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DECENTRALIZED COMMUNICATION SERVICES *for* POST-DISASTER SCENARIOS

Resource Allocation, Prioritization, and Long-Range Communication Support

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ABSTRACT

Our modern society strongly depends on critical infrastructures, such as the central power grid or information and communication technology. When these infrastructures fail during and after disasters, the affected population has no means of communication. At the same time, the increased population density of urban areas coupled with the peoples' expectation to have permanent access to communication systems and to be informed at all times and at any place, has made disaster-management increasingly challenging. Communication is crucial during disasters as it empowers the affected population to organize and help themselves. But even if parts of the communication infrastructure are still intact, the increased communication demand for disaster relief efforts and checking on loved ones typically overloads the available infrastructure. As such, infrastructure-independent and rapidly deployable communication systems are required. Delay-tolerant ad-hoc networks can be used to build communication networks, which propagate messages via the store-carry-forward paradigm directly between neighboring communication devices. Such DTN-MANETs can be formed by the smartphones of the affected population. However, such communication networks must overcome various scenario-specific difficulties, such as limited network lifetime due to limited battery power of the devices, message propagation limitations caused by isolated network areas due to the limited range of device-to-device communication, and network resource restrictions.

In this thesis, we first assess scenario-specific characteristics by conducting and evaluating a large-scale field test. Based on these results, our main contribution is the design and implementation of the decentralized disaster communication system D2CS.KOM, which extends the functionality of conventional DTN-MANETs. We enable D2CS.KOM to allocate available energy resources to the network participants in a fully decentralized way, extending the lifetime of communication devices and thus the overall network. We further propose and integrate a prioritization architecture to improve the propagation of disaster-relevant messages in the network and enable the system to adapt to continuously changing communication demands. Since the mobility of network participants determines the performance of data dissemination in DTN-MANETs, D2CS.KOM overcomes this limitation by utilizing Unmanned Aerial Vehicles (UAVs) to strategically support the dissemination of messages.

We generalize disaster-specific characteristics into the Simonstrator.KOM simulation platform and conduct an extensive evaluation of our contributions. We show that our system extends the communication lifetime of individual nodes and consequently of the overall network while prioritizing disaster-relevant messages. Additionally, we demonstrate the significant support capabilities of UAVs in intermittent DTN-MANETs. In summary, we show that our contributions constitute a significant step towards ensuring communication during and after disasters by improving upon decentralized, infrastructure-independent communication systems.

KURZFASSUNG

Unsere moderne Gesellschaft ist stark abhängig von kritischen Infrastrukturen wie dem zentralen Stromnetz oder Informations- und Kommunikationstechnologien. Wenn diese Infrastrukturen während und nach Katastrophen ausfallen, hat die betroffene Bevölkerung keinerlei Kommunikationsmöglichkeiten mehr. Außerdem erschwert die zunehmende Bevölkerungsdichte in städtischen Gebieten, verbunden mit der Erwartung der Menschen, jederzeit und überall kommunizieren zu können, das Katastrophenmanagement zusätzlich. Kommunikation ermöglicht es der betroffenen Bevölkerung, sich selbst zu organisieren und zu helfen und ist somit der Schlüssel zu einer erfolgreichen Katastrophenbewältigung. Doch selbst wenn die Kommunikationsinfrastruktur noch in Teilen funktionsfähig ist, wird diese durch das erhöhte Kommunikationsaufkommen nach einer Katastrophe typischerweise überlastet. Daher sind schnell einsetzbare und infrastrukturunabhängige Kommunikationssysteme in solchen Situationen dringend erforderlich. Verzögerungstolerante Ad-hoc-Netzwerke (DTN-MANETs) können unter Nutzung der Smartphones der Bevölkerung spontan errichtet werden. Durch die sogenannte Geräte-zu-Geräte-Kommunikation benachbarter Smartphones können Daten ausgetauscht und gespeichert werden, um diese mittels der Bewegung der Bevölkerung weiter im Netzwerk zu verteilen. Für die Entwicklung und den Einsatz solcher DTN-MANETs für die Katastrophenkommunikation müssen jedoch verschiedene szenariospezifische Herausforderungen und Limitierungen berücksichtigt und überwunden werden. Darunter fallen zum Beispiel die begrenzte Laufzeit des Netzwerkes aufgrund der begrenzten Akkuleistung der zugrundeliegenden Smartphones, oder die begrenzten Netzwerkbandbreiten. Weiterhin wird die Nachrichtenverbreitung durch die begrenzte Reichweite der Geräte-zu-Geräte-Kommunikation und der eingeschränkten Bewegung der Bevölkerung in einer Katastrophe zusätzlich limitiert.

In dieser Arbeit identifizieren und untersuchen wir zuerst katastrophenspezifische Merkmale auf Basis von Daten vergangener Katastrophen sowie der Durchführung und Auswertung eines großangelegten eigenen Feldversuches. Aufbauend auf diesen Ergebnissen ist unser Hauptbeitrag der Entwurf und die Implementierung eines dezentralen, infrastrukturunabhängigen Katastrophenkommunikationssystems namens D2CS.KOM. Dieses ermöglicht es, verfügbare Energieressourcen vollständig dezentral den Netzteilnehmern zuzuordnen, um die Kommunikation so lange wie möglich aufrechtzuerhalten. Darüber hinaus integrieren wir eine Priorisierungsarchitektur, welche die Verbreitung von katastrophenrelevanten Nachrichten im Netzwerk verbessert und es dem Kommunikationssystem ermöglicht, sich an die ständig wechselnden Kommunikationsanforderungen in einer Katastrophe anzupassen. Die Bewegungsmöglichkeiten der Netzwerkteilnehmer bestimmen maßgeblich die Datenverbreitung. Um diese Einschränkung zu adressieren, unterstützt D2CS.KOM

hochmobile unbemannte Kleinfluggeräte, kurz UAVs, um die Datenverbreitung strategisch zu unterstützen.

Für eine umfangreiche Evaluation unserer Beiträge verallgemeinern wir katastrophenspezifische Merkmale in unserer Simulationsplattform Simonstrator.KOM. Wir zeigen, dass unser System die Kommunikationsdauer des gesamten Netzwerks verlängert und gleichzeitig katastrophenrelevante Nachrichten im Netzwerk priorisiert. Darüber hinaus demonstrieren wir die signifikanten Beiträge von UAVs zur Vernetzung nicht verbundener Kommunikationsbereiche. Zusammenfassend zeigen wir, dass unsere Beiträge zur Sicherstellung der Kommunikation während und nach Katastrophen beitragen und die Anwendbarkeit dezentraler, infrastrukturunabhängiger Kommunikationssysteme in Katastrophenszenarien verbessern.

CONTENTS

1 INTRODUCTION 1
1.1 Motivation for Post-Disaster Communication Systems 2
1.2 Research Challenges 3
1.3 Research Goals and Contributions 4
1.4 Structure of the Thesis 5

2 BACKGROUND 7
2.1 Critical Infrastructures 7
2.2 Communication Services for Disaster Relief 8
2.3 Communication Networks 9

3 STATE OF THE ART 15
3.1 Infrastructure-independent Communication Systems 15
3.2 Decentralized Resource Allocation 17
3.3 Influence Factors of Message Prioritization 18
3.4 UAV-based Support for Post-Disaster Networks 19

4 POST-DISASTER CHARACTERISTICS AND COMMUNICATION SERVICES 23
4.1 Scenarios Characteristics 23
4.2 Required Services for Post-Disaster Communication Networks 25
4.3 Real-World Assessment in a Large-Scale Field Test 29
    4.3.1 Planning and Execution 30
    4.3.2 Analysis of Collected Mobility Traces 33
    4.3.3 Analysis of Communication Properties 35

5 D2CS.KOM: DECENTRALIZED DISASTER COMMUNICATION SYSTEM 41
5.1 Conceptual Overview of the Communication System 42
5.2 Prolonging the Network Lifetime through Resource Allocation 45
    5.2.1 Scenario Description 45
    5.2.2 Design of a Resource Allocation Service 47
    5.2.3 Resource Allocation Strategies 52
    5.2.4 Ad Hoc On-demand Reservation Vector Auction 54
5.3 Information Selection and Prioritization under Network Restrictions . 60
    5.3.1 Prioritization Challenges in Post-Disaster Scenarios 61
    5.3.2 Architecture for Prioritized Post-Disaster Communication . . . 62
5.4 Long-Range Communication Support 64
    5.4.1 Modules for Long-Range Communication 64
    5.4.2 UAV-based Support Strategies 66

6 EVALUATION 69
6.1 Evaluation Setup and Methodology 69
6.1.1 Simulation Platform 70
6.1.2 Mobility and Communication Characteristics 72
6.1.3 Evaluation Metrics 75
6.2 Impact of the Resource Allocation Service 77
6.2.1 Scenario Model 77
6.2.2 Strategy Parameter Evaluation 78
6.2.3 Evaluation and Comparison of Resource Allocation Strategies . 82
6.3 Impact of Message Prioritization 87
6.3.1 Scenario Model 87
6.3.2 Evaluation of Prioritization Algorithms 89
6.4 Impact of UAV-based Support Strategies 93
6.4.1 Scenario Model 94
6.4.2 Evaluation of UAV-based Support Strategies 96

7 SUMMARY, CONCLUSIONS, AND OUTLOOK 101
7.1 Summary of the Thesis 101
7.1.1 Contributions 101
7.1.2 Conclusions 102
7.2 Outlook 103

BIBLIOGRAPHY 105

A APPENDIX 131
A.1 Disaster Region Analyzing Service (DRAS) 131
A.2 Sed Card Example from the Field Test 135
A.3 Extended Study of the Resource Allocation Service 137
A.4 List of Acronyms 141
A.5 Supervised Student Theses 143

B AUTHOR'S PUBLICATIONS 145

C CURRICULUM VITÆ 149

D ERKLÄRUNG LAUT PROMOTIONSORDNUNG 151

1

INTRODUCTION

Technology has shaped our modern society and made our everyday lives easier, more convenient, and faster than ever. At the same time, we have not only grown accustomed to but are strongly dependent on Critical Infrastructures (CIs) like energy supply or Information and Communication Technology (ICT). Outages show how vulnerable our society is when CIs we take for granted are suddenly unavailable. Mankind has always been plagued by natural disasters, and the number and intensity of weather-related incidents are likely to increase due to climate change [130]. Recent disasters caused by Hurricane Harvey in 2017 or Hurricane Florence in 2018 demonstrated the highly destructive force of nature. Furthermore, the number of unintended disasters of human origin, such as power outages [82, 153] and intended ones such as hacker- and cyber-attacks [4, 126] are rising as well. Disaster management has become increasingly challenging with the increase of population density in urban areas [203]. Coordination and rescue efforts during and after disasters in particular heavily depend on the reliability of ICT. During and after disasters, however, the central power infrastructure or the ICT infrastructure itself is often disrupted, which results in either severely impaired or completely unavailable ICT. Due to this cascading effect, the available communication bandwidth provided by the ICT is reduced to a fraction of its usual capacity.

Societies depend on critical infrastructures

Critical infrastructures often fail in disasters

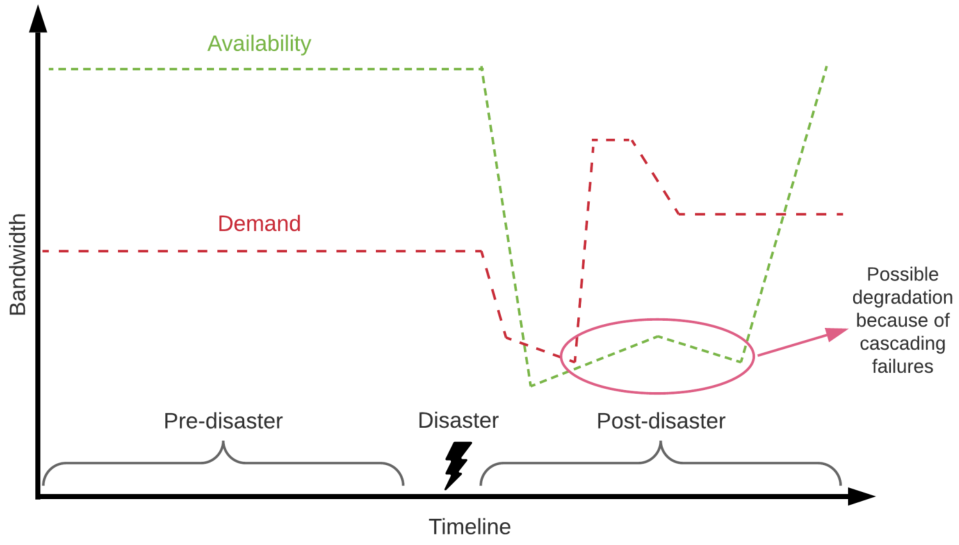


Figure 1: Communication demand and communication availability before and after disasters (adapted from [121, 166]).

High communication demand ...

... low available bandwidth

Once the disaster occurs, the communication demand drops, as people are focusing on getting themselves in safety. However, shortly afterwards the communication demand rises significantly [14, 121, 166], as illustrated in Figure 1. In this thesis, we use the term *post-disaster* for the phase immediately after a disaster until the functionality of the ICT has been fully restored. In the post-disaster phase, people try to call for help, coordinate rescue efforts, and notify family and loved ones. This requires communication, which leads to a communication demand even higher than before the disaster incident and results in a large gap between requested communication demand and available communications bandwidth [14, 63, 102, 178, 179, 203].

1.1 MOTIVATION FOR POST-DISASTER COMMUNICATION SYSTEMS

Infrastructure-independent DTN-MANETs

DTN-MANET post-disaster characteristics

Limited data dissemination

To supply basic means of communication in post-disaster scenarios, Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs), a combination of Delay-Tolerant Networks (DTNs) and Mobile Ad Hoc Networks (MANETs) can be utilized by the affected population and responders. DTNs are a subcategory of MANETs that distribute data in a store-carry-forward fashion and share data whenever two nodes are within communication reach. DTN-MANETs do not rely on any fixed infrastructure or end-to-end connectivity, but instead can be rolled out as needed and are adaptable and relocatable [3, 119, 222]. This makes DTN-MANETs especially suitable for spontaneous post-disaster communication networks using communication nodes, such as smartphones, to communicate directly between two devices in the absence of ICT [9, 205]. Since the communication range of nodes is limited, mobility is one of the main drivers for successful data dissemination in DTN-MANETs. Due to the unpredictability of the individual nodes' movement, many flooding-based routing protocols have been proposed [75, 111, 120, 267]. Enabling DTN-MANET functionality on ordinary smartphones additionally allows the design of arbitrary services for post-disaster communication systems. They may support the affected population to cope with the aftermath of a disaster or enable first responders and help organizations to execute their rescue efforts. The design of such services needs to consider DTN-MANET-specific characteristics in order to be applicable to such networks. For example, no stable communication path can be guaranteed in DTN-MANETs and the necessity of data retransmissions, as a result of flooding-based routing protocols, further increases the aforementioned network resource demand. Depending on the used communication interface (e. g., Wireless Fidelity (Wi-Fi), Bluetooth, Bluetooth LE, Long Range (LoRa), etc.), the communication range and the bandwidth varies significantly. The communication range in combination with the node mobility affects the so-called interconnection time between two nodes that defines the timespan in which data can be exchanged. The interconnection time can vary significantly, resulting in heavy fluctuations regarding *i)* the amount of data that can be exchanged, *ii)* the recall, indicating how well data can be distributed in the overall network, and *iii)* the data dissemination delay.

When it comes to infrastructure-independent communication networks, the lifetime of the communication nodes, such as smartphones, depends strongly on the battery capacity and the energy consumption [51, 52]. In post-disaster networks, a central power infrastructure is often not or only partially available [203, 265]. Thus, the affected population need to use other available energy resources (i. e., battery packs, generators, solar panels, etc. [32, 235]) to prolong the lifetime of their smartphones. However, the allocation of such energy resources in a decentralized system without any central coordination is challenging [283]. Since every single device in a DTN-MANET contributes to the data dissemination in the network, devices running out of energy directly results in a communication performance drop of the overall post-disaster communication network [51, 52].

Limited network lifetime

In this thesis, we study and analyze the characteristics of infrastructure-independent communication systems and propose a system design and services for intermittent post-disaster communication networks. The system addresses the challenges that arise with the utilization of DTN-MANETs in post-disaster scenarios and are explained in the following.

1.2 RESEARCH CHALLENGES

The post-disaster scenario imposes challenges for the effective provisioning of communication utilizing DTN-MANETs. We identified the following research challenges that influence the design of the post-disaster communication system presented in this thesis.

Challenge: *Provisioning of basic services in post-disaster DTN-MANETs.*

Although DTN-MANETs are capable of providing a basic supply of communication, the uncontrollable mobility of nodes results in changing and disrupted communication paths. Therefore, they cannot completely replace the infrastructure-based communication network and resource-hungry services, for example, voice- or video-calls cannot be implemented effectively in decentralized networks. The human factor also plays a relevant role, as the users' expectations of an application need to be satisfied. Especially in the considered scenario, there are specific communication needs that have to be identified and subsequently supported by the post-disaster communication network, for example, SOS calls that reach as many network participants as fast as possible or the possibility to create a resource market for the exchange of goods and services within the DTN-MANET.

Challenge: *Resource constraints, device heterogeneity, and user mobility.*

Due to the nature of people-centric and smartphone-based DTN-MANETs, the behavior and context of users vary greatly over time. These variations include the users' mobility, location, battery level, communication behavior, or the communication interface. As a consequence of user mobility and communication behavior, the characteristics of a DTN-MANET are constantly changing as well, influencing the communication capabilities, for example the available bandwidth, message propagation, or inter-connection times. As already mentioned, the lifetime of mobile nodes is limited and depends on the battery level and the energy consumption.

Challenge: *Influence of disaster-specific constraints and human behavior.*

In addition to the aforementioned challenge regarding network capabilities and device heterogeneity, the considered post-disaster scenario results in more unique characteristics with a focus on human behavior. If one revisits past disasters or talks to experts, it becomes clear that extreme situations strongly influence the behavior of the affected population. The reaction of the affected population differs greatly from everyday behavior and is difficult or even impossible to predict. Current models do not capture these disaster-unique aspects appropriately. This increases uncertainties and variations regarding the DTN-MANET communication capabilities.

1.3 RESEARCH GOALS AND CONTRIBUTIONS

The main objective of this thesis is to model, design, and evaluate infrastructure-independent communication in the event of a disaster to tackle the aforementioned challenges. This objective is divided into the following two research goals:

Research Goal 1: *Identification and modeling of disaster-specific user behavior and communication and interaction characteristics.*

To design post-disaster communication systems, one must first understand and model the disaster scenario in which they are used. This goal focuses on two aspects: *i)* understanding and modeling the scenario and *ii)* deriving essential services. Our contributions include an extensive literature survey of the considered post-disaster scenario and of useful existing services [134, 135, 139]. The findings are used to design and carry out a large-scale field test [9] that mimics a disaster to inspect the usability of new services and to better understand the post-disaster scenario in all its facets. With the field test, we are able to identify, record, and measure user communication and user interaction characteristics under real-world conditions. The resulting insights are the basis of new scenario-specific models for the design and evaluation of post-disaster communication systems.

Research Goal 2: *Provisioning of a decentralized disaster communication system.*

To address the scenario-specific characteristics, we present the Decentralized Disaster Communication System (D2CS.KOM), a communication system that addresses the aforementioned challenges, such as the loss of power supply and unpredictable and highly dynamic user and communication behavior. The occurring resource restrictions have a high influence on the lifetime of the communication nodes and on the network communication capabilities, which is additionally stressed by the increased communication demand. To maintain infrastructure independent communication under post-disaster conditions, we propose mechanisms for decentralized resource allocation of energy resources [136–138]. Thereby, we prolong the individual nodes' lifetime and consequently the lifetime of the overall network. To tackle the high communication demand in post-disaster networks, while considering the restricted communication capabilities, we present our mechanism for adaptive prioritization and information selection [140] based on relevant disaster services and user context information. For network-wide communication, we consider long-range communication devices [80] in combination with mobile communication infrastructure like Unmanned Aerial Vehicles (UAVs) [141]. We model the behavior and characteristics of UAVs and design strategies to demonstrate their significant support capabilities in post-disaster communication networks. Based on our scenario-specific models, we evaluate the proposed mechanisms in a simulation environment. Thereby, we show that our system constitutes a significant step towards ensuring communication in post-disasters scenarios. We improve the applicability of decentralized infrastructure-independent communication systems by focusing on scenario-specific challenges that arise during and after disasters.

Focus on post-disaster communication

With this thesis focusing on post-disaster communication systems, we explicitly consider scenario-specific characteristics and requirements in our design and evaluation. The design of new DTN-MANET protocols is not the focus of this thesis, as many sophisticated protocols have already been proposed [7, 114, 119, 144]. The design of our post-disaster communication system supports the utilization of any suitable DTN-MANET protocol. Existing mechanisms to ensure security or detect and counteract malicious behavior of network participants can easily be integrated into our design. Promising research tackles this issue with secure routing protocols to ensure the fairness for the users and to increase the robustness of the network by detecting, for example, corrupt nodes [35, 132, 165, 225, 232]. Furthermore, there exist different trust mechanisms to create secured authentication and data exchange [10, 39, 44, 229, 234]. In our work we focus on the extreme case with no central infrastructure being available. However, if infrastructure is partially or temporarily available, our system can benefit from hybrid communication mechanisms [209, 212–214, 216].

Detect malicious behavior

Trust mechanisms

1.4 STRUCTURE OF THE THESIS

In this chapter, we gave a short introduction and motivation on our main research goals. Before discussing the state-of-the-art in Chapter 3, we provide additional background on existing infrastructure-based disaster services and on mobile ad-hoc networks in Chapter 2. In Chapter 4, we discuss reports of disasters and identify specific characteristics, such as communication and behavior patterns of the affected population. Based on this study, we planned and realized a large-scale field test. Our findings motivate the design of D2CS.KOM, discussed in Chapter 5. D2CS.KOM extends conventional DTN-MANETs with components to *i)* facilitate and allocate available energy resources to prolong the networks lifetime, *ii)* support information selection and prioritization to cope with network restrictions, and *iii)* provide communication support strategies for partitioned networks. The impact of these components on the communication capabilities of post-disaster DTN-MANETs is evaluated in Chapter 6. The thesis concludes with a summary of our core contributions and an outlook on potential future work in Chapter 7.

2

BACKGROUND

In the following sections, we provide relevant background information about post-disaster communication possibilities and services in absence of Critical Infrastructures (CIs) as motivated in Chapter 1. We start by discussing the role of CIs and give an overview of existing disaster services to highlight the importance of communication and situational awareness in post-disaster scenarios. This follows by an introduction on the relevant technical aspects of the underlying infrastructure-independent communication network based on mobile devices of the affected population.

