitbeck, M. Dias de Amorim, V. Conan, and J.-L. Guillaume: 'Temporal Reachability Graphs'. In: *18th Annual International Conference on Mobile Computing and Networking (Mobicom)*. Istanbul, Turkey: ACM, Aug. 2012, pp. 377–388.

[170] *Wi-Fi Range Demystified – Tutorial*. Xirrus. 2008.

[171] A. Wolff: 'Entwurf und Leistungsbewertung von Ad-hoc-Kommunikationsnetzen für den Katastrophenschutz'. Dissertation. TU Dortmund, 2013.

[172] A. Wolff and C. Wietfeld: 'Process-Oriented Deployment of Ad-hoc Networks in Emergency Scenarios'. In: *2nd International Workshop on Pervasive Networks for Emergency Management (PerNEM)*. Lugano, Switzerland: IEEE, Mar. 2012, pp. 728–733.

[173] D. Xie, X. Wang, L. Liu, and L. Ma: 'Exploiting Time-varying Graphs for Data Forwarding in Mobile Social Delay-Tolerant Networks'. In: *24th IEEE/ACM International Symposium on Quality of Service (IWQoS)*. Beijing, China: IEEE, June 2016, pp. 1–10.

[174] B. B. Xuan, A. Ferreira, and A. Jarry: 'Computing shortest, fastest, and foremost journeys in dynamic networks'. In: *International Journal of Foundations of Computer Science* (2003), vol. 14(02), pp. 267–285.

[175] E. Yanmaz, R. Kuschnig, and C. Bettstetter: 'Achieving Air-Ground Communications in 802.11 Networks with Three-Dimensional Aerial Mobility'. In: *32nd IEEE International Conference on Computer Communications (INFOCOM)*. Turin, Italy: IEEE, Apr. 2013, pp. 120–124.

[176] W. Zhao, M. Ammar, and E. Zegura: 'Controlling the Mobility of Multiple Data Transport Ferries in a Delay-Tolerant Network'. In: *24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*. Miami, FL, USA: IEEE, Mar. 2005, pp. 1407–1418.

[177] Z. Zhao and T. Braun: 'OMNeT++ based Opportunistic Routing Protocols Simulation: A Framework'. In: *10th Scandinavian Workshop on Wireless Ad-hoc Networks (ADHOC)*. Stockholm, Sweden, May 2011.

[178] Z. Zhao and T. Braun: 'SCAD: Sensor Context-aware Adaptive Duty-cycled Beaconless Opportunistic Routing for WSNs'. In: *26th International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC): Mobile and Wireless Networks*. Hong Kong, China: IEEE, Aug. 2015, pp. 2038–2043.

[179] Z. Zhao, T. Braun, D. Rosário, and E. Cerqueira: 'CAOR: Context-aware Adaptive Opportunistic Routing in Mobile Ad-hoc Networks'. In: *7th IFIP Wireless and Mobile Networking Conference (WMNC)*. IFIP. Vilamoura, Algarve, Portugal: IEEE, May 2014, pp. 1–8.

Acronyms

AODV	Ad hoc On-Demand Distance Vector
BATMAN	Better Approach To Mobile Ad-hoc Networking
BATMAN-SF	BATMAN Store-and-Forward
BLE	Bluetooth Low Energy
CAOR	Context-aware Adaptive Opportunistic Routing
CGR	Contact Graph Routing
COTS	Commercial Off-The-Shelf
DEM	Digital Elevation Model
DirMove	Direction of Movement based routing in DTN
DSR	Dynamic Source Routing
DT-DYMO	Delay-tolerant Dynamic MANET On-demand Routing
DTN	Delay Tolerant Network
DTS-OLSR	Delay Tolerant Structured Overlay Link State Routing
DYMO	Dynamic MANET On-demand
EID	Endpoint Identifier
EMS	Emergency Medical Services
ETSI	the European Telecommunications Standards Institute
GIS	Geo Information System
GPS	Global Positioning System
GUI	Graphical User Interface
HAT	Hardware Attached on Top[1]
HRS	Hybrid Routing System
HSBR	Hybrid Social Based Routing
HYMAD	Hybrid DTN-MANET routing
ICMP	Internet Control Message Protocol
IETF	Internet Engineering Task Force
IP	Internet Protocol