2.1 CRITICAL INFRASTRUCTURES

CIs are essential assets for a functioning society and economy. These CIs include, among others, energy power systems, Information and Communication Technology (ICT), transportation networks, water systems, and banking and financial systems [108, 162] as visualized in Figure 2. The issue of power outages has received much attention in recent years due to the high dependency of other CIs, such as the ICT [6], on the power grid and their vulnerability to natural or man-made disasters [4, 82, 126, 153]. Modern societies are becoming increasingly dependent on energy. Society is in the midst of improving, digitalizing, and interconnecting the different CIs, which offer numerous opportunities but also risks and inter-dependabilities [186]. These inter-dependencies are also reflected in the dependency of communication-based emergency response efforts on other ICTs, since the available services for disaster response rely on centralized networks. Many research focuses on CI resilience, to reduce the probability of failure, and to strengthen the ability to recover quickly from difficulties [180, 244].

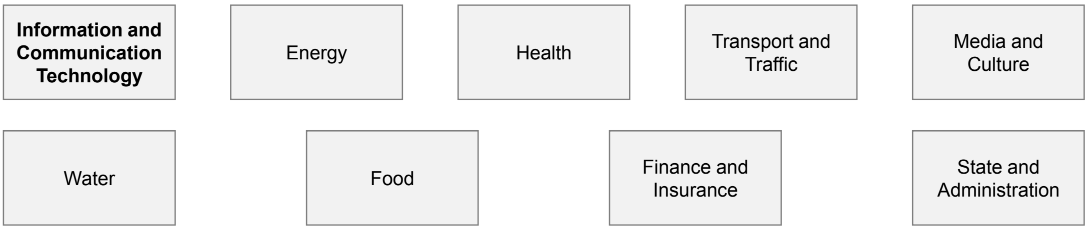


Figure 2: Critical Infrastructure sectors [108].

Communication resilience

In this thesis, we focus on the resilience of the disaster-communication in a CI-independent fashion. We provide a backup system for communication that is fast deployable and can be utilized for disaster relief efforts until infrastructure-based communication is available and stable again.

2.2 COMMUNICATION SERVICES FOR DISASTER RELIEF

Social media, numerous smartphone applications, and messaging services are an established part of today's society and are used every day. At the same time, these services play an increasingly important role in how people prepare, respond, and recover from disasters [184]. All these services rely on the availability of ICT and are rendered useless during infrastructure failures. Even though this thesis focuses on infrastructure-independent emergency communication, we give a short overview of existing and useful infrastructure-dependent applications. Hundreds of disaster-related applications exist [85, 87] and most of them focus on warning the affected population, on strengthening the disaster preparation, and on informing about existing and potential disasters [208]. Besides many private companies, in many countries the corresponding department for civil defense also provide such crisis applications, for example, *NINA* [33, 174, 208] in Germany or *FEMA* [69, 208] in the United States of America. Furthermore, there are systems based on the cellular network, which allow official authorities to send emergency broadcasts to the general public, such as *AMBER Alerts* [118].

Infrastructure-dependent services

Warnings

Besides warn and alert services, there exist a variety of *situational awareness* services, which focus on the understanding of the current disaster situation. To effectively understand and respond to a disaster situation, the affected population, as well as first responders, need to have an up to date overview of the current situation, which can be gathered from different sources and can be combined into one big-picture. The term big-picture can differ significantly depending on the person or groups using situational awareness services. On an individual level, people are interested in the well-being of the family and loved ones, and also, they want to inform others about their status and whereabouts. Services such as *Facebook's Safety Check* [106, 258], *Google's Person Finder* [107] or the Red Cross [253] make such services available when disasters happen. First responder and disaster organizations often need a broader view of the overall situation to improve disaster response. Various tools and services exist that harness different social media sources to extract information about the current situation in a disaster area. For example, the analysis of disaster-related Twitter posts [117, 175, 207], to detect disaster activities, people in need, and even the emotional mood of the affected population. However, Twitter posts often lack precise location information, other social media platform like Facebook offer very precise and sophisticated disaster maps [150]. For instance, these maps include the movement of the population during and after the disaster in comparison to recorded movement behavior prior to the disaster incident, cell tower connectivity, or power coverage. Geospatial disaster maps and other sources of information contribute to various situational awareness services for disaster response.

Situational awareness

Various information sources

The different infrastructure-dependent services presented in this section, demonstrate the significant importance of communication in case of disasters. The services can be used by the affected population and responders alike, and they showcase the various ways to support disaster relief efforts. The surveyed services build the foundation for our proposed set of suitable disaster services for the use in infrastructure-independent communication networks in Chapter 4.

2.3 COMMUNICATION NETWORKS

Communication networks connect multiple end systems via a shared communication medium [193, 252]. Motivated by the post-disaster scenario and the strong dependencies on CIs, we consider only infrastructure-independent communication networks using a wireless communication medium. In computer networking, there exists different addressing methods that define the set of recipients for a certain message. The different addressing methods are categorized in *one-to-one* and *one-to-many* communication and consist of the following recipient attributes, which are also visualized in Figure 3: *i) unicast* for exactly one specific recipient, *ii) broadcast* for everyone within the network, *iii) multicast* for a specific group of recipients, *iv) anycast* for at least one recipient within a group, and *v) geocast* for recipients at a specific location.

Addressing methods

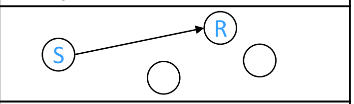
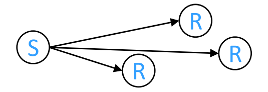
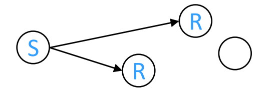
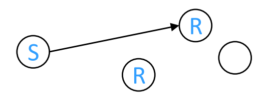
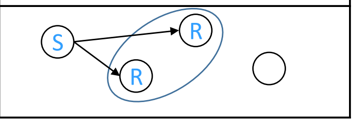
Method	**Describtion**	**Example**
Unicast	Message exchange between Sender (S) and one Recipient (R)	
Broadcast	Message exchange between Sender (S) and everyone in the network	
Multicast	Message exchange between Sender (S) and a group of Recipients (R)	
Anycast	Message exchange between Sender (S) and at least one Recipient (R) of a group	
Geocast	Message exchange between Sender (S) and Recipients (R) within a specific location	

Figure 3: Different addressing methods, including *one-to-one* and *one-to-many* communication.

For the disaster-communication, we use the smartphones of the affected population as communication devices, also called nodes, which are mobile and can directly communicate with each other if in range. This idea is similar to the concept of Peer-to-Peer systems, in which nodes exchange information in a self-organized manner without a central coordination entity [64, 243]. For smartphone-based communication networks, we consider Wireless Fidelity (Wi-Fi) as underlying communication technology because of high throughput and high communication range (cf. Section 4.3), while other technologies such as Bluetooth or Bluetooth LE are also suitable for low throughput applications. In these networks, all participants share the same physical communication medium. Communication in wireless networks is based on broadcasts to allow neighboring nodes to overhear any communication.

Shared communication medium

Consequently, multiple network nodes can transmit data at the same time, resulting in collisions and information loss. Wireless networks can use *collision avoidance* to address this problem [252]. Instead of trying to send messages and detecting a collision, the nodes wait for an idle period of the shared medium.

Self-organizing networks

The term Mobile Ad Hoc Networks (MANETs) is used to describe networks, which communicate in a self-organizing and decentralized fashion. In MANETs, data transmissions can take place whenever there is an end-to-end communication path between the sender and the receiver, which consists of one or multiple hops. Due to the mobility of the nodes, communication pathways are frequently interrupted caused by nodes going out of communication range, running out of energy or the communication is obstructed by other means.

Therefore, routing protocols for wired networks cannot be applied to MANETs and the nodes themselves need to discover and maintain end-to-end communication paths in the network for data transmissions. There are three main categories for MANET routing protocols [151, 157]: *i)* proactive protocols [110, 191], where each node maintains routing tables that are periodically updated, *ii)* reactive protocols [112, 190], where end-to-end communication paths are discovered on-demand, and *iii)* hybrid protocols [91, 169] that combine both categories. Additionally, there exist different broadcasting techniques for one-to-all communication [90, 127].

Delay-tolerant networks

Store-carry-forward

Depending on the movement behavior of the nodes, areas of the network can become completely disconnected from other parts of the network without an end-to-end communication pathway between these areas. At the same time, nodes might join different network partitions over time, depending on their movement. To enable communication under these challenging and dynamic conditions, Delay-Tolerant Networks (DTNs), as an extension of MANETs, can be used. While many expressions for delay-tolerant networks, like *Opportunistic Networks*, *Intermittently Connected Networks* or *Challenged Networks*, are used in the literature, we refer to them as Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs) in this thesis as DTNs extend the functionality of conventional MANETs. DTN-MANETs utilize the storage capabilities of the nodes, enabling them to carry received messages until they can be forwarded to new communication neighbors, known as the *store-carry-forward* principle. This principle often results in the dissemination of multiple message duplicates to multiple communication nodes in the network to increase the probability of successful message delivery and is known as *flooding*. The data dissemination in DTN-MANET relies on repetitive hop-by-hop broadcasts [144] throughout the network and existing MANET routing protocols cannot be applied. There exist various forwarding protocols for DTN-MANETs [7, 114, 119, 144], that can be categorized into two main types: flooding-based forwarding and knowledge-based forwarding.

Flooding-based forwarding

In flooding-based forwarding, message duplicates are forwarded in the network to increase the probability of successful message delivery to the destination. Besides pure flooding, other protocols reduce the number of duplicates in the network to reduce network load and make the forwarding more efficient and less resource hungry. Efficient forwarding can be achieved, for example, by defining an upper limit of duplicates [241], or by applying forwarding probabilities for each message based on the nodes forwarding history [75, 143]. To reduce the number of forwarded messages between neighboring nodes, they can compare their buffer state beforehand only to exchange unknown messages [111, 267].

Figure 4 illustrates an example for the delayed ($t_1 - t_5$) flooding-based forwarding from node A to E, based on the DTN-MANET store-carry-forward principle.

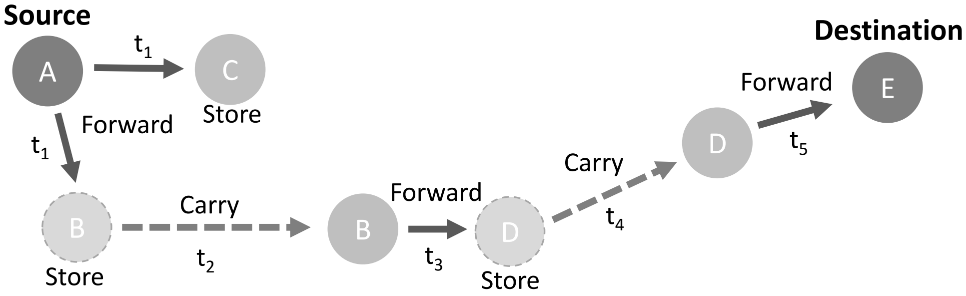


Figure 4: The store-carry-forward principle used in DTN-MANETs.

Knowledge-based forwarding

The second type of message propagation in DTN-MANETs are knowledge-based forwarding protocols. These protocols require additional information about the network topology or node characteristics beforehand. The knowledge is used to forward messages only to selected nodes, which are more suitable to deliver the messages to the destination compared to random nodes. Examples are time-, location- or social-based forwarding. Time-based forwarding can be used if the contact with specific nodes occurs periodically [284], location-based forwarding [131, 233] only transmits messages in the direction to the destination and social-based [53] forwarding passes messages only to nodes with already had contact with the destination.

Data ferries

Thus, DTN-MANETs do not require end-to-end communication for successful data transmissions. DTN-MANETs utilize mobile nodes as so-called *data ferries* to enable delayed communication between disconnected network areas, which can also be made possible by other means of transportation, for example, cars [261, 284].

On a global perspective, the disaster communication networks we are considering in this thesis consist of two parts: *communication islands* and *communication bridges* [8, 200, 284], visualized in Figure 5. Areas with high node densities around a Point of Interest (POI), such as city centers, a marketplace, or whole villages are referred to as communication islands. From a communications perspective, islands are isolated from each other and are only connected through the movement of DTN-MANET nodes, the data ferries. The movement and the message forwarding of the data ferries are referred to as communication bridges. The Communication inside a communication island is further referred to as *intra-island communication* and between islands as *inter-island communication*.

Since end-to-end connections between communication partners cannot be guaranteed, flow-based Internet Protocols like TCP/IP [252] cannot function properly in such partitioned networks. To allow inter-island communication, DTN-MANETs rely on the *bundle* layer overlay protocol, which is located between the application and transport layer in the five-layer Internet protocol stack [119], illustrated in Fig-

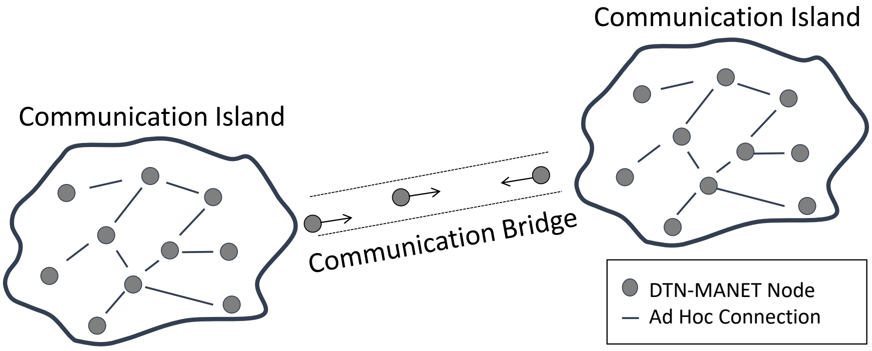


Figure 5: Communication Islands and Communication Bridges in DTN-MANETs.

ure 6. A *bundle* combines the data and control information of a message in one atomic entity. Bundles can be delivered asynchronously from source to destination via several intermediate nodes. Thereby, between each pair of DTN-MANET nodes, the transmission medium can be different, for example, Wi-Fi or Bluetooth, to allow the interoperability between different communication technologies, devices, and overall network types. Nodes in DTN-MANETs are identified by unique identifiers, called Endpoint IDentifiers (EIDs). In the case of smartphone-based DTN-MANETs, the MAC-address of the node's communication interface or the phone number can be used as EID. EIDs can also refer to a group of nodes to support one-to-many communication, for example, multicast [119].

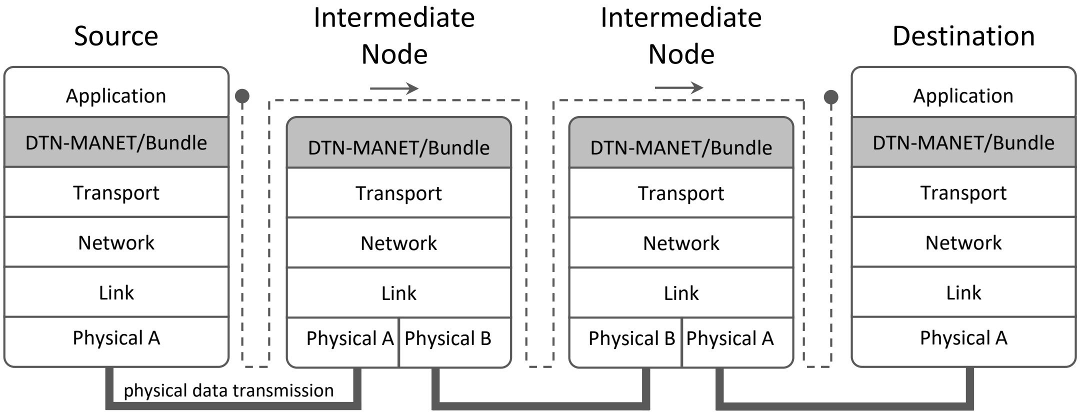


Figure 6: DTN-MANET protocol stack (adapted from [119]).

In this thesis, our proposed communication system for post-disaster communication relies on the explained infrastructure-independent network type DTN-MANET. As explained in this section, data messages are propagated in the network via the store-carry-forward principle in a robust but delayed fashion. We are utilizing the smartphones of the affected population as communication nodes to create such intermittent mobile networks, consisting of communication island and bridges due to the uncontrollable and unpredictable movement of the users. Even though there exist several designs to combine DTN-MANETs with the Internet [60], we purely rely on DTN-MANETs communication to avoid any dependency on potential unstable or unreliable infrastructure during and after disasters. We demonstrate the applicability of DTN-MANETs under real-world conditions by conducting and analyzing a field test with 125 participants in Chapter 4, before we present our contributions in Chapter 5 focusing on the arising scenario-specific communication challenges. In the next chapter, we provide relevant state-of-the-art and discuss existing approaches.

3

STATE OF THE ART

In this chapter, we provide relevant state-of-the-art as foundation for our communication system discussed in Chapter 5. We discuss the utilization of infrastructure-independent communication systems with the focus on the applicability in disasters and evaluation methods in Section 3.1. We present an overview of the relevant research in the area of decentralized resource allocation in Section 3.2, which aims to prolong the lifetime of a communication system. Methods to determine the importance and disaster relevance of messages in post-disaster communication networks to enable messages prioritization are discussed in Section 3.3. For the deployment of highly mobile data ferries to enable communication between network islands, we discuss the characteristics of Unmanned Aerial Vehicles (UAVs) and their applicability in disasters in Section 3.4.

3.1 INFRASTRUCTURE-INDEPENDENT COMMUNICATION SYSTEMS

Self-organizing, decentralized, and wireless networks, like Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs), have a wide range of application scenarios. Popular examples include Wireless Sensor Networks (WSNs) [195], and with increasing popularity Vehicular Ad Hoc Networks (VANETs) [52] and people-centric networks [51, 52]. WSNs are used to collect, integrate, and transmit data for specific tasks [195]. Nodes in WSNs are typically limited by their computing power, communication range, storage capabilities, and battery capacity. Possible application tasks are, for example, surveillance, environmental monitoring, health-monitoring, and structural-monitoring [28, 51, 231]. VANETs also support a variety of different applications in their field, such as traffic information, infotainment services, or safety-related applications [51]. Especially safety-related applications profit from the low latency of direct vehicle-to-vehicle communication, which is crucial for applications like collision avoidance or cooperative maneuvering [1, 109].

People-centric networks

In people-centric networks, the humans, rather than the devices, are the focal point of communication [42]. In this thesis, we focus on smartphone-based post-disaster communication networks, which fit well to this network type, since the affected population itself creates and propagates the data. By now, some smartphone-based infrastructure-independent communication systems for post-disasters situations, were proposed [81, 104, 149, 158, 176]. These include a variety of different disaster applications, specifically designed to work in DTN-MANETs. Examples are, exchanging text messages [104], a social network [155], disaster mapping [257], or sending and receiving distress signals [2, 158]. Furthermore, some approaches focus on additional support for smartphone-based communication systems. To improve the communication capabilities of DTN-MANETs, additional hardware [79], vehicles [58, 261] or reconfigured wireless home routers [155] can be utilized.

To evaluate the applicability of the mentioned or similar systems and applications for post-disasters situations, researchers utilize either simulation tools or small test-beds. Although simulation-based evaluation provides advantages in terms of reproducibility, and cost-efficiency, the consideration of specific disaster characteristics is crucial for realistic simulations. Especially in smartphone-based DTN-MANETs, where the performance of the network typically depends on the node mobility, realistic movement models are essential for representative performance evaluation. Most existing works rely on synthetic movement models, for example, random walk or random waypoint [18]. To improve the expressiveness of simulation results, researchers have already proposed different mobility models for post-disaster systems [170, 262]. However, most of the models are based on weak assumptions about the movement behavior such as walking speed or grouping, etc., without being able to prove if such assumptions depict reality. As surveyed in [18], there are a plethora of trace-based movement models based on real human movement records. However, these trace-based models cover everyday movement patterns, which do not apply to disaster scenarios. Other models are based on the disaster behavior of professional help organizations, such as firefighters [38]. Since the DTN-MANETs that are considered in this thesis are based on the smartphones of the affected population, such models are also not applicable. There exist some studies on human mobility in disasters, but the datasets are either not representative or not publicly available [146]. If testbeds are used to evaluate the applicability of a communication system or application, the number of devices used or the user behavior are also not representing a disaster-situation and its characteristics.

Evaluation models

Disaster-related models

While most of the mentioned approaches take into account the use of the smartphones of the affected population, they ignore disaster-specific characteristics. Important characteristics are: *i)* the limited network lifetime due to constrained battery power of the devices in the absence of the central power grid, *ii)* insufficient network resources in combination with high communication demand, and *iii)* message propagation limitations caused by isolated network areas due to the finite range of device-to-device communication. Hence, these characteristics have to be addressed by disaster communication systems by-design since these characteristics have a major impact on the communication network capabilities (cf. Chapter 4). Furthermore, the evaluation procedures of the related approaches demonstrated the need for either a representative real-world deployment or the availability of sophisticated simulation tools that can accurately simulate a post-disaster scenario. Motivated by the surveyed smartphone-based communication systems, we are presenting the design, execution, and evaluation of a large-scale field test in Chapter 4. The resulting insights are the basis of new scenario-specific models for the design and evaluation of post-disaster communication systems in Chapter 6.

3.2 DECENTRALIZED RESOURCE ALLOCATION

Limited battery lifetime

In DTN-MANETs the battery lifetime of the utilized smartphones is decisively responsible for the provisioning of post-disaster communication. Communication nodes running out of energy is typically countered with the reduction of the power consumption, by data aggregation [280] or energy-aware routing schemes [219, 255]. While these actions to reduce the energy consumption of communication nodes can complement the contributions presented in this thesis, our focus lies on the utilization of physical and infrastructure-independent energy resources to prolong the lifetime of communication nodes. Due to the nature of DTN-MANETs, these resources need to be allocated in a completely decentralized fashion. While there is no related work focusing exclusively on the allocation of vital resources in DTN-MANETs, there are different areas where the underlying concept of resource allocation and decentralized consensus have been studied. These concepts can be applied to our scenario to some extent or serve as impulses for our contributions. Hence they are discussed briefly in the following.

Concept of resource allocation

The use of auction-based [101] resource reservation schemes or the negotiation of leasing contracts [11] has been studied for the allocation of network resources, such as the available bandwidth or the nodes' storage. The economic sector also uses decentralized market protocols for allocating tasks among agents that compete for scarce resources [270]. In these scenarios, agents trade tasks and resources at prices determined by an auction protocol and have the requirement of reliable end-to-end communication at any given time.

In the field of game theory, the resource distribution problem in decentralized networks can be formulated as a finite extensive game with imperfect information [95, 183]. Stavrakakis et al. [242] examined the equilibrium for the problem of choosing between a set of limited low-cost and unlimited high-cost resources while the costs are the same for every player at any time. They found that providing additional information, for example, the numbers of concurrent competitors may result in higher costs for the individual players than in the case without any additional knowledge.

Limited resources

One example for the competition of limited resources emerges in the search and allocation of free parking spots or charging stations for electronic vehicles [20, 21, 24, 56, 57, 197, 228, 249, 267]. Ayala et al. [21] formulated the problem as a finite assignment game where the closest player wins a parking spot for the costs of the traveled distance while other players pay fixed costs for fruitless attempts. Parking spots can also be defined as gravitational forces [20], leading players to areas with the most parking spots instead of the closest one or also taking into account the freshness of the parking spot information [249]. Other approaches rely on central communication infrastructures for coordination while selecting dedicated coordinators or a global selector for the resource allocation [57, 197, 228]. Different approaches formulate the allocation problem using Markov chains [40] or queuing theory [24, 56] to predict the availability and utilization of resources. The reverse situation of resource allocation is addressed by considering the problem of recharging static wireless sensor nodes with mobile vehicles [113, 271].

While the idea of formulating the decentralized allocation of vital resources in DTN-MANETs as a game theoretic problem is reasonable, the mentioned concepts of the resource allocation cannot be applied fully to our problem for the following reasons: *i)* most of the concepts rely on central infrastructure-based coordination using global network knowledge, *ii)* the costs to compete for a resource are often assumed to be equal for each node, but in reality, the costs vary individually per node based on, for example, the location of the node, *iii)* many concepts assume an instant allocation of resources, but in our considered scenario, nodes need to consume a resource at its location, which requires travel time, *iv)* resources can be freed after they are allocated, as it appears in the parking spot allocation, which is not true for our scenario, and most importantly, *v)* the assignments of resources based on the decisions of the nodes are considered to be independent of each other. This is not true for our scenario since the decisions of the nodes influence future decisions of other nodes in the network because the number of available resources and the nodes' demands for energy changes constantly over time.

All the above concepts assume stable conditions and the availability of global knowledge about the current situation. However, the unique nature of post-disaster scenarios cannot fulfill these two assumptions, as frequent and unpredictable changes to the environment are common, and the central communication infrastructure is not available. To model the resource allocation of limited resources in the considered scenario, simplifications like a stable environment, knowledge about the available resources, and knowledge about the node behavior need to be assumed. These assumptions simplify the problem to the extent that an appropriate representation of the scenario is no longer given. Thus, game-theoretic models are hardly representative in this particular scenario, as their expressiveness is very restricted, which leads to the limited applicability of game-theory to post-disaster networks.

Inspired by the related work presented in this section, we propose new resource allocation protocols for the utilization of physical and infrastructure independent energy resources to prolong the battery lifetime of communication nodes in Section 5.2.

3.3 INFLUENCE FACTORS OF MESSAGE PRIORITIZATION

While DTN-MANETs can be utilized to support essential means of communication without the need for any infrastructure, the increased communication demand in post-disaster situations may overload the network. The large gap between the available and the requested bandwidth in the post-disaster communication scenario prevents the majority of messages to be distributed in the network, and it also profoundly influences the message propagation delay.

Favor important messages

To apply any kind of message prioritization to cope with the limited communication capabilities, a difference in the message importance and disaster relevance needs to be detectable. If the message attributes are not known beforehand, for example, by the message application itself [103, 152, 230], the definition and detection of content and context relevant attributes are essential to compare and differentiate messages to apply message prioritization.

Message content

Based on the content of text messages, natural language processing methods can be applied [30, 121] to identify different message attributes and their relevance to the disaster. In these works, different classifiers are used to categorize messages that were exchanged between first responders during post-disaster relief operations after the major earthquake in Nepal 2015. They were able to differentiate between messages with relation to the disaster and sentimental ones, to prioritize them accordingly. Other works also focus on the message typecasting in post-disaster situations. An extensive categorization of message content is done in the *CrisisLex* [182], a lexicon with crisis-related terms that frequently appear in relevant messages posted during different types of disasters. Besides, various machine learning approaches [48, 105] can be applied to classify and categorize messages as well as newer approaches, for example, neural networks [45] or deep learning [171]. Likewise, the classification based on the textual content of messages, multimedia content, such as pictures and videos, can be utilized [70, 263, 273]. Computer vision and image processing algorithms can be used to recognize disaster relevant contents, for example, roadblocks, fires, or injured people. Furthermore, these mechanisms can be used to detect similarities in multimedia contents to reduce the priority of duplicate content and, thus, reduce the load in the network [19, 68]. If the importance and the disaster relevance cannot be determined beforehand, opportunistic networks can be used to detect the popularity of messages. Here, popular messages, which are determined to be important ("liked") by the DTN-MANET nodes, are assigned a high priority and are favored in the distribution process [264].

Message context

Besides the content of messages, the context of the users can be taken into account to determine relevant attributes for the message prioritization. Context information that can be utilized are, for example, vital signs of a person [78], the users' activity [134], the battery level of the smartphone [37, 147], the location or movement direction of the user [89, 148, 233] or the users' role, such as, a citizen or a first-responder [149]. It is also possible to consider communication characteristics as message attributes [135, 147, 202, 272], for example, the number of the nodes' communication neighbors, the message age, remaining Time to Live (TTL) or size.

For our work, the important aspect is the opportunity to apply these mentioned algorithms and mechanism for the attribute determination beforehand to enable message prioritization in post-disaster DTN-MANETs. The message prioritization favors the distribution of specific messages while penalizing the distribution of other messages, resulting in complex interactions regarding message distribution and message delay, which will be further discussed and evaluated in Section 5.3 and Section 6.3.

3.4 UAV-BASED SUPPORT FOR POST-DISASTER NETWORKS

Since the communication in DTN-MANETs is based on the store-carry-forward principle, the data dissemination is mainly influenced and limited by the degree of movement by the network participants. While the DTN-MANET communication theoretically works well in areas with high node densities, in the so-called communication islands, the movement areas between islands, the communication bridges, are often to sparsely frequented by nodes (cf. Section 2.3). This results in weak and highly delayed inter-island communication (cf. Section 2.3). UAVs are suitable data ferries for the support of DTN-MANETs, due to their high mobility and controllability. In general, the increasing availability and popularity of UAVs in recent years attracted much attention from researchers and practitioners of many application fields. In the following, we are surveying different UAV types, possible applications with a focus on civil usage and emergency response efforts and UAV simulation models, which is eventually the foundation of one core contribution in this thesis.

UAV-based data ferries

Many different types of UAVs exist, differing in properties, such as size, configuration, mass or flying range [161, 167]. The two main type categories are fixed-wing UAVs and rotary-wing UAVs.

UAV types

Fixed-wing UAVs can be compared to regular small airplanes that generate lift from the airflow over the wings. These UAVs fly very efficient and allow high payloads, high altitudes, and long operation times. Disadvantages are imprecise handling, restricted maneuverability, and the lack of the ability to hover in the air.

Rotary-wing UAVs use rotating blades to generate lift, like helicopters, and are also often called *Multicopters*. Their advantage is the possibility to freely move in any direction that allows higher flight stability, the ability to hover and vertical take-off and landing in addition to straightforward and precise maneuverability. Their drawbacks are short flight times and low payloads.

We consider a post-disaster scenario where the fast applicability and controllability of data ferries is crucial. Therefore, we are focusing on rotary-wing UAVs, since they can hover in the air, which is essential for sufficient communication duration and stable communication links with ground nodes. Additionally, their possibility to vertically take-off and land is crucial in the case of obstructed disaster regions.

UAV operations

Existing research of UAV operations describe several use-cases for civil [96] and emergency response applications [66], such as: *i)* improvement of Internet of Things (IoT) applications [163] and cell coverage [154, 218], *ii)* wireless sensor recharging [113], *iii)* inspection of power lines [67], *iv)* environmental scanning [285] and aerial contamination measurement [54], *v)* disaster area mapping [199], *vi)* coastal surveillance [259], *vii)* forest fire localization [27], *viii)* search and rescue missions [206, 223], or *ix)* message relaying for rescue team members on incident sites [23, 159].

Most of the mentioned research used specific prototypes or mathematical models to prove the feasibility of their approaches and to gather insights into their system's behavior. Other UAV system evaluations use simulations, which is also our evaluation tool of choice since it allows the repeatability of realistic system behavior if sophisticated UAV representations are available. Existing UAV simulation possibilities work either only for a specific use-case and are not adaptable [59] to other scenarios, or the simulations are over-simplifying the UAV functionalities [27, 67, 160], such as the energy consumption and the resulting operation time.

For the contributions in this thesis, it is essential to design and evaluate the application of UAVs in combination with DTN-MANETs to analyze the potential impact on the overall communication capabilities. We propose different UAV-based communication support strategies in Section 5.4 to support DTN-MANETs in post-disaster scenarios. We extend our existing simulation platform by UAV representations for a repeatable and customizable evaluation of different support strategies applying different scenarios in Section 6.4.

4

POST-DISASTER CHARACTERISTICS AND COMMUNICATION SERVICES

In this chapter, we survey past disasters and identify common characteristics. The survey focuses on the analysis of the behavior of the affected population and their communication- and interaction-characteristics. Based on the post-disaster scenario, we introduce a set of services for post-disaster communication in Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs), followed by the design and execution of a large-scale field test, reproducing a disaster scenario with 125 participants. During the field test, the peoples' behavior, communication, and interaction were recorded. We conclude this chapter with the analysis of the recorded data and provide insights into challenges for post-disaster communication networks.

4.1 SCENARIOS CHARACTERISTICS

The International Federation of Red Cross and Red Crescent Societies (IFRC) defines a disaster as follows: "A disaster is a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses [...]. Though often caused by nature, disasters can have human origins" [204]. Moreover, even beyond their origins, no two disasters are the same. Some disasters can be predicted well, such as snowstorms [12, 281], bush-fires [83, 276] or hurricanes [76, 265]. Other disasters, for example, earthquakes and resulting tsunamis [84, 129, 177, 187, 274] or man-made disasters [153, 194] are difficult to predict at an early stage. Disasters differ greatly in their magnitude, their time span, and the threats they pose. Especially in urban areas, the impact on the population is particularly strong and will get even stronger with the future rise of population densities [203]. However, the analysis of various past disasters reveals several common characteristics related to infrastructure disruptions and the behavior and needs of the affected population, although differences may arise in the relative significance of each characteristic.

Disaster types

The following characteristics are identified: *i)* Loss of power supply and communications [185, 187, 203, 265, 274], *ii)* lack of information [50, 83, 274], *iii)* response difficulties [31, 187, 265, 274], *iv)* use of social media and similar applications [5, 220, 278, 279], *v)* high communication demand [14, 121], *vi)* isolation and separation of people [125, 181], *vii)* search and rescue missions [97, 203, 265], *viii)* disaster specific movement behavior of the affected population [73], *ix)* resource requests and demands [29, 77, 266], *x)* collaboration of the affected population [98, 256] and self organization [29, 77, 266], and *xi)* dynamic communication behavior and changing relevance of information [102, 198, 203, 240].

Disaster characteristics

Loss of power and ICT

A key characteristic is the loss of power supply and Information and Communication Technology (ICT) [185, 187, 265, 274], resulting in a lack of information available to the population along with response difficulties [50]. In the case of the Great East Japan Earthquake in March 2011, the affected Japanese network providers reported the loss of an estimated 1.9 million fixed-line services and 29,000 mobile base-stations, rendering the ICT inoperable [203]. In the case that ICT is still partially available, the utilization of social media or other applications in disasters show that a smartphone is an indispensable tool for disaster response and communication is key to cope with the aftermath of a disaster [5, 220, 278, 279]. The need for gathering and exchanging information results in high demand for communications, which can often no longer be met by the remaining infrastructure [14, 121].

Disaster movement behavior

Besides the fact that the sudden occurrence of a disaster results in the separation of families and friends, the movement of the affected population during and after a disaster differs from their everyday life behavior and has a high individual variability per citizen [73]. In addition, it can be observed that there are areas that are visited more often than others during a disaster. Highly frequented areas are generally referred to as Points of Interest (POIs), such as emergency shelters, city centers or hospitals [146, 238, 239]. In general, the mobility of the affected population cannot be influenced, and the movement possibilities are often strongly limited by the effects of the disaster, for example, flooded streets (Figure 7).

Figure 7: Puerto Rico after Hurricane Maria September 23, 2017 (Photo by Kris Grogan)[1].

Pro-social behavior prevails

It is important to mention that pro-social behavior of the affected population prevails in disasters in contrast to looting, violence, and helplessness, which are confirmed as myths or are exceptions [98, 256].

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[1] CBP Photography, CBP Responds to Hurricane Maria, 2017 `https://flickr.com/photos/cbpphotos/albums/72157685552269492`

The loss of energy supply and ICT also severely affects the supply of vital goods to the population [192]. Cooling chains for food can no longer be maintained, and the central water supply and most gas stations can only operate with the availability of power supply. Various analyses of Twitter messages and similar platforms [29, 77, 266] show that the population is trying to exchange important resources during and after a disaster in a self-organized manner. The analyses show that the most popular resource is energy [29, 266], which can be provided in the form of batteries, generators or solar panels independently of the central energy infrastructure and are used, for example, to recharge mobile phones.

Trading resources

The multitude of messages sent during and after a disaster can be divided into different categories [123, 203], for example, the message type such as emergency messages, warnings, search queries or normal text messages. Further categories can be determined by the users context, for example, their location [233] or the users role (first responder or civilian) [149]. The related work [102, 198, 203, 240] indicates that such categories differ in their importance and frequency, which is of great relevance for a disaster communication system. An emergency message, for example, should reach its destination as fast as possible, while other messages with no relevance to the disaster can be delayed or even dropped. Another example are warnings about an arising threat that should reach as many citizens as possible and as quickly as possible. With a functioning communication infrastructure, the relevance is already taken into account, for example, by automatically giving priority to emergency calls (e. g., 112 in Europe and 911 in the USA) to be able to provide help as quickly as possible. Furthermore, applications based on the cellular network like *AMBER Alerts* (America's Missing: Broadcast Emergency Response) [118] in the USA or *KatWarn* and *NINA* [208] in Germany, allow authorities to provide relevant information to the public (cf. Section 2.2). In case of a disaster, it can be observed that the number of messages of certain categories and their importance change over time [102, 198, 203]. It is common that in the direct aftermath of a disaster, emergency messages are the prevailing message type. After some time, safety-related information and search requests get more prominent and important [102].

Different message types

Disaster relevance

Changing communication behavior

The identified characteristics of the post-disaster situation, as well as the behavior and communication characteristics of the affected population and their needs, have to be considered to provide post-disaster communication via DTN-MANETs.

4.2 REQUIRED SERVICES FOR POST-DISASTER COMMUNICATION NETWORKS

Self-organized communication in the event of a disaster can be used by different groups of people with varying requirements and message contents. However, different groups during and after a disaster are not clearly distinguishable. In addition to professional organizations (cellular providers, red cross, etc.), civilians directly affected by a disaster also often act as first responders and form new ad-hoc relief organizations [188, 237]. The consideration of past disasters and discussions with experts have led to the conclusion that communication between the civilians

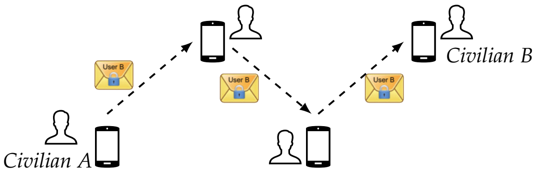
Focus on civilians

in the disaster area has special vital importance. In contrast to many established relief organizations, civilians do not have dedicated means of communication. Therefore, we concentrate on basic services for post-disaster communication that focus on the communication needs and capabilities of ordinary civilians. A suitable way for infrastructure-independent communication are smartphone-based DTN-MANETs.

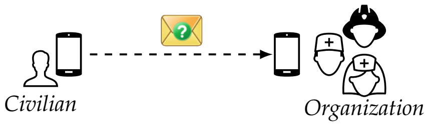
Utilization of DTN-MANETs

Communication pathways

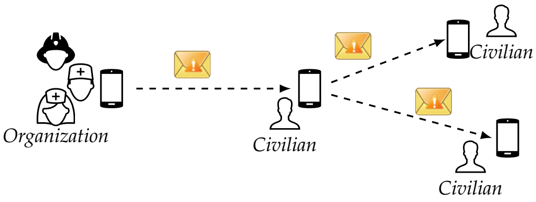
DTN-MANETs are a combination of delay tolerant and mobile ad-hoc networks, which can be easily built with ubiquitous communication devices, such as smartphones, and can be utilized by civilians, responders and organizations. As depicted in Figure 8 the set of services should facilitate three different communication pathways while being able to use different forms of addressing methods, for example, unicast, broadcast, geocast etc. (cf. Section 2.3): *i)* civilian-to-civilian (C2C) communication, *ii)* civilian-to-organization (C2O) communication, and *iii)* organization-to-civilian (O2C) communication. Organization-to-organization (O2O) communication is outside of the scope of this thesis since dedicated hardware, systems, and specially designated communication frequencies are available for O2O communication.



(a) Civilian-to-civilian (C2C), e. g., unicast private message.



(b) Civilian-to-organization (C2O), e. g., anycast help request.



(c) Organization-to-civilian (O2C), e. g., broadcast warning messages.

Figure 8: The three communication pathways for post-disaster communication [135].

Services for post-disaster communication

Together with the German Federal Office of Civil Protection and Disaster Assistance (BBK) and several experts from different German Fire Departments, we identified a set of services for post-disaster communication in DTN-MANETs. These services were created under consideration of the identified common characteristics of past disasters in Section 4.1 and based on a survey of international civil protection applications in [87] and Section 2.2. This set contains the following services for post-disaster communication in DTN-MANETs:

SOS Messages

This service is used to send an urgent call for help. These so-called *SOS Messages* are addressed to authorities to get professional help (C2O). Due to the distribution properties of the ad-hoc network, such SOS messages also reach surrounding communication nodes, which can act as first responders to provide fast help (C2C). This type of message is considered very important because, in the worst case, the distribution of *SOS Messages* can be vital.

Messaging Service

This service allows the exchange of messages between civilians affected by a disaster with similar functionality to SMS or WhatsApp (C2C). The possibility to exchange text messages is important to support the collaboration of the civilians and to assist the self organization. However, due to the DTN-MANET characteristics, the user does not know whether or how much delayed a message will reach its destination.

I am Alive Notifications & Person-Finder

I Am Alive Notifications are used to share status information with other network participants (C2C), for example, family and friends. *I Am Alive Notifications* can include important information such as the health condition or the current or next targeted location. The *Person-Finder* service provides the counterpart of *I Am Alive Notifications*. The service allows searching for a specific person in the network. If the subject receives a *Person-Finder* message, it automatically generates a *I Am Alive Notification*. If forwarding nodes receive a *Person-Finder* message of a node from which they have already received a *I Am Alive Notification*, it is sent back to the requester (C2C). This functionality is similar to services that rely on existing infrastructure, such as the *Facebook's Safety Check* [106], the *Google's Person Finder* [107], or Non-governmental organization (NGO) websites like the red cross [253].

Information/News

This service allows responders to make official announcements regarding the ongoing disaster situation or potentially evolving new threads to the public (O2C). For this service, the broadcast or the geocast (cf. Section 2.3) addressing method is suitable to either inform the overall network or only civilians in a specific area.

Situational Awareness & Disaster Mapping

This service allows civilians to report observations of the disaster area to other civilians or organizations (C2C & C2O). For example, damages or threats can be reported, or collaborative disaster maps can be created. Such collaborative maps can be used, for example, to record the area of any type of infrastructure blackout. In case of a power blackout, users can share information of available or unavailable power supply in combination with their current position. A service like the Disaster Region Analyzing Service (DRAS) [139] utilizes and constantly combines newly received data to build a map. Over time, such a situation map becomes more complete and detailed, as shown in Figure 9. Such a map allows civilians (C2C) or infrastructure providers (C2O) to determine the area affected by an infrastructure blackout and allows civilians to move to areas where the infrastructure is still intact or helps infrastructure providers to plan restoration actions. A detailed description about the functionality, implementation, and evaluation of DRAS can be found in Section A.1 and in [139]. Here we demonstrate that DRAS successfully is able to detect and calculate the affected area of an ICT blackout, while being able to cope with dynamic scenario changes.

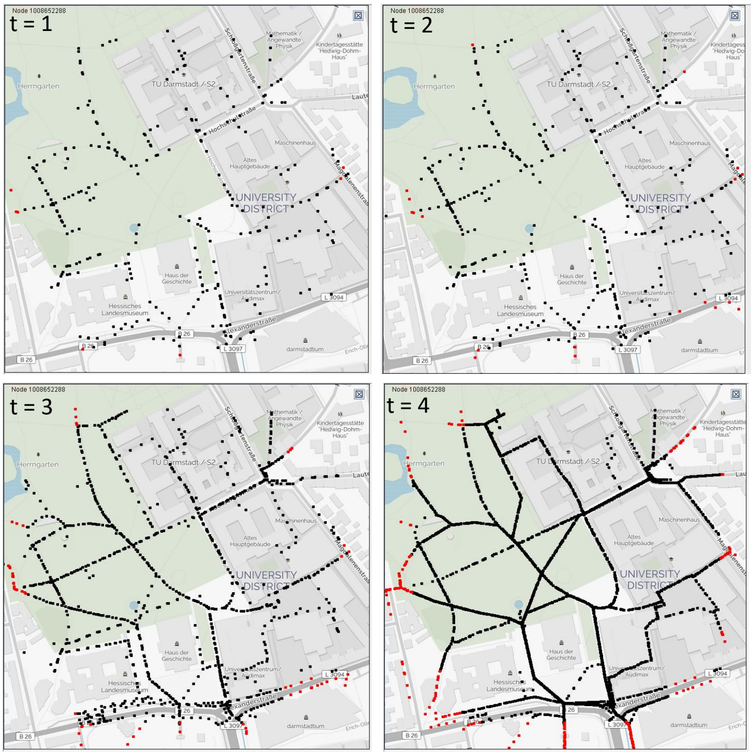


Figure 9: Temporal sequence of a node's knowledge of the post-disaster area. Black dots represent locations inside the blackout area without intact infrastructure, red dots represent locations outside the affected area (OpenStreetMap) [139].

Resource Market Registry

This service provides an exchange platform for arbitrary physical resources such as food, medicine, shelter, fuel, or similar. The *Resource Market Registry* empowers the affected population (C2C) to independently self organize requests and demands for required resources. Because physical resources have to be collected in person, the relevance of a resource-demand or -request depends on the distance to it. Since DTN-MANETs cannot guarantee stable communication paths, the allocation of resources in post-disaster networks is challenging. As a result, resources cannot be reliably allocated because there is no central coordination, and the decision to go to a resource is made by each node individually. Resources, therefore, cannot be blocked and are allocated in a first-come-first-serve manner. As one possible resource, we focus on the distribution of energy in this thesis (cf. Section 5.2), as this prolongs the lifetime of the individual nodes and consequently of the overall DTN-MANET.