1 https://www.raspberrypi.org/blog/introducing-raspberry-pi-hats/

LOS	Line of Sight
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MPR	Multi Point Relay
NIC	Network Interface Card
NOR	Name Resolution over Routing
ns-2	Network Simulator version 2
ns-3	Network Simulator version 3
OLSR	Optimized Link State Routing
OMNeT++	Objective Modular Network Testbed in C++
ONE	Opportunistic Network Environment
OSI	Open Systems Interconnection
Pen-Prophet	Priority Enhanced Prophet
PROPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
QoS	Quality of Service
RAPID	Resource Allocation Protocol for Intentional DTN
RFC	Request for Comments
RREP	Route Reply
RREQ	Route Request
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
RWP	Random Way Point
SAR	Search and Rescue
SCAD	Sensor Context-aware Adaptive Duty-cycled
SCAR	Sensor Context-Aware Routing
SCORP	Social-aware Content-based Opportunistic Routing Protocol
SEREMA	Self-organized Routing in heterogeneous MANETs
TCP	Transmission Control Protocol
TETRA	Terrestrial Trunked Radio
THW	Technisches Hilfswerk
TIN	Triangulated Irregular Network
TTL	Time-To-Live
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
USB	Universal Serial Bus
USGS	US Geological Survey
UTM	Universal Transverse Mercator

WKT	Well Known Text
XML	Extensible Markup Language

List of Symbols

d_m	deviation threshold for first responder movement patterns
d_d	deviation threshold for dog movement patterns
d_r	radius of a circular threshold in quasi-static movement patterns
E	end point coordinates of a movement pattern
p_{fwd}	transition parameter to configure forwarding decisions
p_{fwd_c}	transition parameter to configure the number of receiving child nodes when forwarding
$rand$	rand number used to select receiving child nodes when forwarding
$ratio_{\ deadline\_misses}$	deadline miss ratio, indicating the number of messages delivered after the given timing deadline over all messages sent
$rate_e$	data rate available for the traversal of an edge
$ratio_{\ errors}$	error ratio, indicating the number of messages lost and delivered too late over all messages sent
$rate_l(t_e, from, to)$	data rate available on the link between nodes $from$ and to at time t_e
S	starting point coordinates of a movement pattern
t_{deliv}	delivery delay, total time that is required to deliver a message from the sender to the destination
t_e	time stamp of an connection event in a Connection Trace
t_{rcvd}	reception time, the earliest point in time when the copy of a message arrives at the vertex in question of all possible incoming edges
t_{start}	starting time, the earliest point in time when a message can be forwarded to the next hop using the edge in question
t_{trans}	transmission delay, time required for the transfer of a message between two nodes using a given link
t_{wait}	waiting time, time that a message has to wait, until it can be forwarded to the next hop

$weight(e_{u \to v})$	edge weitgt used in Dijkstra algorithm to calculate shortest path

List of Software and Tools

BonnMotion	https://sys.cs.uos.de/bonnmotion/index.shtml
GrassGIS	https://grass.osgeo.org/
IBR-DTN	https://github.com/ibrdtn/ibrdtn
OpenJump	http://www.openjump.org/
OpenStreetMap – Export von Kartendaten	http://www.openstreetmap.org/export
OMNeT++	https://omnetpp.org/
ONE	https://akeranen.github.io/the-one/
osm2wkt – OpenStreetMap to WKT conversion	http://www.chrismc.de/osm2wkt/
R	https://www.r-project.org/
Viking	https://sourceforge.net/projects/viking/
WireShark	http://www.wireshark.org/

Glossary

UTM is a special projection that is used to convert spherical spatial data to planar coordinates (e. g. for maps). It uses a special approximation of the earth surface as reference for the conversion.

WKT is a text-based file format developed to describe spatial data