Tasking

The *Tasking* service focuses on utilizing human resources to recruit suitable personal to fulfill a particular task (C2C & O2C). Such tasks can be, for example, the collection of information about infrastructure damage or the number of affected people at a specific location. If such a task additionally consists of technical processing steps of the collected data, such as image processing, classifier or data aggregation, there are additional mechanisms to distribute and merge these processing steps among the network participants [172].

The proposed set of services is a tool for civilians to cope with the aftermath of disasters when no infrastructure based communication is available. The services address the communication needs of the civilians and support them with their disaster management efforts, including the communication possibilities to professional help organizations. Only text-based implementation of the set of services would keep the amount of exchanged data low, to take into account the uncertain and varying communication capabilities of DTN-MANETs.

4.3 REAL-WORLD ASSESSMENT IN A LARGE-SCALE FIELD TEST

Test under real-world disaster conditions

To assess the functionality of the presented services for the use in post-disaster ad hoc networks, it is essential to assess their usage and performance under realistic conditions. As discussed in Section 3.1, existing simulation models for post-disaster communication networks are not sufficient to represent the disaster-specific characteristics identified in Section 4.1. Especially the representation of real-world behavior of the affected population during and after a disaster is crucial to evaluate the applicability and limits of the proposed set of services for ad-hoc post-disaster communication. To overcome this issue, we have conducted a large-scale field test that aims to represent a post-disaster situation as realistically as possible. With the realization of the field test and a followed up questionnaire, we provide an extensive level of detail about the behavior, communication and interaction characteristics of the affected population, as well as detailed characteristics about the functionality and application possibilities of smartphone-based DTN-MANETs in post-disaster scenarios. The gathered insights and recorded data are used to confirm the identified disaster characteristics and to evaluate and improve the proposed services upon their usage in the field test and the subjective feedback from the participants. Furthermore, the recordings are used to address the gap of missing simulation models of disaster scenarios.

Foundation for simulation models

4.3.1 *Planning and Execution*

125 participants and 3 villages

The field test took place on a military training area near Paderborn, Germany in September 2017 as part of the Smarter project[2], involving 125 participants over the course of one day and was conducted in cooperation with the German Federal Office of Civil Protection and Disaster Assistance (BBK), the German Federal Agency for Technical Relief (THW), local fire departments and other NGOs. The field test area consisted of three different villages (A, B, C) as highlighted in Figure 10. The linear distance between Village A and B is 3.7 km and between B and C is 660 m. The movement paths between the villages are limited according to the paths marked in blue and result in distances of approximately 5 km between Village A and B and approximately 1 km between B and C.

Figure 10: Layout of the military training area *Senne* near Paderborn, Germany. Three different villages A, B and C are highlighted (Google Maps, 2019)[3][9].

Representative test environment

The architectural features of the various villages consisted of ordinary houses with stone walls, as depicted in Figure 11, showing the top view of Village B. Additionally, there existed special buildings such as a gas station, a church, or an airport, allowing the participants to immerse themselves in the scenario. These conditions also make it possible to ensure realistic communication characteristics for the DTN-MANET, for example, varying communication ranges depending on the signal attenuation by objects, obstacles, or terrain. On top of that, there is no cell phone coverage in the field test area.

Scripted disaster events

The field test scenario was a long-lasting power outage caused by severe weather and the resulting failure of the cellular network. To create a more realistic post-disaster situation with stress among the participants, there were two special events during the field test in which professional actors were engaged. The first event was a lightning strike into a gas station. Several people pretended to be seriously injured and needed immediate help and had to be brought to safety. The second event was an accident in a chemical power plant in which toxic substances leaked out and

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[2] http://smarter-projekt.de [Accessed July 1st, 2019]

[3] Bilder © Google, Bilder © 2019 GeoBasis-DE/BKG, GeoContent, Maxar Technologies, Kartendaten © 2019 Geobasis-DE/BKG (© 2009)

Figure 11: The top view of Village B in the field test area.

spread throughout the village, injuring people and resulting in the evacuation of the area. Over the entire duration of the field test (9:30 - 16:30), the actors continuously contributed to the scripted disaster situation, to make the situation appear as realistic as possible. These actors are specially trained for such exceptional situations and are often used in the training of police or fire brigade personnel. One actor, for example, played a mother desperately looking for her child while the participants of the field test did not know beforehand that such scripted events will occur.

Professional actors

Once a real-world scenario was defined, and the field test procedure was planned, an infrastructure-independent communication system needed to be provided to the field test participants. In cooperation with the project partners of Smarter[4], we implemented the following set of emergency services based on the identified services in Section 4.2 within an Android application: *i)* SOS Messages, *ii)* Messaging Service, *iii)* I am Alive Notification, *iv)* Person-Finder, and *v)* Resource Market Registry. To enable the direct communication of smartphones in reach, we relied on *Nexmon* [227], a C-based Wireless Fidelity (Wi-Fi) firmware modification framework and IBR-DTN [62, 224], a lightweight, modular and highly portable bundle protocol implementation (cf. Section 2.3). In a usability test with 10 smartphones, we achieved communication ranges up to 200 m with Line of Sight (LOS) of the devices and dry weather.

Enable ad-hoc communication

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[4] http://smarter-projekt.de/projektpartner [Accessed July 1st, 2019]

At the start of the field test, each of the 125 participants got a charged smartphone with the ad-hoc mode enabled and the disaster services installed. All participants were evenly distributed in the three different villages. As already identified in Section 4.1, a common characteristic of spontaneously occurring disasters is the separation of families and loved ones, followed by the subsequent desire to reunite again. The services *I am Alive Notification* and *Person-Finder* can help to reach this goal. For the field test, this means that also family affiliations among the participants have to be mapped. So-called *Sed Cards* were created for each participant individually, including;: *i)* a fictional name and age, *ii)* the names of relatives and friends, *iii)* the place of residence (Village A, B or C), *iv)* a listing of individual tasks, and *v)* desired items. Every participant had a list of different tasks that should increase the mobility of the participants and the interaction with others. Such tasks are, for example, meeting family members at their homes, building a large SOS sign from logs or obtaining certain items. Each smartphone address book was configured in such a way that only known persons, regarding the *Sed Card*, were included. Every participant started with three different items that had to be traded according to the items on the *Sed Card*. Additional resource items, such as food, drinks, or first aid kits, were also hidden in the villages. Whether the objects were exchanged using the emergency services (e. g. *Resource Market Registry*) or by communicating with other nearby participants was entirely up to them. A copy of an example *Sed Card* can be found in the appendix (Section A.2).

Sed Cards *for fictional characters*

Tasks and physical resources

To be able to evaluate the field test in detail later on, we used a custom logging framework to record the application interaction, sensor data, and network characteristics. To be able to capture the usage and usability of the services during the field test, all interactions with the application were recorded as well as all incoming and outgoing messages.

Field test recordings

Regarding the sensors of the smartphone, the following sensor readings were recorded every second and stored in a local database: *i)* Global Positioning System (GPS), *ii)* brightness, *iii)* accelerometer, *iv)* air pressure, and *v)* gyroscope. Our main focus lies on the GPS motion patterns of the participants, to gain insights on the movement behavior in post-disaster situations and the resulting transport of messages in the DTN-MANET. In previous work, we have shown that the set of sensors besides the GPS values are sufficient to reliably recognize a person's activity and to differentiate if the person is performing a disaster-related activity [134]. Such activities can be, for example, running down or up stairs, crawling on the floor, or walking with an injured leg.

We focus on the analysis of the performance of the smartphone-based DTN-MANET. We recorded all the information that we could access provided by the IBR-DTN [62, 224] bundle protocol implementation to assess the store-carry-forward principle of the network. This included details about: *i)* the received and sent messages with the information about the disaster service type, *ii)* one-hop neighbors, and *iii)* connection events like connection setups and disconnections.

The recording of the data led to increased energy consumption and, thus, also a reduced running time of the devices. However, since the field test could not be repeated, the reliable collection of data over the entire duration of the field test had a high priority. Therefore, each smartphone was additionally equipped with a battery pack to compensate for the increased energy consumption.

4.3.2 *Analysis of Collected Mobility Traces*

Data preprocessing

As usual, before analyzing large amounts of real-world data, the accuracy must be verified, and the data must be pre-processed if necessary. Unfortunately, not all devices successfully recorded data during the field test. Due to user misuse, hardware failure, software problems, or the loss of devices, we were only able to record and analyze network and application usage data of 119 out of the 125 devices. Regarding the tracking of GPS sensor readings, for the same reasons, only 96 GPS traces could be recorded. Since the devices never had access to the cellular network or the Internet, there was no perfect time synchronization between all devices. However, a uniform time stamp is necessary to bring the different logs of the devices into relation to each other. Therefore, we consider the device with the most number of connections to other devices as the reference time. With this ground truth, we were able to synchronize all other devices based on this time. The relevant timespan for our analysis is the time in which all participants resided the field test area. For organizational reasons, however, it was not possible to distribute all participants from the base-camp to the various villages with buses at the same time. Based on a GPS sensor data evaluation of the devices, the time span for the data analysis was chosen, starting from the time when all participants reached their starting village until the first persons left the field test area via bus. Therefore, the considered timespan for the following analysis of the field test is 10:30 until 15:30.

GPS sensor data

In the following, we focus on the analysis of the recorded GPS sensor data during the field test and derive conclusions about the individual movement of the participants, including interactions with their neighborhood.

Movement Behavior of Participants

Based on the recorded GPS traces, we analyze the individual movement characteristics of the participants. Figure 12 presents the walking speed in a ten second time window for our specific scenario, resulting in an average movement speed of 2.14 km/h. In addition, the analysis resulted in an average walking distance of 11.39 km.

Movement characteristics

Approximately 35 % slow movement below 1 km/h can be observed, which is the result of the movement characteristics inside the villages and when groups of participants meet in between them. The movement speed peak between 4–5 km/h reflects normal movement in between the villages. The observed characteristics also match up with the assumed movement speed of pedestrians in other research and observations [17, 34, 49, 251].

Figure 13 shows the overall GPS positions of the field test participants on an underlying map of the area. It can be seen that the participants roaming between the different villages using the designated pathways. As described in Section 4.1, one iden-

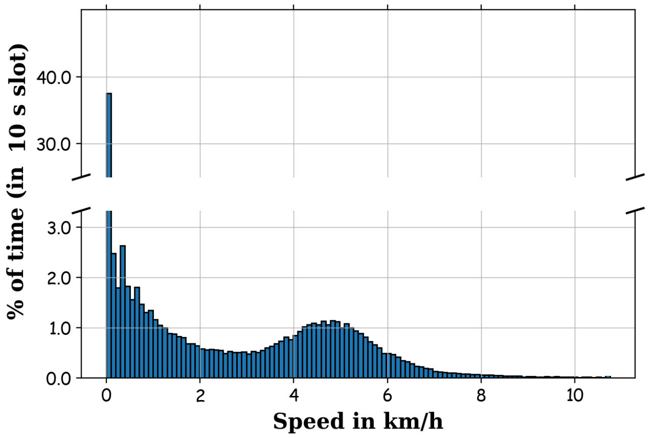
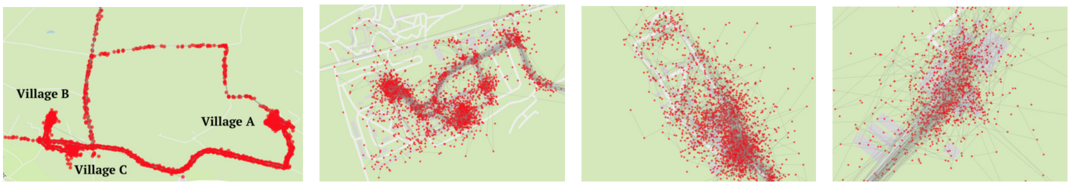


Figure 12: Walking speed of the participants during the field test [9].

tified characteristic of the post-disaster scenario is the presence of high frequented areas, the POIs. While the different villages themselves already represent such POIs, especially Village A also contains POIs itself. This can be seen in Figure 13b having high frequented areas such as the church where lunch was served, or the gas station where the disaster event took place.



(a) Field Test Area (b) Village A (c) Village B (d) Village C

Figure 13: GPS traces of the participants during the field test [9].

Group movement

Furthermore, we analyzed the temporal course of the GPS traces throughout the field test and observed that the participants tend to join together in groups when they leave a village. For the field test, our analysis results in an average number of 3.9 groups with a minimum number of 1 group and a maximum number of 9 groups, while the average group size is 6.2 persons. The analysis also reveals interactions between meeting groups, which mostly consisted of family members and close friends regarding their *Sed Cards*. If two groups meet, they stop for an average of 10 s before moving on again. Due to human behavior in such a situation, it is evident that people want to exchange information about the situation verbally. For the utilized DTN-MANET communication network, this group actions result in additional contact time with other communication nodes in close range to synchronize and exchange data.

Neighbor Statistics

Based on the GPS data, we also recorded the neighbors of the participants with respect to different communication distances. Figure 14 shows the number of potential communication neighbors for the distances 25, 44, and 110 m, aggregated over 2 min. These distances are derived from Figure 15a in the next paragraph focusing on the network data analysis. 50 % of the successfully established connections were established at a distance of up to 25 m. The average distance of all connections was 44 m and 90 % of all connections were established between nodes not further away than 110 m. On overage, each participant had between 6–8 neighbors.

Communication neighbors

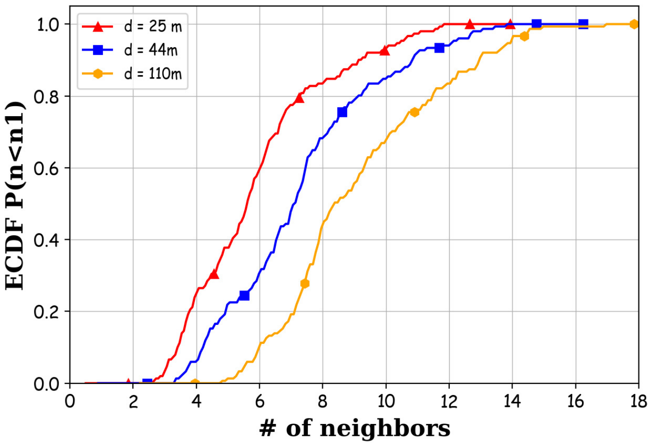


Figure 14: Neighbor statistic based on GPS traces [9].

4.3.3 *Analysis of Communication Properties*

As already described in the previous section, the collected field test data must be preprocessed and prepared before analysis. Based on the recorded information provided by the IBR-DTN [62, 224] bundle protocol implementation, we concentrate on the analysis on a communication network perspective in the following. We focus on the characteristics of the connection establishment, the generated traffic, and the message propagation properties.

Connections

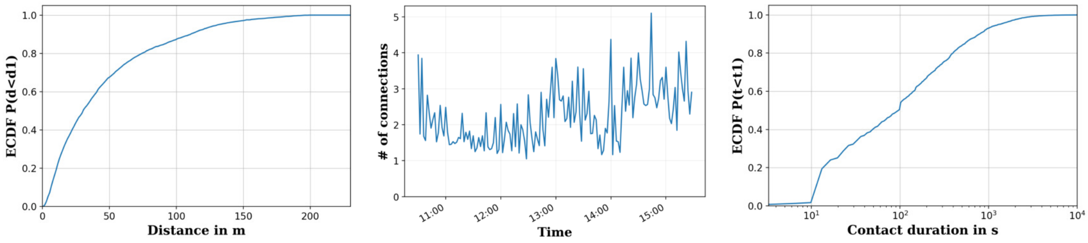
Whenever we detect a communication connection in the recorded field test data, we calculate the distance between the devices pair based on the GPS data. The Empirical cumulative distribution function (ECDF) of the device pair distance in Figure 15a shows that approximately 90 % of the established connections are within a range of 110 m. Still, we see that connections could also be established with an impressive range of more than 150 m during the field test. Compared to the maximum range of 200 m measured in our usability test with 10 devices, mentioned in Section 4.3.1, the lower range during the field test can be explained with the lower probability of LOS,

Connection distances

the rainy and humid weather, and the fact that most participants carried the devices in their pockets.

Number of connections

Figure 15b visualizes the connections per host over time, aggregated over 2 min. The visible peaks of the number of connections match with the start and the end of the field test, where the participants are situated in the three different villages. The remaining peaks, starting at 13:00, reflect the two conducted disaster events that attracted the participants and led to more devices in the communication range.



(a) ECDF of the connection distance.

(b) Average node connections over time.

(c) ECDF of the connection duration.

Figure 15: Node connection characteristics during the field test [9].

Connection duration

The ECDF in Figure 15c presents the connection duration of device pairs on a logarithmic time scale. More than 50 % of the connections had a duration of more than 100 s. This is a consequence of *i)* the communication range using the Wi-Fi interface, *ii)* the restricted movement of the participants inside and outside the villages, *iii)* the merger to form groups, and *iv)* the associated group encounters. This information is very helpful to determine the communication capacities in a smartphone-based ad hoc network. Properties, such as the maximum buffer- or message-size, depend to a large extent on the available bandwidth and connection duration.

Traffic & Application Usage

Communication traffic

In the course of the field test, each participant could send and receive messages via the provided smartphone. These messages were distributed throughout the DTN-MANET until all network nodes were reached or the message Time to Live (TTL) of 60 min was exceeded. A total of 1,834 messages were generated by the participants throughout the field test. The share of the message types is shown in Figure 16.

Here it can be seen that all available services were used and, depending on the service, with varying frequency. Additionally, we investigated the size of the different messages created, resulting in a mean message size of 290 bytes with a standard deviation of 568 bytes. The small message size can be explained by the fact that the implemented services are text-based and did not support multimedia content at the time of the field test.

Service utilization

Furthermore, we have observed the utilization of all services throughout the field test. Figure 17 shows the aggregated number of messages received by all participants during the entire field test in a 2 min time window. It is important to note that it includes all generated messages and their forwarded duplicates. Received messages

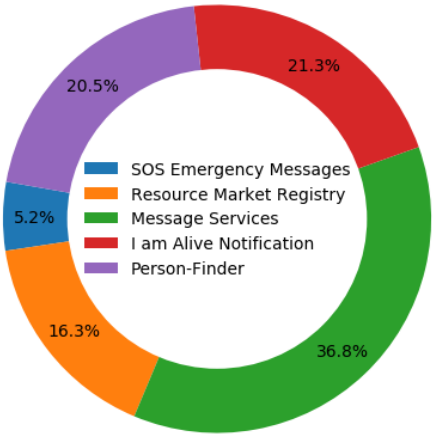


Figure 16: Usage of the different disaster services during the field test [9].

or duplicates of messages are only displayed to the user if the node is in the recipient list of the message. Otherwise, messages are automatically duplicated and forwarded in the network without any user interaction.

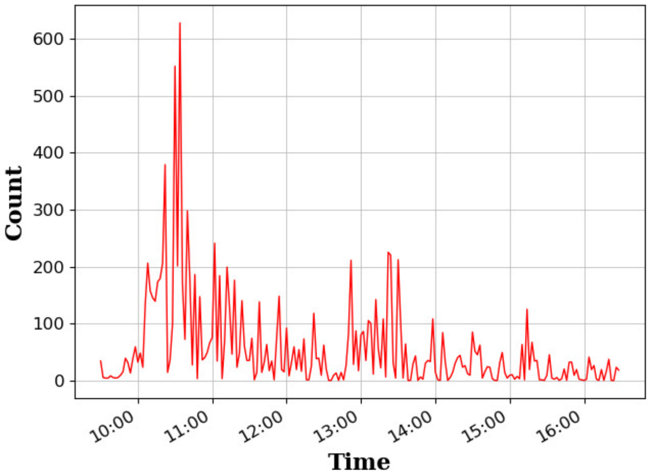


Figure 17: Number of received messages [9].

Traffic characteristics

Figure 17 shows that the communication demand at the beginning of the field test is very high and therefore a high exchange of messages takes place as soon as the participants have arrived in the villages. The message reception then decreases steadily until food trucks entered village by village (approx. 12:30) and the two disaster events started. These events resulted in a peak of received messages and can be explained by the fact that new messages were generated by the participants to inform or react accordingly to the happening events. Additionally, many participants came in communication reach with other devices and synchronized their stored messages.

Propagation Delay

One of the most important parameters for the evaluation of the performance of DTN-MANETs in post-disaster situations is the propagation delay. It indicates how well data can be distributed throughout the entire network. Especially in the given field test scenario with the three different villages (communication islands) and the paths connecting the villages (communication bridges), the mobility of the users has a great influence on the propagation delay and limits the network-wide communication capabilities. With the use of the recorded network data per device, we can analyze how many network participants received a message within the message TTL of 60 min. Here we are only considering broadcast messages of the available disaster services, whose goal was to reach as many participants in the network as possible. Figure 18 displays the message propagation delay of the best-distributed broadcast during the field test as well as for the median, considered at the expiration of the TTL.

Broadcast propagation

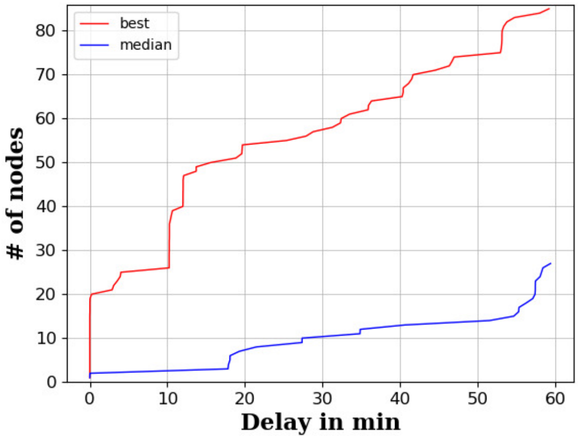


Figure 18: Message propagation delay during the field test [9].

On average, messages were successfully transmitted to 27 nodes or 21.77 % of the network participants, which demonstrates the limited communication capabilities of DTN-MANETs. The best-distributed broadcast reached a total of 86 nodes or 69.35 % network subscribers. This is the result of having a high node density in the villages and the group forming behavior of the participants. Whenever a node reaches a new village, or two groups meet, message propagation will take place with almost no delay, which also explains the steps visible in Figure 18. The best performing broadcast reaches 20 devices in under a second, suggesting that the broadcast was created in a village and was promptly spread throughout all nearby devices. After 10 min, the next large propagation step of this broadcast suggests that due to the mobility of the users, the broadcast was successfully carried to another village and forwarded. This is most likely between Village B and C with a distance of approximately 1 km.

Limited message propagation

Sociological Evaluation of the Field Test

In addition to the technical analysis, the participants filled out a questionnaire [25] after the field test and interviews took place. Although this sociological evaluation is not the focus of our work, we want to briefly discuss the key findings that influence the design of the post-disaster communication system. The evaluation showed that the participants were considering the use of a smartphone-based DTN-MANET in the event of an infrastructure failure as very useful. The functions of the set of services were found to be sufficient for disaster management efforts. The participants further evaluated the different services according to their importance for disaster management purposes. The order of the available services with descending importance is the following: *i) I am Alive Notification*, *ii) Resource Market Registry*, *iii) Messaging Service*, *iv) SOS Messages*, and *v) Person-Finder*. The service, which was most frequently used according to the participants was the *Resource Market Registry*, which confirms our assumption of valuable goods during disaster an the willingness to share and cooperate. Criticism of the communication system was also mentioned. Many participants were not aware or did not understand the store-carry-forward principle of the DTN-MANET and therefore, they did not know that the communication potential depends on the mobility of the network participants.

Participant review

Service priority

In addition, the participants mentioned that they did not know whether their messages had reached their destination and criticized the long message delay. Also, participants wanted the support of multimedia content, for example, for the *Messaging Service*. The complete sociological evaluation can be found in the report from the German Federal Office of Civil Protection and Disaster Assistance (BBK) [25].

Summary

The execution of the field test resulted in important insights, which have to be taken into account when designing a DTN-MANET to communicate in post-disaster scenarios. The analysis of the field test showed the capabilities and limitations of the communication network and also confirmed many of the disaster characteristics identified in Section 4.1.

Successful real-world application of DTN-MANETs ...

The formation of communication islands in the villages with additional POIs within the villages could be shown in the field test, as well as the inter-island communication through the movement of the participants. The results show that the use of smartphone-based DTN-MANETs can be used to provide communication in the considered scenario. The combination of high node density in the villages, the group forming and the achieved high communication ranges results in the fact that communication partners were always available and generated messages reached at least one other node. Additionally, it results in sufficient long connection durations to exchange data. With the theoretically available bandwidth of Wi-Fi Direct [43] in combination with the text-based services provided, the bandwidth of the network has not yet been exhausted. Therefore, the support of multimedia content, such as SOS voice messages or video recordings might also be possible. The exchange of a higher data volume together with the varying usage of the set of different services during the field test and the determined priority order of the services motivates us to

... in disaster situations

Need for data prioritization

investigate the application of data prioritization in DTN-MANETs with insufficient communication bandwidth and limited buffer size in Section 5.3.

Modeling of group movement

A new insight from the field test analysis is the formation of mobile groups of people and their interactions, which is currently not sufficiently considered by existing mobility models (cf. Section 3.1). In Chapter 6, we describe the implementation of group mobility behavior and group encounter actions in our simulation framework, to allow more sophisticated evaluations of post-disaster communication systems that rely on DTN-MANETs.

The field test revealed that the movement of the participants is not sufficient for reliable and network-wide data dissemination in the considered scenario while reaching only 21.77 % of the network participants. This challenge will be addressed in Section 5.4 by utilizing additional communication devices or controllable data-ferries to support the DTN-MANET on the ground.

Data propagation needs to be improved

The resource market, according to the subjective statement of the participants, was the most frequently used service during the field test. The service successfully supports the self-organization of the population in times of a disaster by empowering them to offer or demand important resources. In the field test, the resource *energy* was not considered due to the increased energy consumption by the data logging. All smartphones were supplied with sufficient energy for the duration of the field test, which is normally not the case. Energy resources play an important role in setting up and maintaining DTN-MANETs in the event of infrastructure failures. Therefore we concentrate on decentralized energy resource allocation strategies in Section 5.2, to extend the lifetime of individual devices and, consequently of the overall network.

Allocate energy to nodes

On an educational level, participants in DTN-MANETs need to be taught that data is disseminated via the store-carry-forward principle in a delayed fashion to adapt their behavior. This can be, for example, the generation of message content that fits in the delay-tolerant nature of the network and still has a relevant meaning even if received delayed. Additionally, network participants can adapt their movement to carry and distribute data in isolated network areas.

5

D2CS.KOM: DECENTRALIZED DISASTER COMMUNICATION SYSTEM

In this chapter, we propose the Decentralized Disaster Communication System (D2CS.KOM) based on Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs), which enables communication in case of a disaster. As shown in Chapter 4, DTN-MANETs can be used to offer communication capabilities independently of any infrastructure. However, the functionality of the network is limited in comparison to a centrally coordinated communication network. Restrictions are, for example, no fixed communication paths due to the mobility of users, limited resources, the sparsity of mobile nodes, or limited communication ranges. When utilizing and designing such networks, a useful application is constrained by the limited functionality and the weaknesses mentioned above. Especially the use of DTN-MANETs in post-disaster scenarios results in an even more challenging field of application, due to the disaster characteristics as identified in Chapter 4 and from the findings of the conducted field test. Examples for these characteristics are the lack of power supply, the high and varying communication demand in combination with the limited communication opportunities between isolated communication islands. D2CS.KOM can tackle these characteristics and challenges in its core components while providing support for the ongoing post-disaster communication. Especially for post-disaster situations, D2CS.KOM provides new functionalities and thus ensures a situation-aware application. D2CS.KOM extends conventional DTN-MANETs with the following components: *i)* the facilitation and allocation of available energy resources to prolong the network lifetime, *ii)* the support of information selection and prioritization to cope with restrictions within the network, and *iii)* the provisioning of different support strategies to build communication bridges between intermittent communication islands with the use of additional technologies.

Overcome network restrictions

New DTN-MANET functionalities

With D2CS.KOM we are able to investigate the identified challenges within a communication system while a general architecture allows the integration of different components and solution approaches. Figure 19 provides an overview of the different contributions in this thesis and illustrates their relationship. The findings and results from the identification of disaster-specific characteristics and challenges based on past disaster reports and the outcome of the field test analysis motivated us to design D2CS.KOM with its different core components. D2CS.KOM's components are assigned to either support the intra-island communication, such as the resource allocation and the information selection and prioritization or to support the inter-island communication by establishing communication bridges via long-range communication modules or Unmanned Aerial Vehicles (UAVs). Based on the post-disaster communication capabilities of D2CS.KOM, different services are supported by the system to enable the affected population for disaster-response and disaster-relief efforts, as

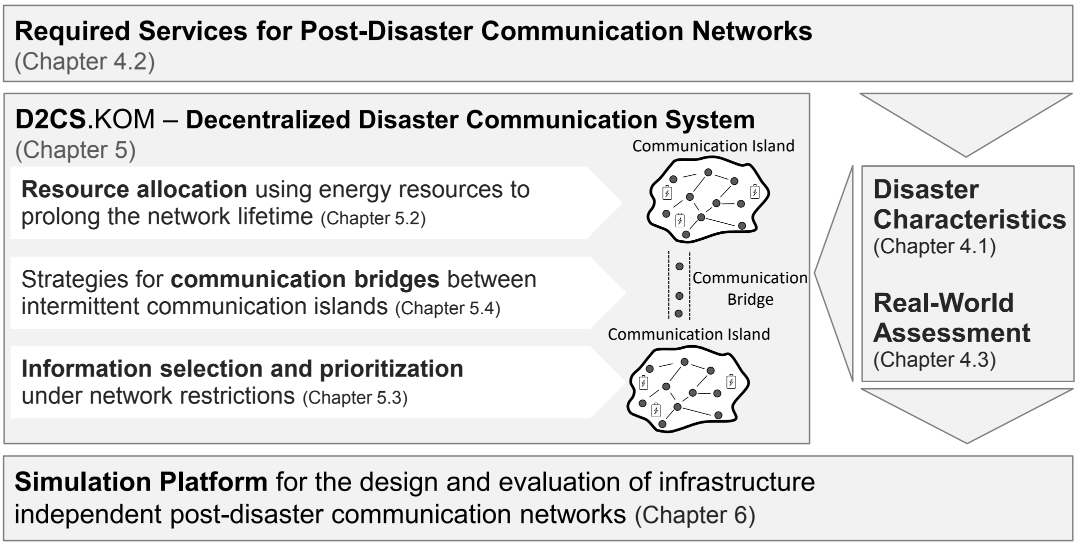


Figure 19: Overview of our contributions and their relations.

discussed in Section 4.2. The identified disaster characteristics, as well as the results from the field test analysis, are used to extend and configure our simulation platform to be able to represent post-disaster simulation scenarios, including the users' behavior and interaction characteristics. Consequently, this enables us to evaluate D2CS.KOM and its components in representative scenarios as well as in an exact replication of the conducted field test in Chapter 6.

5.1 CONCEPTUAL OVERVIEW OF THE COMMUNICATION SYSTEM

In this section, we describe the general architecture of DTN-MANETs, which provides the higher-level communication functionality for infrastructure-independent communication to D2CS.KOM. Based on this architecture, the following sections present the individual components of D2CS.KOM, which address the different identified challenges for post-disaster communication.

In a DTN-MANET each node can serve as a data-source, data-sink or forwarding-station as explained in detail in Chapter 2. When messages are created, they are propagated to neighboring nodes and receiving nodes must therefore individually decide, whether the received message should be forwarded, stored or discarded. The architecture supports ubiquitous mobile communication devices with various capabilities, such as different communication interfaces or sensors, and supports existing communication protocols, which are suitable for ad-hoc communication. In this thesis, we do not focus on the design of new DTN-MANET protocols within this general architecture. Our goal is to generally and systematically ensure that smartphone-based, infrastructure-less communication can be made more useful in the event of disasters. The general architecture is used as a black box to allow the investigation of our different contributions on top regardless of routing protocols or other architecture properties. Adapted from the Delay-Tolerant Network (DTN) protocol stack

Ubiquitous devices and sensors

in Section 2.3, the general communication architecture for DTN-MANETs consists of different layers and components visualized in Figure 20. Single or combined parts of the general architecture marked with dashed lines or arrows in Figure 20 are used by the different D2CS.KOM's components and are described at the end of this section.

General architecture

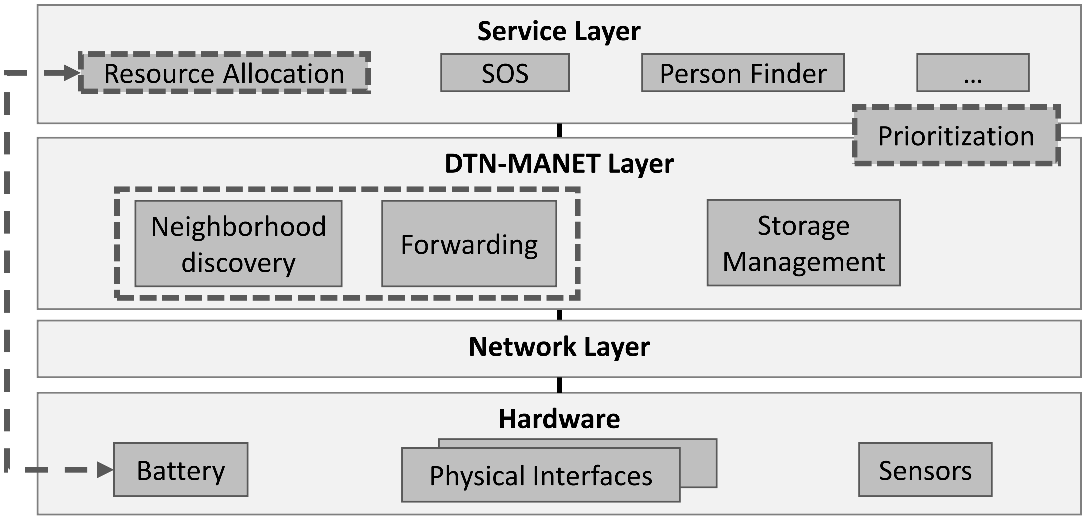


Figure 20: General architecture for DTN-MANET communication, adapted from [119, 135]. Components addressed within D2CS.KOM are highlighted with dashed lines.

The *Service Layer* is the topmost layer, containing all disaster-specific services offered by the communication system as discussed in Chapter 4. Service-specific messages can be created by the user or automatically by the service and contain at least one recipient. Messages are then passed to the *DTN-MANET Layer* for further processing. Vice versa, messages that are addressed to the local node and are received by the lower layers are forwarded to the corresponding service.

The *DTN-MANET Layer* is responsible for message handling and can send and receive messages via the underlying *Network Layer*. Relying on broadcast messages via the *Network Layer*, the *DTN-MANET Layer* implements a neighborhood discovery service to keep track of currently available communication partners. With a periodic beaconing procedure, nodes propagate their presence via the wireless medium to be able to be discovered by neighboring communication nodes. If messages are stored and neighbors are available, the *Forwarding* component is responsible for the data distribution supported by the underlying *Network Layer*. The *Forwarding* supports any Mobile Ad Hoc Network (MANET) or DTN-MANET routing protocol, as discussed in Section 2.3. If no neighbors are available or a specific node is not in the communication range, messages can be stored. The *Storage Management* is necessary for the DTN-specific store-carry-forward principle and manages both generated as well as received messages. It supports updating, sorting, reordering and deleting messages into queues, which are further processed by the *Forwarding* component.

In contrast to fixed networks, the *Network Layer* within D2CS.KOM is only responsible for one-hop communication, as no end-to-end paths are maintained. According to the message addressing and the routing protocols from higher layers, the *Network*

Layer together with the physical communication interfaces propagate messages using the broadcast address to which all nodes in the communication range are listening to or the unicast address for a specific node.

All of the components mentioned above rely on the actual hardware components of the individual node. A communication node contains different sensors, for example, a Global Positioning System (GPS) sensor to determine the location of a node or different motion sensors to gain context information. Sensor information is made available to the *Service Layer* to provide a wider range of service functionality. The hardware includes one or more physical communication interfaces, such as Wireless Fidelity (Wi-Fi) or Bluetooth, which can be used by the *Network Layer* for the physical data transmissions. All hardware components require sufficient energy, and depending on the utilization of these components, their energy consumption can vary significantly [46, 116, 282]. Especially in the case of a disaster, the common occurring power blackouts make energy to recharge smartphones a sparse resource. Therefore, the battery has to be taken into special consideration, since it determines whether a node can still communicate and contribute to the DTN-MANET or not.

Including sensor information

Energy as a limited resource

The continuity and accessibility of the communication network are restricted by the battery power of the individual communication nodes. Especially in disasters, with no other means of communication, D2CS.KOM has the primary goal of ensuring continuous provisioning of communication and maintaining the possibility for post-disaster communication for as long as possible. To prolong the lifetime of the network, we propose a dedicated resource allocation service as one of the core contributions of D2CS.KOM that has access to the battery state of a communication node (cf. Figure 20). The resource allocation service propagates information about the locations of available energy resources in the network. This information is then used by the service to assign suitable energy resources to the network participants, who then can move to the resource to recharge their battery. However, especially in decentralized networks, such an allocation is difficult because the properties of DTN-MANETs prevent a common consensus about the network state, the available resources, and current competitors. The resource allocation results in complex interactions between different allocation strategies, the lifetime of communication nodes and the communication capabilities of the overall network, which are discussed in Section 5.2 and evaluated in Section 6.2.

Provisioning continuous communication

The second contribution of the communication system is the possibility of data prioritization. The *Prioritization* component of D2CS.KOM has cross-layer functionality in between the *Service-* and the *DTN-MANET Layer* as displayed in Figure 20. The limited capacity of DTN-MANETs in combination with the high and continuously changing demands of communication after a disaster potentially overloads the network and requires different message and context prioritization mechanisms, as discussed in Section 3.3. In the prioritization process, it is particularly important to create suitable prioritization mechanisms for post-disaster situations, which can consider dynamic scenario-specific communication characteristics. The *Prioritization* component is an essential part of D2CS.KOM. The different prioritization mechanisms and their influence on the network capabilities are described in Section 5.3

Data prioritization

Dynamic communication demand

and evaluated in Section 6.3. In addition to resource allocation and message prioritization, we put a special emphasis on the difficulties of reliable communication provisioning between different communication islands.

To address this problem, we look at the possibilities of deploying additional communication devices that allow long-range communication links or utilizing special data ferries to transport information across communication islands. In particular, we investigate the utilization of long-range and low-bandwidth communication interfaces, such as Long Range (LoRa) [128], in addition to the use of highly mobile and controllable UAVs. UAVs are equipped with the same communication interfaces and functionalities like DTN-MANET nodes, such as the neighborhood discovery or different forwarding mechanisms (cf. Figure 20). In Section 5.4, we briefly investigate the reasonable use of long-distance communication modules in different environments after we put our main focus on UAV-based support strategies for DTN-MANETs, which are evaluated in Section 6.4.

Establish communication bridges

5.2 PROLONGING THE NETWORK LIFETIME THROUGH RESOURCE ALLOCATION

The performance of a DTN-MANET and the applied services are strongly dependent on the number of participating nodes and the available battery capacity, as these render the communication potential of the network. As already shown in past disasters, such as the Great East Japan earthquake in 2011 or Hurricane Sandy 2014, much of the communication (when communication was possible at all) revolves around available energy sources and power outages [29, 266], confirming the high importance and interest in energy supply. Although we assume that the central power grid is no longer available, there are still possibilities to supply the communication nodes with energy. Energy resources such as generators, solar panels, cars, small or large batteries are still available in the event of a disaster and can be used to recharge battery-powered mobile devices. As discussed in Section 3.2, until now, little research has focused on distributing external physical resources across a network. Approaches that exist rely on a central infrastructure for the allocation of limited resources, such as assigning available charging stations for electric cars. Since we are considering fully decentralized networks, these approaches cannot be applied, which is why we propose a decentralized resource allocation service in this work.

Infrastructure independent energy resources

The resource allocation service is a background service of D2CS.KOM, which does not affect the concurrent use of other services. The service utilizes the communication capabilities of the DTN-MANET to make the distribution of knowledge about energy resources within the network possible [136–138].

Decentralized resource allocation

5.2.1 *Scenario Description*

Besides the energy-constrained DTN-MANET nodes, our scenario considers the existence of non-mobile and limited energy resources that can be discovered and consumed. Each resource has a discovery range in which it can be visually detected by others. Additionally, the discovery range can be increased by technical means, for example, by sending out a discovery signal. Figure 21 shows the different components of the scenario. It displays different node groups in communication range and also isolated nodes. Some nodes are tagged, meaning that they are low-powered and have a current demand for energy. If so, a node can move to a known energy resource to recharge. The resource allocation service ensures that information about discovered resources is disseminated within the network. The dissemination of resource information enables nodes, which are out of reach of the discovery range of resources, to also try to consume them. However, when a node reaches the location of an energy resource, it cannot generally be guaranteed that the resource is still available.

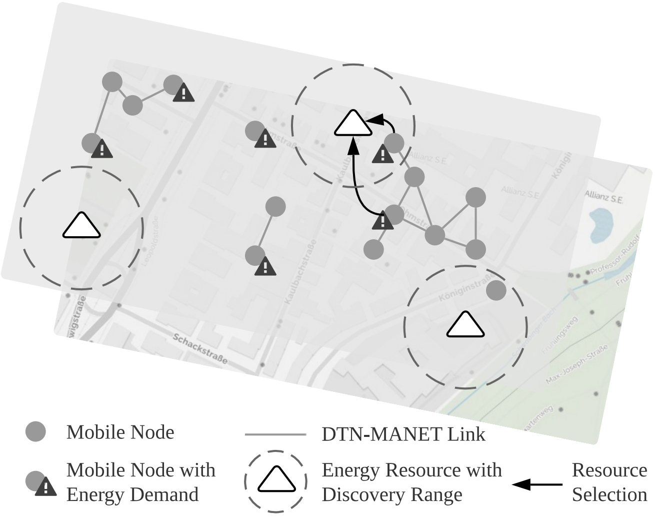


Figure 21: Different scenario components for resource allocation in DTN-MANETs [138].

Discovery of energy resources

Depending on the sub-scenario, energy resources already exist in the area or can be deployed. Energy resources are, for example, car batteries, solar panels, generators, or battery packs deployed from trucks [32] or other means [235]. Once placed, the resources are not known to nodes beforehand. Resources are equipped with Resource Demand Beacons (RDBs), which advertise their location, the available amount of resource units, and a unique RDB-ID. This is achieved via periodic broadcast messages, similar to the neighborhood discovery mechanism used by DTN-MANET protocols (cf. Section 5.1). Once all resources of an RDB have been consumed, the RDB continues to advertise its depletion-state for a fixed number of times before it goes offline. Nodes passing through the communication range of an RDB, record its information, and the resource allocation service automatically determines if the node has a current demand for energy. The user itself can trigger this demand, or it can be triggered automatically by the service if the smartphone is reaching a threshold for a minimum charge level. Nodes decide individually how much energy they want to consume, insofar as the maximum battery capacity cannot be exceeded. If a node decides to move to an RDB, it needs to take a detour from its original movement destination. We assume that this effort is not favored by participants in the network, especially if the amount of energy at an RDB is lower than expected or even empty on arrival. This can happen if more nodes want to recharge at a specific RDB than the amount of available resources can support. Adopting the terminology from [242], we call this phenomenon *over-competition*. Over-competition could easily be solved with a centralized service, where nodes can reserve specific amounts of resources. In DTN-MANETs though, this global knowledge can often not be achieved [283]. Therefore, one goal of the resource allocation service is to systematically create strategies to reduce the amount of over-competing nodes. The resource allocation service interacts with the user in the form of notifications of suitable resources and provides navigation to the resource location. This results in a higher energy drain rate while walking to an RDB since the device requires both a powered-on display and GPS sensor to navigate the user to the target. Consequently, a person must, therefore, invest time and additional energy to compete for an energy resource. We define three different node states; Roaming, Heading and Offline, as shown in Figure 22.

Over-competition

Energy consumption states

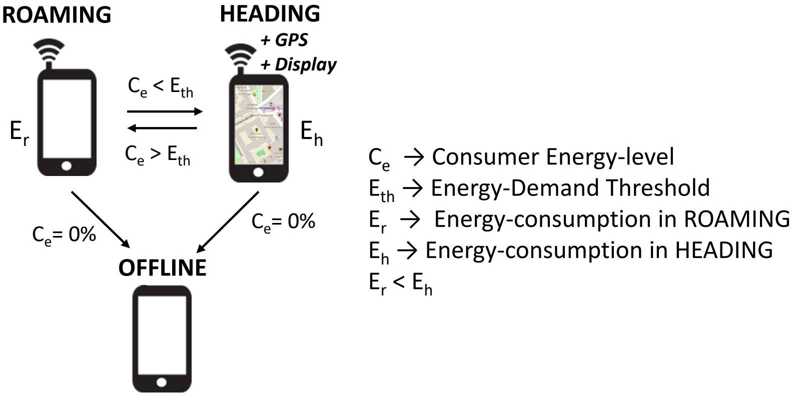


Figure 22: The three different node states (Roaming, Heading, Offline) [137].

A node in the Roaming state walks around unaffected by any of the available RDBs, for example, searching for family and friends or participating in disaster response efforts, as has already been seen in the conducted field test in Chapter 4. Independent of the movement or the disaster service used, the node's battery is reduced by E_r resource units per second. When a node has a demand for energy ($C_e < E_{th}$) and is being navigated to a resource, suggested by the resource allocation service, it switches to the Heading state and consumes E_h resource units per second. E_h consist of E_r plus the additional energy cost for powering the display and the GPS sensor. If a node's energy C_e depletes, it switches to the Offline state, not being able to participate in the DTN-MANET anymore. An exemplary process of the energy level characteristics of a node regarding the different consumption states is displayed in Figure 23.

5.2.2 *Design of a Resource Allocation Service*

The core functionality of the resource allocation service is to prolong the network lifetime by supporting the network participants in finding available energy resources. Besides disseminating resource information, the resource allocation client, running

Recharge support

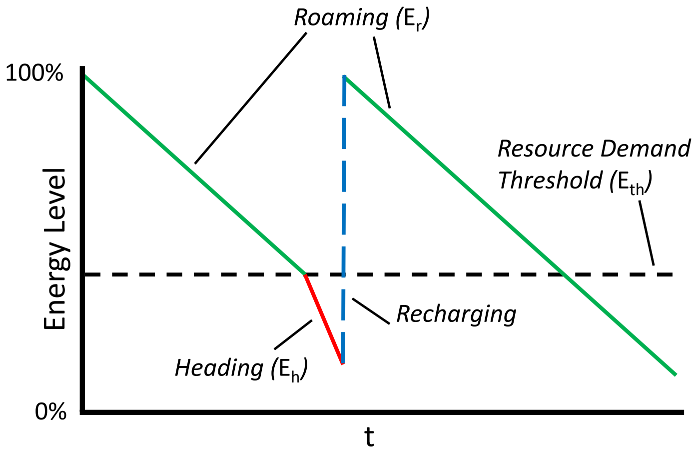


Figure 23: Energy level characteristics for a node.

on each DTN-MANET node, has the following objectives: *i)* to decide if a node has a current energy demand, *ii)* to calculate the expected reward when obtaining known RDBs, *iii)* to filter out RDBs with a negative reward, for example, more energy needs to be invested in reaching an RDB than the RDB contains, and *iv)* to decide whether or not to move to an RDB and to select the best RDB candidate.

The design of the resource allocation service and the interaction with the RDBs and other DTN-MANET nodes are visualized in Figure 24. The design allows to create and analyze different resource allocation strategies as a composition of different interchangeable components. The components of the resource allocation client and their interactions are described in more detail in the following.

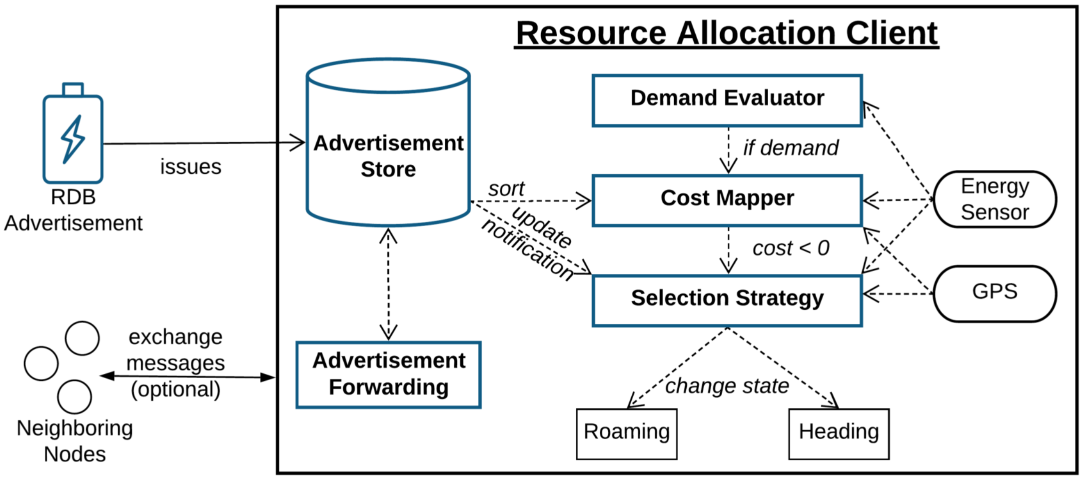


Figure 24: The resource allocation client, and its components and their interactions, adapted from [137].

If a node receives an RDB advertisement, the information is stored in its *advertisement store*, in case the information is new. Depending on the configured advertisement strategy, advertisements are shared with neighboring nodes. If the *demand* *evaluator* confirms a demand for energy, the *selection strategy* is initiated. The *selection strategy* obtains all information from the *advertisement store* and maps each RDB a cost value using the *cost mapper*. The costs are calculated by a configurable cost function and express the gain a node can retrieve by heading to an energy resource. Costs greater than zero imply that the node would invest more energy through the additional Heading consumption state than it would be able to regain at the RDB. The *selection strategy* then chooses the RDB with the lowest negative costs and changes the node's state into Heading. In the Heading state the service notifies the user and starts providing route information. Dependent on the utilized selection strategy, it may also send and receive additional information such as a resource reservation, as later discussed in Section 5.2.3. The strategy can include a re-evaluation of the current decision, based on new gained knowledge during the Heading phase. For example, if a resource with lower costs is discovered, the strategy changes the targeted energy resource, or if new advertisements indicate the depletion of the targeted resource the Heading attempt is canceled. After arriving at the resource, if energy is available, the node recharges and switches to the Roaming state again until the demand evaluator triggers again. All components involved in the resource selection process are by design exchangeable to be able to systematically analyze their impact on the resource allocation process. Their characteristics and variations are discussed in the following.

Resource Advertisements

Periodic RDB advertisements are used to inform nodes about the available amount of a resource and its characteristics in form of a tuple (*RDB-ID*, *BSN*, *TTL*, e_{max}, *loc*, t_{BSN}). The elements of the RDB advertisement are the following: *i)* a unique RDB identifier, *ii)* the RDB's Beacon Sequence Number (BSN), *iii)* a maximum hop count (TTL) to limit the network flooding, *iv)* the amount of energy e_{max} available, *v)* the RDB's location *loc*, and *vi)* a time-stamp t_{BSN} when the advertisement was sent out.

Broadcast resource information

The BSN is an indicator of the freshness of an advertisement and is incremented every time the amount of available energy changes at an RDB. Nodes use the BSN information to decide whether to insert or update their advertisement store or to discard advertisements with outdated information. An RDB can also advertise for a limited time if no energy is available anymore. This information is essential for nodes currently heading to a specific RDB, to have to opportunity to cancel the Heading attempt before reaching the targeted resource.

Advertisement Store

Nodes are able to receive advertisements in three different ways: *i)* by overhearing an RDB broadcast, *ii)* by advertisement dissemination of other DTN-MANET nodes, or *iii)* as a payload of messages sent out by the selection strategy. The advertisement store only saves new or fresher information based on the advertisements RDB-ID and the BSN. Selection strategies can register themselves at the store to be notified whenever advertisements with a newer BSN or for an RDB not yet known are received. Due to the limited data dissemination capabilities in DTN-MANETs nodes may not

Keep track of available resources

hear from RDBs for a longer time, and the advertisement store becomes outdated. With increasing time, the probability that energy resources are already depleted and RDBs went offline rises. Therefore, the advertisement store can be configured with an *expiration time* to automatically remove old advertisements from the store using the *timestamp* of the advertisements.

Advertisement Forwarding

Sharing knowledge

Sharing advertisements is necessary for a functioning resource allocation in DTN-MANETs. Based on the DTN-MANET layer in the D2CS.KOM architecture (see Figure 20), any kind of advertisement dissemination strategy can be supported, using any suitable MANET or DTN routing protocol. As already mentioned, the focus of this thesis is not the design or evaluation of diverse routing protocols suitable for D2CS.KOM. Although we have applied and investigated a variety of protocols in [72, 138], we are only considering the following protocol in this thesis as a suitable example for the advertisement dissemination. For the advertisement dissemination, we employ a variant of the epidemic routing protocol SPIN-1 (Sensor Protocol for Information via Negotiation) [99]. The protocol uses a three-way-handshake to exchange RDB information: *i)* advertisement announcement, *ii)* request, and *iii)* response. Periodically at random intervals, each node broadcasts a shortened view of their advertisement store, only containing the RDB-IDs and respective BSNs. Other nodes overhearing this broadcast compare their known advertisements with the announcement. For each missing or outdated RDB information, nodes request the full information from the announcement originator via unicast, ensuring a faster and more reliable transmission.

Demand Evaluator

The demand evaluator is responsible for initiating the resource selection process. This can be triggered by user inputs via the application, or by deriving the actual battery state of the smartphone. We use a simple value-based comparison method, based on a configurable threshold and readings from the energy sensor. The energy threshold is an important parameter that needs to be configured carefully according to the utilized selection strategy. On the one hand, the threshold needs to assure that the node still has sufficient battery capacity to be navigated to a selected RDB. On the other hand, the amount of charging attempts and interruptions by the service should be as few as possible. A detailed parameter evaluation of the optimal threshold for different selection strategies is discussed in Section 6.2.

Cost Evaluator

Cost evaluation

The cost evaluator is responsible for calculating the individual costs for the node to recharge at a known RDB. It sorts the RDB entries in the advertisement store according to the calculated costs, which is then further used by the selection strategy. In the case of equals costs, the RDB with shorter distance goes first. A node's cost mapper is calculating the costs for each known RDB based on a line of sight distance d to the node and the expected energy amount r'_e available. Each cost mapper further requires the additional energy consumption rate E_h in the HEADING state compared to the consumption state E_r in the ROAMING state and an estimate for the velocity v of the node.

To determine the additional power consumption, required for the powered on display and the GPS sensor, while heading to a resource, we consulted different power consumption studies for smartphones [46, 116, 282]. These studies allow us to model the smartphone power consumption dependent on different active components, such as the CPU, display, GPS, Wi-Fi-Interface, etc. Our calculations of the two different energy consumption states resulted in the energy ratio $E_h = 3.11 \cdot E_r$. The detailed composition of the energy consumption is discussed in [138]. For the average human walking speed v we use 1.2 m/s, based on the findings of the conducted field test analysis in Chapter 4 and [17, 34, 49, 251].

Based on these values the cost mapper determines validity of RDBs by checking whether the node would run out of energy e_c before reaching the RDB as seen in Equation 1, or if the additional energy consumption of the HEADING state outweighs the expected energy amount r'_e at the RDB as seen in Equation 2.

$$e_c \leqslant E_h \cdot (d/v) \tag{1}$$

$$r'_e \leqslant (d/v) \cdot (E_h - E_r) \tag{2}$$

Determine invalid resources

Invalid RDBs will not be considered for the resource selection process. While any kind of a cost-mapping function can be supported by the resource allocation service, we propose two example cost mappers, with the first one being the default for the evaluation in Chapter 6:

- *MaxDistance* favors the nearest RDB to the node, returning a cost of $-1/d$, with d being the line of sight distance of the node and the RDB at the time of the cost determination.
- *MaxGain* favors RDBs that allow the node to fully recharge its battery to c_e^{max}. The cost mapper returns a cost of $-\min(c_e^{max} - c_e, r'_e - E_h(d/v))$, taking into account the additional energy consumption of the HEADING state and the expected amount of energy at the RDB.

The two cost mapper functions are suitable examples for calculating the costs depending on the node's and RDB's attributes. The resulting costs in terms of the distance to the resource as well as the expected reward depending on the available energy at the RDB are the key factors if physical energy resources that need to be collected in person are considered.

Selection Strategy

A selection strategy decides based on the sorted advertisement store extended with the information of the cost, whether and to which RDB a node should head to in order to recharge its battery. Strategies can access the DTN-MANET Layer to send and receive messages, enabling the design of collaborative resource allocation strategies. The next section will explain the design of different resource allocation strategies used to prolong the lifetime of an emergency communication network.

5.2.3 *Resource Allocation Strategies*

Compete or not to compete

The selection strategy is the essential component of the resource allocation service. The decision to compete or not compete for limited energy resources does not only influence the lifetime of the consuming node but also the lifetime of all other nodes within the network. This is because the communication capabilities of a DTN-MANET are dependent on the number of participating nodes in the network [275]. In addition, in the post-disaster scenario, every node should be able to communicate as long as possible. Resource allocation in DTN-MANETs has the goal to improve the overall lifetime of the network and not only of individual nodes. Even though the selection strategy needs to cope with the decentralized characteristics of DTN-MANETs, it should try to achieve an equal resource allocation among all network participants and try to avoid nodes that waste time and energy by heading to resources they cannot consume in the end.

Allocation strategies

The strategies that are discussed in this section, can be divided into *non-cooperative* and *cooperative strategies*. Non-cooperative strategies are not utilizing the communication potential of the DTN-MANET for the allocation service, resulting in nodes not disseminating advertisements. We use non-cooperative strategies, named *En Passant*[1] and *Oracle*, as baseline approaches. *En Passant* only selects RDBs in direct reach and *Oracle* is assuming a central knowledge entity that is aware of every RDB. In contrast to the two baselines, cooperative strategies disseminate knowledge about known energy resources and can further be divided into strategies with and without disclosure of node context. All our selection strategies discussed in the following section assume selfish behavior by the nodes, meaning that they are consuming as much energy at an RDB as possible.

En Passant

With *En Passant* nodes only consume energy resources that they discovered themselves while having a demand for energy. Adapted by the state-of-the-art, this is the same situation compared to the "view only" parking place relevance estimation method discussed in [57] for parking space assignment addressed in Chapter 3. No advertisement dissemination takes place and additionally nodes do not store discovered RDBs in their advertisement store. The probability of over-competition is very low with this strategy, since the low distance to the RDB upon discovery. This also results in short times spent in the more energy consuming HEADING state. As a drawback, *En Passant* results in nodes often not knowing any available resources when they have demand and available may not be consumed. We use this strategy as a

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[1] Named after a chess move by which a pawn attacks an opponent's chess figure while passing it.

lower baseline in our evaluation, as it does not use any form of communication for resource allocation resulting in no additional message overhead.

Oracle

Although we do not assume a functioning communication infrastructure in our scenario, we would still like to compare the different allocation strategies against a centralized approach, as it would be used in the non-disaster case. The so-called reservation *Oracle* knows all locations and charge states of every node in the network and all locations and available resources of active RDBs. If a node has demand for energy, the *Oracle* provides it with instant access to a first-come-first-served resource reservation mechanism. It reserves the amount of energy needed to fully recharge the node at the RDB with the lowest costs. The Oracle, therefore, eliminates over-competition, as reserved resources are not allocated more than once. Additionally, in theory, global knowledge allows us to allocate all existing energy resources that can be reached by the nodes. The time a node needs to spend in the HEADING state can vary greatly, depending on the location of the reserved RDBs. Furthermore, the *Oracle* is not taking resources into account who appear after a reservation is granted. This results, similar to the discussed parking space assignment problem [57] in Chapter 3, in nodes traveling longer distances to reserved resources, while passing closer RDBs on their way. The *Oracle* is used as an upper baseline in our evaluations.

Greedy Selection

The *Greedy Selection* strategy is a cooperative resource allocation strategy that distributes knowledge in the network by disseminating RDB advertisements as described in Section 5.2.2. Compared to the *En Passant* strategy, nodes can compete for energy resources they did not discover themselves and are always heading to the RDB with the lowest cost. The dissemination of information about depleted energy resources also makes it possible to cancel a HEADING attempt before the node reaches the empty RDB. Theoretically, similar to the *Oracle*, nodes can achieve a common state of knowledge about available RDBs, which is the basis of the individual cost mapping process and individual resource selection. This will most likely result in the consumption of all discovered RDBs by the network participants. The *Greedy Selection* strategy does not disclose any node context to other nodes in the DTN-MANET, for example, the nodes location, the current energy state, or the targeted RDB. Therefore, nodes are unaware of other competitors, heading to the same targeted energy resource.

In the case of the selection strategies already presented, the available communication potential of the DTN-MANET for cooperative coordination and allocation of available energy resources is not yet utilized.

5.2.4 *Ad Hoc On-demand Reservation Vector Auction*

Ad Hoc On-demand Reservation Vector Auction (AORVA) is a cooperative selection strategy with the disclosure of the node's context information, in the form of resource reservations. AORVA utilizes the communication of the individual outcome of the node's decision procedure, containing whether other nodes in the network are competing for a certain energy resource. With this additional information, other nodes can react to those decisions by changing their own decision, to avoid over-competition and unsuccessful HEADING attempts.

Avoid over-competition

AORVA is based on the principle of decentralized auctions by sharing an expression of interest in a specific energy resource in the network. AORVA is inspired by the Chaos primitive for all-to-all data sharing [127] and by the Ad Hoc On-demand Distance Vector (AODV) [190] proactive routing protocol for MANETs (cf. Section 2.3). Chaos combines requests or values in the network with the help of a merge operation to achieve consensus in the network. Round by round requests or values are merged when received and only distributed in the network if the result of the merge changes. AORVA adapts this principle by providing an auction merge algorithm to allocate resources to the highest bidders. AODV is a reactive routing protocol that discovers communication routes only when needed. If a route to the desired destination is found, a so-called *route response* is sent back the same path it reached the destination to prevent routing loops. AORVA adapts this idea to re-route information about reservation cancellations.

More knowledge, better decisions

The interest in a particular resource is represented by a reservation, which contains a bid and the amount of energy the node intends to consume. Other nodes in the network use these reservations to know in advance the current competitors of a specific RDB and to derive their chances if the HEADING attempt is profitable. Nodes in the network maintain a *reservation vector* in their advertisement store. Reservation vectors are initially empty for every RDB known by the node. Nodes can reserve energy resources by adding their demand and the bid to the reservation vector of the desired RDB, which is then periodically distributed in the network via *reservation request* messages including the node's incremented Request Sequence Number (RSN). Receiving nodes approve the reservation by combining the reservation vector with their local copy via a *merge operation*. Reservations are approved in decreasing order of their bids until the expected amount of energy at the RDB depletes. If the requesting node's reservation is part of the merged vector, the node forwards the request to its neighbors. Otherwise, the node informs the requester by sending back a *reservation response*, as sketched in Figure 25.

Resource reservations

Since DTN-MANETs cannot guarantee constant communication paths due to the nodes unpredictable mobility, AORVA does not utilize reservation acknowledgments. Nodes creating a reservation request switch optimistically to the HEADING state until they reach the targeted RDB, discover new resources, or receive a reservation response containing the cancellation of their reservation. By disseminating reservation vectors in the form of reservation requests and reservation responses, AORVA tries to achieve a local consensus of RDB assignments. As discussed and analyzed

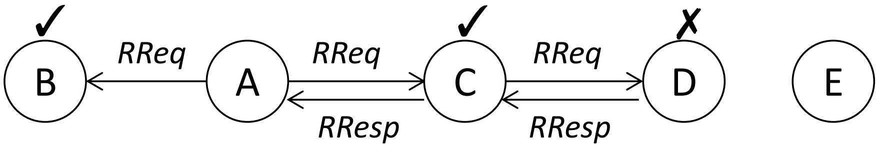


Figure 25: *Resource request* (RReq) by node A, approved by all nodes except of node D, which is sending back the negative acknowledgment in form of a *reservation response* (RResp) and will not forward the original RReq further [72].

using the field test data in Chapter 4, achieving a global and up-to-date consensus in a DTN-MANET is very unlikely. However, in the case of resource allocation, this is not necessary, because there exists a strong local interdependence between the location of an RDB and the location of a node. With an increasing distance between a node and an RDB, the probability of competitors closer to the resource is increasing as well as the additional energy that needs to be invested while in the HEADING state.

High relevance of resource locations

Reservation Vectors, the Auction Merge Operation, and Bid Types

Every node maintains reservation vectors for every known RDB. If a node reserves resources or receives a reservation request, it updates the corresponding vector. A reservation vector of the tuple (*RDB-ID*, *BSN*, e_{max}, *R*), containing the unique RDB identifier RDB-ID, its last known BSN, the expected amount of energy available at the RDB e_{max} and a set of reservations *R*. A reservation r has the form of (*NodeID*, *RSN*, *t*, b_t, e_{res}), including the node's unique identifier *NodeID*, the current RSN, the time t the reservation was created, the bid b_t of the reservation at time t and the amount of reserved resources e_{res}. The total reserved energy amount of all reservations cannot exceed the available amount e_{max} at the RDB, so $e_{max} \geqslant \sum_{r \in R} r.e_{res}$ must always apply. Nodes can only reserve resources at one RDB at a time, which is assured by a node's RSN that is increased with every reservation request. Nodes remove obsolete reservations, by only considering reservations with the highest RSN for each node. If a reservation is not granted by the merge algorithm explained below, the reservation is removed from the reservation vector. Nodes are not allowed to alter the reservations of other nodes to obtain a valid reservation. Instead, they respond with an updated vector, and the requester itself can decide if the amount of unreserved energy resources is worth to reserve again with a new reservation request.

The reservation creation time t is used by AORVA in two ways: First, reservations are no longer taken into account if they are older than a defined *reservation vector lifetime*. Second, if, for example, the distance between the node and the RDB is used for the reservations bid b_t, t is used to estimate the distance decrease since the reservation was issued. Based on the concept of the charging process of wireless sensor nodes in [271], AORVA uses a combined bid function of the distance to the RDB and the current energy level of the node. Nodes are assumed to be in an emergency state if their charge level is critical. As shown in Equation 3, nodes use a bid b_t of the inverse of the distance d^{-1} if in emergency state, otherwise the negative distance $-d$.

$$b_t = \begin{cases} d^{-1} & \text{if Emergency State} \\ -d & \text{else} \end{cases} \tag{3}$$

According to Equation 4 the bid $b_{t'}$ at current time t' is calculated based on the original bid b_t using the velocity estimate ν (1.2 m/s). The current bid $b_{t'}$ is considered during the auction merge operation.

$$b_{t'} = \begin{cases} \left(b_t^{-1} + \left(t' - t\right)\nu\right)^{-1} & \text{if Emergency State } (b_t > 0) \\ \min\left(b_t + \left(t' - t\right)\nu, 0\right) & \text{else } (b_t \leqslant 0) \end{cases} \tag{4}$$

Merge reservations

The auction merge algorithm (cf. Algorithm 1), is used to allocate resources to requesting nodes. The *auction merge* is performed whenever a node creates or receives a reservation vector that differs from the local copy. The contradicting vectors need to be merged to determine, which reservations are granted. The merge results is a new reservation vector combining the information of the two input vectors. The nodes with the highest current bids $b_{t'}$ will get granted the requested e_{res}, in descending order (cf. Algorithm 1 line 23). If the requested energy is higher than the unreserved energy left (e_{left}) for an RDB the reservation is skipped to favor other reservations with lower e_{res}. If the BSNs and the e_{max} values of the vectors differ, the reservation with the lower BSN is ignored since the reservation was based on old RDB information. If both reservation vectors contain a reservation for the same node, the vector with the highest RSN is taken into account (cf. Algorithm 1 line 11). If the auction merge results in granting all requested reservations, the initial reservation request updated with the combined reservation vector (cf. Algorithm 1 line 28) is disseminated further to neighboring nodes.

The combination of two different reservation vectors using the merge algorithm is symmetric and unambiguous. With $\oplus$ as the merge algorithm and the vectors A, B and C, the following conditions apply when all the following example operations happen at the same time t': First, it holds that $A \oplus B = B \oplus A$, since the order of the reservations does not matter. Second, $A \oplus B = C \Rightarrow A \oplus C = C \land B \oplus C = C$ applies, because the outcome does not change if the resulting vector C is merged again with the vectors used for its creation. This way, it can be guaranteed that the outcome of the auction merge is always the same, regardless of which node performed the operation, and regardless of whether an already merged vector is used as input.

Reservation Requests

If a node has demand for energy, it chooses the RDB with the lowest cost in its advertisement store. Instead of assuming the advertised energy amount from the RDB, the node considers the energy amount left by taking into account already existing reservations with higher bids. The node merges a newly generated reservation, including the reserved amount of energy and its bid, with the locally stored reservation vector.

Algorithm 1 Auction merge algorithm [136].

```
procedure AuctionMerge(A, B)
    if $A.BSN < B.BSN \wedge A.e_{max} \neq B.e_{max}$ then
        $\uparrow B$
    end if
    if $B.BSN < A.BSN \wedge B.e_{max} \neq A.e_{max}$ then
        $\uparrow A$
    end if
    $Union[] \leftarrow \emptyset$
    for $r \leftarrow A.R \cup B.R$ do
        if $\neg expired(r) \wedge \neg obsolete(r.RSN)$ then
            if $r.NodeID \in Union$ then
                if $Union[r.NodeID].RSN < r.RSN$ then
                    $Union[r.NodeID] = r$
                end if
            else
                $Union[r.NodeID] = r$
            end if
        end if
    end for
    $e_{left} \leftarrow A.e_{max}$
    $R \leftarrow \{\}$
    for $r \leftarrow$ reservations in Union sorted in descending order of bid value at current time $t'$ $(b_{t'})$ do
        if $e_{left} \geqslant r.e_{res}$ then
            $e_{left} \leftarrow e_{left} - r.e_{res}$
            $R \leftarrow R \cup \{r\}$
        end if
    end for
    $\uparrow$ new ReservationVector(A.RDB-ID, max(A.BSN, B.BSN), $A.e_{max}$, R)
end procedure
```

As the example in Figure 26 shows, this can result in the cancellation of reservations with lower bids.

If a suitable RDB is determined, the node increments its RSN and sends out a reservation request. A reservation request has the form *RReq*(*NodeID*, *RSN*, *Adv*, *R*, *TTL*, *HSeq*), containing the node's identifier *NodeID* and its current RSN, the last known advertisement *Adv* of the RDB, the merged reservation vector *R*, a maximum hop count *TTL*, and the hop sequence *HSeq* containing a list of forwarding nodes. We include the advertisement of the RDB in the request so receiving nodes with older information can update their advertisement store. Initially, *HSeq* only contains the originating node and forwarding nodes add their identifier before disseminating the *reservation request* further. After broadcasting the reservation request, the node will start heading to the targeted RDB until: *i)* the node's reservation is canceled after the merge with a received reservation request for the targeted RDB, *ii)* the node receives a reservation response addressed to itself, or *iii)* when receiving a new RDB advertisement and the node re-evaluates its reservation. Due to the unpredictable movement of the nodes and the frequent discovery of new communication neighbors, the node sends out its reservation request periodically with an incremented RSN and an updated bid.

RDB-ID: 1 *BSN:* 1 e_{max}: 100

NodeID	RSN	Bid	t	e_{res}
A	1	10	0	50
B	1	8	0	30
C	1	3	0	10

(a)

$\oplus$

RDB-ID: 1 *BSN:* 1 e_{max}: 100

NodeID	RSN	Bid	t	e_{res}
D	1	9	0	40

(b)

=

RDB-ID: 1 *BSN:* 1 e_{max}: 100

NodeID	RSN	Bid	t	e_{res}
A	1	10	0	50
D	**1**	**9**	**0**	**40**
C	1	3	0	10

(c)

Figure 26: Estimating the expected resource amount at an RDB and reserving resources in AORVA. (a) is the local vector for RDB 1 at node D, (b) is D's reservation request for 40 resources and (c) the result of the *merge algorithm* [72].

Reservation Request Forwarding and Reservation Response

Cancel reservations

In AORVA every node is capable of answering a reservation request. If any node detects that a reservation can no longer be granted, the node is responsible for informing the requesting node by sending back a reservation response. This procedure is inspired by the AODV protocol [190] where every intermediate node can answer to a route request if the required information is available. When a node receives a reservation request, the following procedure is executed:

First, the node compares the *Node-ID* and the corresponding RSN included in the reservation request with its locally stored information. If the RSN in the request is lower than or equal to the local information of the RSN in combination with the corresponding node, the reservation request is ignored. This avoids the storage of obsolete reservations and prevents dissemination loops. Otherwise, the node updates its local information about the requesting node. Next, the node compares the advertisement included in the request with its local advertisement store. If the BSN is higher, the node updates its local information. Otherwise, the local advertisement replaces the RDB information of the reservation. In any case, the node combines its local reservation vector for the respective RDB with the vector from the request, using the merge algorithm. Before the merge, the current bids are projected and updated considering the time passed since the reservation. The node's local vector and the vector from the request are replaced with the merge result. If the requesting node is still part of the merged reservation vector and the maximum hop limit has not been reached, the node forwards the reservation request to its neighbors and adds its identifier to the hop sequence *HSeq*. If the requesting node is not part of the reservation vector, the reservation is not granted, and the node answers with a reservation response

(RResp). Utilizing the hop sequence, the response is sent back via the reverse path, containing the merged reservation vector. Receiving nodes update their local vectors with the merge result and remove themselves from the hop sequence until the response reaches the originator of the request. Upon the arrival of the reservation response, the originator cancels its HEADING attempt if it still targets the same RDB and restarts the resource selection again.

The following example in Figure 27 demonstrates the full resource reservation process of AORVA. For simplicity, we are considering money (€) as a time-independent resource bid, which does not need to be recalculated before the vector merge. Node A wants to reserve 50 resource units (ru) at RDB1, which has a capacity of 100 ru. Node A only knows its own reservation and forwards its reservation request to its neighbors B and C. Both nodes have already indicated their interest in the same RDB and merge the new reservation with their local vector. After the merge, Node B's reservation is canceled due to the higher bid of Node A and insufficient resources left for the initial reservation (70 ru). Afterward, Node B forwards the request. The reservation of Node C is higher than A, but both reservations are granted because the reserved amount of energy resources is less than the amount available. The merged vector, containing both reservations, is forwarded to Node D. Node D has not reserved any resources, but it stored a reservation of Node E in its local vector. Due to the higher bid, Node A is no longer part of the merged vector. Node D sends back a reservation response to Node A via Node C, and both nodes update their local reservation vector. Receiving the response, Node A cancels its HEADING attempt and starts the resource selection process again.

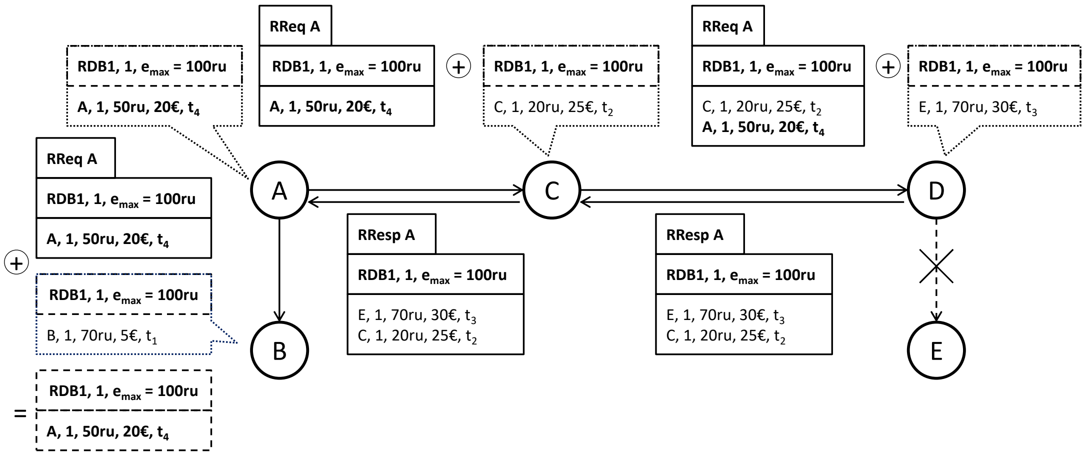


Figure 27: Example of a resource reservation process of AORVA. Node A initiates a *reservation request (RReq)* in the form of (NodeID, RSN, reserved resources, bid, creation time). Local vectors at nodes are marked with dashed lines. The merging of vectors from the *reservation response (RResp)* is omitted [136].

In this section, the resource allocation service was introduced, which as a core contribution of D2CS.KOM aims to provision continuous communication and to maintain the possibility of post-disaster communication as long as possible. The scenario considered, includes the availability of energy resources to prolong the lifetime of the individual nodes and consequently of the overall DTN-MANET. The resource allocation client has been explained in detail for its various components and their interdependencies and interactions between each other. Non-cooperative and cooperative resource allocation strategies have been presented for the allocation of energy resources. The non-cooperative strategies *En Passant* and *Oracle* are used as baseline approaches to evaluate and understand the performance of the cooperative strategies. Cooperative strategies like *Greedy Selection* use the distribution of advertisements in the network to share knowledge about discovered resources. This communication-based cooperation enables the nodes to allocate resources in a fully decentralized manner, but without revealing their own states and decisions. AORVA, on the other hand, additionally communicates its own decision in the network to reduce over-competition for the limited energy resource. A detailed evaluation of the various strategies and the determination of relevant parameter values is described and discussed in Section 6.2 based on the transfer of the considered scenario in a simulation environment described in Section 6.1.

5.3 INFORMATION SELECTION AND PRIORITIZATION UNDER NETWORK RESTRICTIONS

High and changing demands

Need for timely and reliable message delivery

In Chapter 4, the extensive survey of post-disaster communication characteristics in addition to the conducted field test revealed that the limited capacity of DTN-MANETs cannot fully replace infrastructure based communication. The combination of high and continuously changing demands of the communication after a disaster potentially overloads the network while the unpredictable movement of the network participants further limits data dissemination. At the same time, the timely and reliable delivery of messages is crucial for disaster response efforts and self-help of civilians. Message prioritization can be applied to cope with these restrictions to ensure that the most relevant information in the current situation is disseminated in a timely and reliable fashion. In the prioritization process, it is particularly important to create suitable prioritization mechanisms for post-disaster situations, which can consider dynamic scenario-specific communication characteristics.

Message prioritization is an essential part of D2CS.KOM for the post-disaster communication, and it is crucial to understand the impact of the respective prioritization on DTN-MANETs to design adaptive approaches. In this section, we present the modular extensions for prioritized communication as part of the D2CS.KOM architecture (cf. Figure 20), including different prioritization mechanisms and a discussion of the post-disaster prioritization challenges. The architecture is the basis for the evaluation of different prioritization algorithms in Section 6.3, focusing on the impact on the communication network.

5.3.1 *Prioritization Challenges in Post-Disaster Scenarios*

Prioritization is a challenging issue, considering the changing communication behavior of the affected population throughout the post-disaster situation. As a result, the relevance of specific messages is determined by the message content, message type, or the user's context. Thus, the relevance also changes over time and is hard to quantify [203, 240]. Prioritizing relevant data always results in penalizing other data if the available communication resources are insufficient. Especially in the considered post-disaster scenario, it is crucial to understand the potential impact and interactions of message prioritization on DTN-MANETs and their capabilities for timely and network-wide data dissemination under network restrictions.

Reduce communication load

The goal of message prioritization is to reduce the load on the network that is caused by unimportant messages, to increase the probability of successful data propagation of high prioritized messages. Furthermore, prioritization should ensure that important messages reach as many recipients in the network as possible and as fast as possible. Prioritization, therefore, favors specific messages and delaying or completely dropping less relevant ones. Recent work showed that post-disaster messages could be grouped into distinct categories [123, 203]. Categories are, for example, warnings, reuniting efforts or requests for help, which are similar to the services that were available during the field test [9, 135] described in Chapter 4. Additionally, one unique characteristic about the post-disaster communication is that the number of messages of certain categories and their importance change during a disaster, as discussed in [102, 198, 203] and schematically illustrated in Figure 28. In the direct aftermath of a disaster, emergency messages are considered to be most important and are also the most prevailing message type. In the further course of the disaster, other message types, such as safety-related information and guidance information for the affected population, get more important and take over a larger portion of the available bandwidth in the DTN-MANET. Past disasters showed [102, 198, 203] that emergency messages are continuously generated through the further stages of the

Trending message types

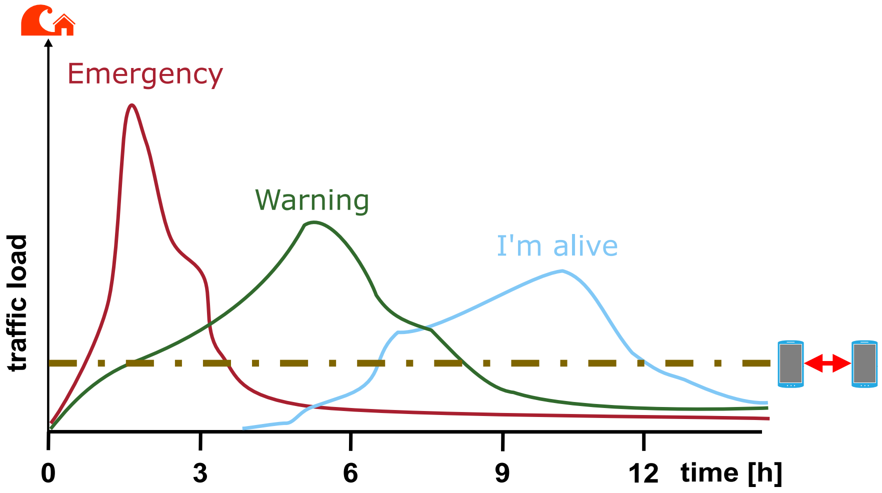


Figure 28: Illustration of time-dependent traffic load per message type [140].

disaster with a lower frequency, while the network is already dealing with a huge communication demand consisting of other message types. To always ensure the delivery of important message types, for example, emergency messages, a static prioritization order of the occurring message types can be utilized. While the prioritization of vital messages is desired, there are implications considering the disaster-specific communication message trends visualized in Figure 28 and the DTN-MANET store-carry-forward principle. Duplicates of already distributed high prioritized messages are blocking new messages with a lower priority from being forwarded in the network. Therefore, flexible and adaptive prioritization schemes are needed for post-disaster communication considering environmental and contextual changes, such as disaster-related content, the user's location, or even the activity [134] of the user.

5.3.2 *Architecture for Prioritized Post-Disaster Communication*

Based on existing research (cf. Section 3.3), disaster-specific message types are either predefined by the respective service or can be derived based on the message content or the user's context. D2CS.KOM enables prioritization by adding a generic and customizable message storage as part of a prioritization layer to the general architecture of DTN-MANETs. The message prioritization exclusively operates on the message storage as illustrated in Figure 29, separating the prioritization from the DTN-MANET functionality. This separation enables us to evaluate the impact of different prioritization mechanisms on the performance of the post-disaster communication network in Section 6.3.

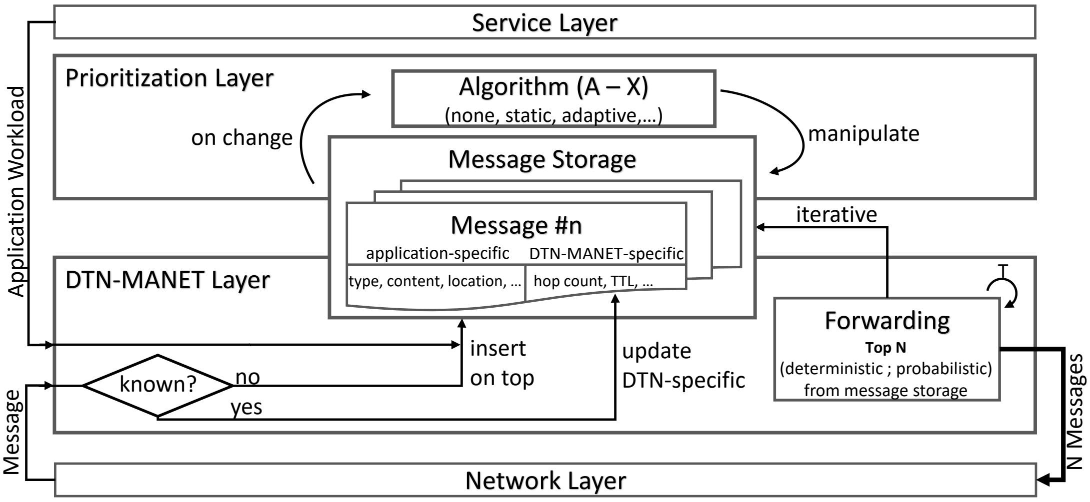


Figure 29: Architecture for prioritized post-disaster communication [140].

Messages can be annotated with two types of additional meta-information: *i)* DTN-MANET-specific meta-information, such as the hop count or the timestamp depending on the utilized routing protocol, or *ii)* application-specific meta-information such as the message type or the user's context depending on the used service. The meta-information can be updated when a message is received or forwarded as displayed in the lower part of Figure 29. Whenever a new message is sent by the application or received through the network for the first time, it is stored in the message storage. If the message is already stored the DTN-MANET-specific meta-information can be updated. Typically, the message storage of DTN-MANET nodes operates similar to a stack, adding new messages on the top. Depending on the available network capacity, the top N messages from the storage are forwarded periodically to neighboring nodes, often in combination with filtering methods [36, 200] or optimized transmission processes [267] to reduce the network load or to skip messages already known by the communication neighbors.

The prioritization process is modeled as a manipulation of the message storage, that makes it possible to remove or reorder messages. Messages older than the Time to Live (TTL) are deleted from the storage to limit the messages being stored and to reduce the network demand. It is important to mention that a reasonable TTL is highly dependent on the considered scenario and utilized services and might even differ, depending on the message content, type, or the user's context. The access to the DTN-MANET- and application-specific meta-information is an important aspect for the message prioritization to construct a scenario-specific prioritization order. In the following, we introduce three prioritization algorithm examples, which manipulate the message storage of the network participants. These examples are used as a foundation to show the usability of the introduced architecture, to assess insights of the impact of different prioritization algorithms on the DTN-MANET communication performance and discuss their applicability to the considered post-disaster scenario. The following examples contain two edge-cases of possible manipulations of the nodes message storage. On the one hand, no message reordering is executed, and on the other hand, a predefined importance-order determines the manipulation of the stored messages. A third algorithm exemplifies the possibility of considering meta-information of messages to adapt the manipulation of the message storage.

Prioritization algorithms

NO PRIORITIZATION. With this algorithm, the prioritization only has the basic task to periodically remove expired messages from the message store. This basic task is included in every prioritization algorithm to prevent the continuous dissemination of outdated messages. Due to the stack-like behavior of the message storage, newly received messages are also propagated first again.

STATIC PRIORITIZATION. The static prioritization relies on a predefined order of message types that determines the importance of the different types. For post-disaster communication networks, this order can be defined by disaster relief organizations or other experts. Every time a message is stored, the static prioritization algorithm reorders the messages according to the predefined order. Within one message type, messages are sorted by their age, with new messages on top to ensure timely dissemination of new information in the network.

ADAPTIVE PRIORITIZATION. Motivated by the communication behavior illustrated in Figure 28, the adaptive prioritization algorithm ranks message types according to the number of messages received or generated by the node itself for a predefined time window. Over time, the algorithm tries to capture the change in the message frequency of a specific message type and the type's resulting relevance to the post-disaster communication. The highest priority is allocated to the most prominent message type, and the prioritization order is changed accordingly. If two or more message types have the same rank, the algorithm falls back to the static prioritization behavior. To ensure that new trends can be detected by the prioritization algorithm, newly generated messages are propagated at least once to the neighbors of the originator, regardless of their type.

To assess the impact of the different prioritization algorithms, the architecture can be used to observe the interactions between the DTN-MANET with the message prioritization and the specific dynamics of the post-disaster scenario communication characteristics. In Section 6.3, we discuss a proof-of-concept evaluation, highlighting the impact of prioritization on the delay and recall in DTN-MANETs with different message types and message relevance.

5.4 LONG-RANGE COMMUNICATION SUPPORT

Relevant locations

As already shown in Chapter 4, it is in the nature of humans in disasters to form groups and meet at relevant locations, so-called Points of Interest (POIs), which play an essential role in case of a disaster. Such POIs can be, for example, a market place or a hospital or – thinking in more substantial dimensions – whole villages or cities. When DTN-MANETs are utilized for the post-disaster communication in those places, communication islands will form, as discussed in Section 2.3. Resulting from the field test analysis in Section 4.3, the high node density in communication islands is sufficient for post-disaster communication. Since the intra-island communication is feasible, the results from the conducted field test further revealed that inter-island communication is hindered by the insufficient movement of nodes between them. The limited movement results in highly delayed message transfers or, depending on the message TTL, even message expirations.

Inter-island communication

In this section, we put a particular emphasis on the difficulties of providing communication between different communication islands reliably. To address this goal, we are looking at the reasonable use of long-range low-bandwidth communication modules in different environments after we put our primary focus on the use of highly mobile and controllable UAVs, which are used as data ferries to enable inter-island communication.

5.4.1 *Modules for Long-Range Communication*

One simple idea to interconnect two regional isolated communication islands with each other are via a single communication link using long-range communication devices. To be able to evaluate the applicability of such devices, to support post-disaster inter-island communication, we conducted two proof of concept evaluations in different environments. One of the concepts is focusing on the Line of Sight (LOS) communication between two modules and the other concept evaluates the communication capabilities in an urban environment.

Line of sight experiment

The LOS experiment was conducted in partnership with different experts of low-cost robust outdoor disaster communication relay devices (*Serval Mesh Extenders* [80]). Mounted on cars for sufficient energy supply, two devices were positioned 4 km apart from each other in LOS, with a link throughput of approximately 1 kB/s. For further details, the interested reader is referred to [135]. The experiment has shown that a kilometer-wide inter-island communication is possible but limited by the low bandwidth. The applicability of such devices is further restricted by the necessity of a flexible ad-hoc positioning of them at the edges of potential communication islands, which are often not known beforehand. Especially in post-disaster scenarios, the devices have to be positioned and be functional as soon as possible, in the best case, even before the disaster occurs. Furthermore, it is necessary that the affected population has access to the long-range communication modules, which is often impossible or dangerous.

Urban environment experiment

Since communication after disasters is occurring in the areas where people are located, our second concept for long-range communication evaluates the use in urban areas. We conducted a field experiment to measure the achievable communication distances in a city environment to gather the impact of signal attenuation caused by buildings and other obstacles. For the experiment, we used two LoRa communication modules [128], one located on top of a building (~15 m) near the city center of Darmstadt, Germany, and one mobile device positioned at various locations in the city. We used the configuration setting for the maximum communication range, applying a spreading factor of 12 and a bandwidth of 125 kHz, resulting in a throughput of 183.11 bit/s. A detailed description of the module configuration and their influence on the communication range can be found in [65]. The measurements presented in Figure 30 show the successful and unsuccessful data transmission depending on the distance between the two devices and the attenuated distance. The blue Pareto-optimal measurements show that the maximum distance between the two communication modules in the urban environment is below 600 m with an attenuated distance of approximate 140 m. The heavy drop in the communication range, compared to the 4 km line of sight experiment clearly shows the strong influence of obstacles on the communication capabilities of state-of-the-art long-range communication. While the reduced communication range is sufficient to connect nearby communication islands, for example, separated from each other caused by flooded streets or other impassable obstacles, bridging higher distances without a LOS is often not possible.

Since disasters can take place almost everywhere without any warning, the deployment of additional communication devices beforehand or after the disaster is difficult and often dangerous. Additionally, the exact location of communication islands and their separation from each other can have dynamic nature and is hard, if not even impossible, to predict. Therefore, we are focusing on highly mobile and controllable UAVs equipped with DTN-MANET communication capabilities, to function as data ferries to enable inter-island communication.

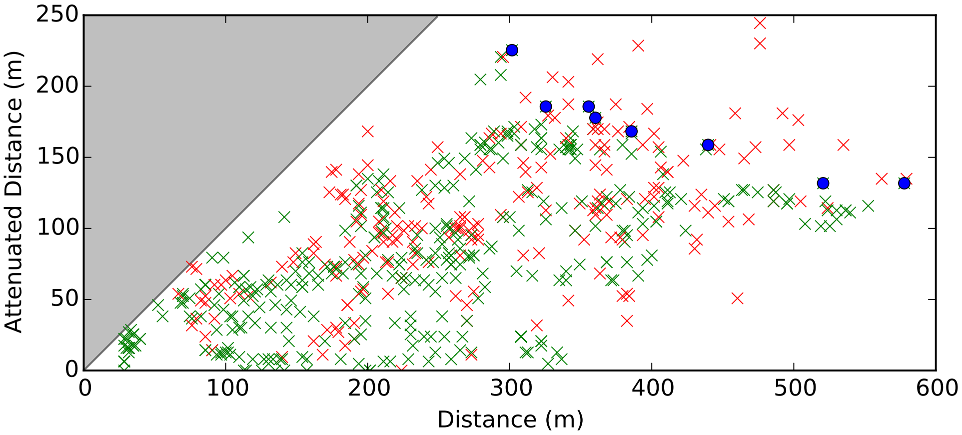


Figure 30: Measurements of successful (green crosses) and unsuccessful (red crosses) data transmissions, depending on the distance between the two modules and the attenuated distance. Pareto-optimal successful transmissions are marked with blue dots [65].

5.4.2 *UAV-based Support Strategies*

In recent years, the increasing commercialization and the resulting growth in popularity of UAVs have attracted the attention of researchers and practitioners alike. Besides UAV applications in the private and commercial sector [96], they can be operated to support emergency response efforts and search and rescue mission [223], which is discussed in detail in Section 3.4. The analysis of the recorded field test data in Chapter 4 made clear that the inter-island communication cannot be sufficiently provided by the uncontrolled movement of DTN-MANET nodes. Especially for high prioritized messages, such as emergency messages, long propagation delays, and poor dissemination in the network are unacceptable (cf. Section 5.3). A single or multiple autonomous UAVs can collaborate to support the communication capabilities of the DTN-MANET on the ground to increase the performance of post-disaster communication. As drafted in Figure 31, UAVs can act as data ferries to spontaneous build communication bridges by facilitating message transport between intermittent communication islands.

Support post-disaster communication

UAVs have identical communication capabilities as nodes on the ground and are easy to integrate in the network. UAVs also are taking advantage of other DTN-MANET node functionalities, such as the periodic beaconing procedure, to detect new communication neighbors in reach (cf. Section 5.1). The challenges that appear are the design of suitable communication support strategies, including the discovery of communication islands and the occurring communication demands as well as the coordination of multiple UAV data ferries. In this section, we present two fundamental example strategies for UAV-based support strategies in DTN-MANETs, to demonstrate the versatile application of UAVs. The impact of different strategy settings on the DTN-MANET ground communication, such as the number of utilized

UAV-based support strategies

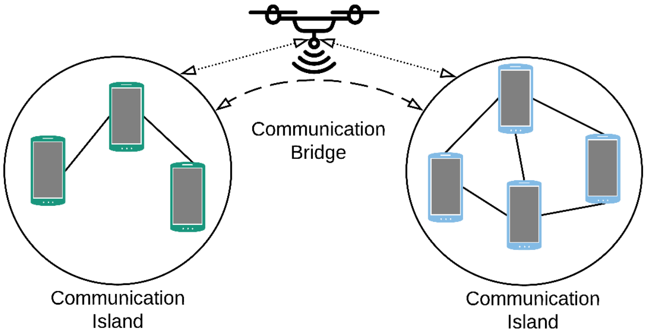
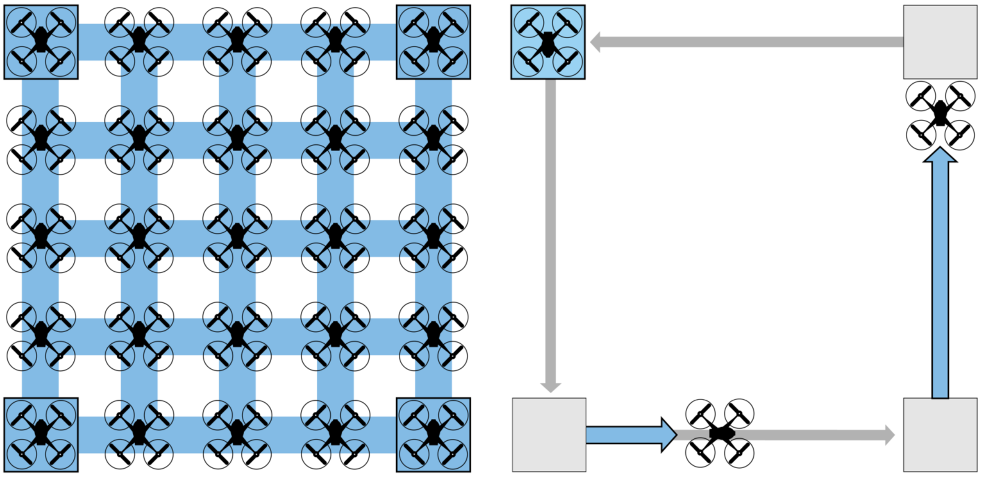


Figure 31: UAV-based inter-island communication [141].

UAVs, is evaluated in Section 6.4, with the main focus to investigate to what extent UAVs would have supported communication during the conducted field test.

UAV characteristics

The main differences of UAVs compared to ordinary DTN-MANET nodes, are *i)* the freedom of movement in three dimensions independent from obstacles on the ground, *ii)* higher movement speed up to 15 m/s, *iii)* a lower battery lifetime (15–25 min) caused by the additional energy consumption of the UAV propulsion, and *iv)* the need to for a base-station to allow battery recharge or battery replacement. In order to demonstrate the various possible applications of UAVs and their impact of the field test replication (cf. Section 6.4), we present two fundamental state-of-the-art strategies in the following: the *relay mesh strategy* [159] and the *data ferry strategy* [284], illustrated in Figure 32.



(a) Relay mesh strategy.

(b) Data ferry strategy.

Figure 32: UAV support strategies [141].

The idea of the relay mesh strategy is to provide the best possible communication support on the ground without any limitations of the number of utilized UAVs. In a configurable distance to each other, UAVs form a connected grid above the area of the DTN-MANET communication islands on the ground. Each UAV relays messages between ground nodes over the dedicated aerial relay network. The advantage of this strategy is the full coverage of the affected area, with expected short delivery delays and exhaustive message distribution over the area. However, the large number of UAVs reduces the practicability, while the dynamic movement possibilities are also mostly unutilized. As an example, full coverage of a $4\,\mathrm{km}^2$ area requires at least 178 UAVs, considering the observed transmission range from the field test ($\approx$110 m) for the DTN-MANET-to-UAV communication and vice versa and 150 m for the UAV-to-UAV communication based on [88, 133, 277]. UAVs need to fly back to a base station to recharge or replace their battery as soon as their operating time reaches an end. Therefore, the provision and exchange of replacement UAVs are necessary.

The data ferry strategy (cf. Figure 32b) fully utilized the dynamic and controllable movement of the UAVs to support the communication between different communication islands. UAVs are hovering over the center of the communication island for the data exchange, before flying to the next island. This procedure is repeated until the UAV's battery depletes. This strategy allows the deployment of different numbers of UAVs, resulting in different UAV-island contact frequencies. If the locations of the communication islands are not known, UAVs need to detect them first in the discovery phase. In this phase, UAVs swarm out to localize communication nodes via the periodic beaconing procedure for the DTN-MANET neighborhood discovery. The collected information is combined in a heat-map at the base-station and communication islands are identified based on the locations with the highest node densities. The advantage of this strategy is the higher applicability in post-disaster situations since the number of required UAVs is significantly lower compared to the relay mesh strategy and the high movement speed of the UAVs allows the coverage of a larger area. It is expected that the strategy performs in between the two extreme cases – no utilization of UAVs and the relay mesh strategy – in terms of the communication performance of the DTN-MANET on the ground.

A comparison of the impact of the different support strategies for post-disaster DTN-MANETs is presented in Section 6.4. In the evaluation, we focus on the comparison of the two presented strategies compared to the communication performance without the use of UAVs and the influence of different strategy and scenario settings, such as the number of used UAVs or the message TTL of the DTN-MANET communication.

6

EVALUATION

To demonstrate the advantages of our proposed Decentralized Disaster Communication System (D2CS.KOM) in supporting communications in the event of a disaster, we present a detailed evaluation of the entire system in this chapter. In Section 6.1, we present the setup of the evaluation environment including the simulation platform SIMONSTRATOR.KOM [209, 210], the evaluation scenario, and the parameters that our assessment is based on. We then assess the impact of D2CS.KOM's core components (presented in Chapter 5), namely *i)* the allocation of available energy resources using different resource allocation strategies, *ii)* message prioritization, and *iii)* the provisioning of different support strategies for inter-island communication, on the overall communication network.

Besides a common evaluation scenario described in Section 6.1, we are considering individual scenario settings for the evaluation of D2CS.KOM, which are necessary to highlight the overall potential of the different core components: For the evaluation of the resource allocation service, we consider an additional scenario to simulate a situation with high over-competition for energy resources, as described in Section 6.2. To be able to understand the impact of message prioritization in Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs), we model a post-disaster traffic-workload in Section 6.3. The traffic-workload is necessary to construct message-specific attributes, such as different messages types, which are utilized by the different prioritization algorithms. For the evaluation of Unmanned Aerial Vehicles (UAVs) utilization to support inter-island communication in Section 6.4, we use the recorded data and the analysis results from the conducted field test to model this real-world scenario within our simulation platform. This replication of the field test allows us to simulate the influence UAVs could have had on the communication network.

The component-specific scenario characteristics and simulation parameters are described in the corresponding sections.

6.1 EVALUATION SETUP AND METHODOLOGY

In the conducted field test in Chapter 4, we demonstrated that smartphone-based DTN-MANETs can be successfully used to provide a basic supply of communication in the event of a disaster. However, evaluating different parameter variations or potential scaling effects in additional field test repetitions is not feasible due to the excessive planning required and the costliness of implementation. Furthermore, such additional tests would not serve to fully investigate the impact of parameter variations since the exact same conditions must always be fulfilled to produce reliable statements – which is not the case with human behavior. Therefore, the evaluation of D2CS.KOM relies on a simulation-based evaluation that supports the representation of the dynamic nature of DTN-MANETs and the characteristics of wireless ad-hoc communication. Especially the movement of the simulated nodes has to reflect human behavior and social ties during the simulation to provide suitable scenarios. Additionally, the simulation framework needs to be expandable to integrate the key features of D2CS.KOM and the findings from the field test.

The event-based simulation environment SIMONSTRATOR.KOM [209, 210] and the underlying simulation engine PEERFACTSIM.KOM [246] constitute a perfect basis for our evaluation, since it already supports a social movement model, the integration of external data sources, and the possibility to implement new functions and extensions. The attributes and functionalities of the SIMONSTRATOR.KOM and PEERFACTSIM.KOM are described in Section 6.1.1. In contrast to the field test, simulation-based evaluations are not bound to the availability of hardware or individual communication devices, allowing us to cope with scalability issues and the integration of various devices, such as UAVs or energy resources. The simulation framework supports synthetic system properties, such as workload- or mobility models, as well as the integration of real-world data, such as the field test recordings. The recordings include the nodes' movement traces based on the Global Positioning System (GPS) sensor and the communication logs (cf. Section 4.3).

We describe the common scenario used for the evaluation of the different components of D2CS.KOM in Section 6.1.2, including the scenario-specific characteristics and models. Furthermore, we explain the utilized metrics to determine the performance characteristics of the different components of D2CS.KOM in Section 6.1.3 including a description of the different plot types used in the evaluations.

6.1.1 *Simulation Platform*

For the execution of the evaluation we use the SIMONSTRATOR.KOM [209, 210] prototyping platform in combination with the overlay simulator PEERFACTSIM.KOM [246], which was originally implemented to simulate Peer-to-peer (P2P) networks. By continually expanding its functionalities, the Java-based platform now supports DTN-MANETs and the possibility to design versatile scenario compilations. The SIMONSTRATOR.KOM platform allows researchers to design and evaluate developed communication mechanism throughout prototypical deployments or simulation-based evaluations. As shown in Figure 33, the SIMONSTRATOR.KOM platform structure is divided into three core components or capabilities: *i)* the framework that enables researchers to design communication systems, *ii)* its interconnections to different *runtime environments*, and *iii)* the execution and evaluation of designed *mechanisms*.

Core components

The framework abstracts the properties of decentralized mobile systems and allows event-controlled and time-related simulations to be carried out. The scheduling mechanisms support the abstraction of time and operations are passed as events to the framework, so the representation of time can be simulated deterministically. Random numbers during a simulation are retrieved using fixed seeds, ensuring reproducibility of experiments. In our simulations, we run ten different seeds to consider the effects of randomness on the simulation results. The instrumentation interfaces

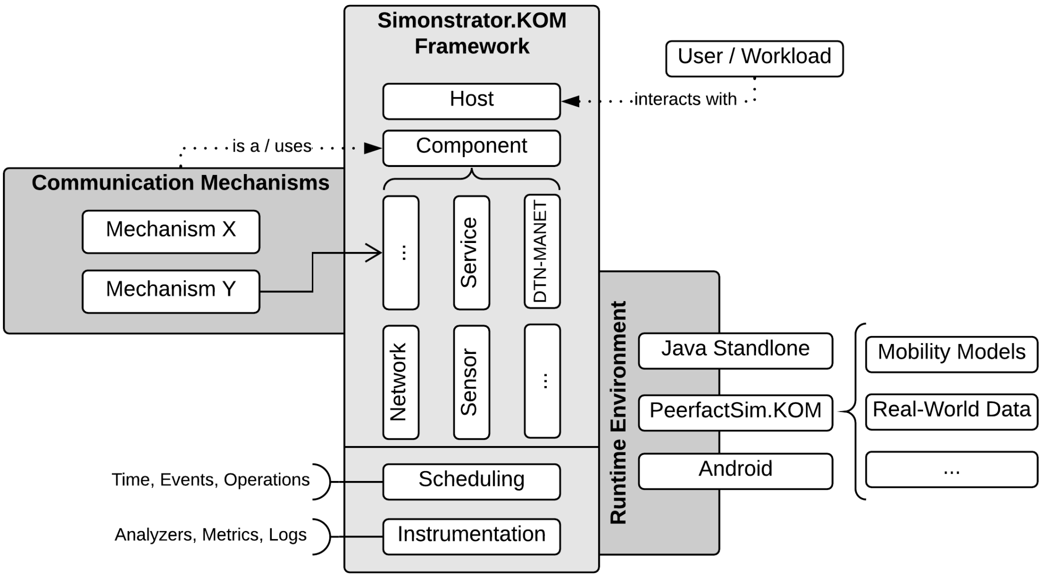


Figure 33: Overview of the Simonstrator.KOM prototyping platform architecture, adapted from [209, 210].

allow to measure data to gain an understanding of the system properties during the simulation runtime. The integration of analyzers and metrics can be used to capture the properties of a system that are necessary for debugging and evaluation.

Components represent platform-specific functionalities, such as the abstraction of sensors (e. g., GPS or battery), layers (e. g., ISO/OSI, TCP/IP), or means of communication (e. g., Wireless Fidelity (Wi-Fi), Bluetooth). The Simonstrator.KOM architecture allows to construct *hosts* as compositions of different components, which represent, for example, DTN-MANET nodes, energy resources, or UAVs with their distinct capabilities in our experiments. Mechanisms utilize the framework to implement specific behavior and inter-relations between different components or hosts. D2CS.KOM contributions for resource allocation, message prioritization, and strategies for communication bridges are therefore integrated as mechanisms in the Simonstrator.KOM platform.

Hosts as component compositions

The Simonstrator.KOM framework can be used by different runtime environments allowing researchers to execute simulations, perform emulations, or support rapid prototypes on real-world devices with minimal changes. The Simonstrator.KOM supports runtime environments for Java standalone projects, Android devices, the vehicular network simulator SUMO [26], the overlay simulator PeerfactSim.KOM [246] and other simulation frameworks.

We utilize the overlay simulator PeerfactSim.KOM to evaluate the different components of the proposed D2CS.KOM. It allows us to model the dynamic scenarios to represent the different characteristics of mobile post-disaster networks, such as node or communication characteristics. PeerfactSim.KOM supports node mobility, realistic Wi-Fi propagation, and contention simulations. The simulator supports further interfaces to other applications, such as SUMO, to integrate vehicles and their behavior into the simulation [156] or the integration of the BonnMotion [15] mobility trace generator. To improve the usability of PeerfactSim.KOM for the design of post-disaster communication networks, we integrated the recorded data from the field test in the simulation platform, to be able to replicate the behavior of the participants.

6.1.2 *Mobility and Communication Characteristics*

In our considered common post-disaster scenario for the evaluation of D2CS.KOM, the mobile network nodes represent the affected population. Since the movement characteristics of the nodes dictate the network topology and interaction patterns of the nodes, the choice of the mobility model used in the simulations is fundamental for the evaluation of DTN-MANETs. Mobility models used during simulations have a high influence on the communication capabilities and consequently on the performance of D2CS.KOM and its components. In DTN-MANETs, the dissemination of data is typically dependent on the nodes' mobility as a result of the applied store-carry-forward principle. Comprehensive surveys of mobility models for ad-hoc networks can be found in [16, 18, 22, 41, 115, 236, 260] and disaster-specific mobility models are discussed in Section 3.1.

Modelling node movement

The realistic representation of human movement and social behavior [47, 164] in combination with disaster-specific attitudes [146, 238, 239, 248] is essential for the evaluation in this work. Therefore, we use and customize a social movement model [215] that relies on the use of real-world attraction points. Attraction points are used to model social-, scenario- or application-specific Points of Interest (POIs). These attraction points are mapped to real-world locations, which are used as interaction- and meeting-places by nodes. Especially in the case of a disaster, the social relation between nodes is important (cf. Chapter 4) and should not be neglected. For example, families or groups of friends tend to meet at the same attraction points, or the movement of a single node influences the behavior of its socially connected nodes. One specific insight from the analysis of the conducted field test in Chapter 4 is the occurrence of different group encounter actions when groups of participants meet. Social interactions took place between meeting groups, such as certain pause-times to verbally communicate with each other, or changing group formations. The presumed smartphone-based DTN-MANETs are people-centric networks (cf. Section 3.1) and especially in the case of a disaster, the affected population tends to interact more frequent with strangers compared to normal life activities [55, 145]. Since the existing simulation mobility models do not support such group encounter behavior, we extend the social movement model [215] with the following encounter actions, visualized in Figure 34. Groups in PeerfactSim.KOM consist of one group leader and one or more group participants. The group participants follow the group leader to its next desired attraction point. Whenever they encounter another group, they perform one of the following actions: *i)* stay together for some time, *ii)* merge to one single group, *iii)* mix group participants, *iv)* completely dissolve, or *v)* move on with no interaction. Additionally, to the group encounters and the movement in between attraction point, nodes or groups have an exploration probability of selecting other

Social relations

Group encounter actions

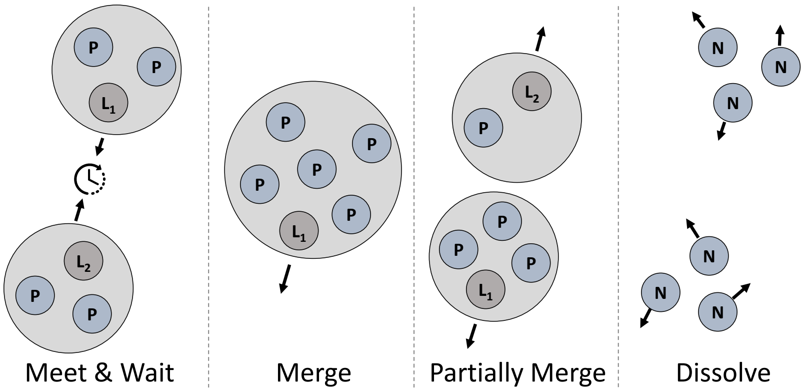


Figure 34: Group encounter actions, adapted from [269]. L = Group Leader, P = Group Participant, N = None.

locations besides high frequented locations. This exploration behavior reflects search and rescue effort of the affected population, people looking for family and loved ones or trying to discover vital resources.

Frequently visited attraction points

The simulations are performed on a map of a residential area in the city of Darmstadt, Hesse of 4 km², made available from OpenStreetMap[1]. The map includes all public parks in the vicinity of the downtown campus of Technische Universität Darmstadt, which we use as attractions points during our evaluation, representing evacuation spots and safe havens. Initially, nodes are placed on a random location at the beginning of a simulation. The node movement is restricted to pedestrian walkways provided by the map topology.

802.11 Wi-Fi model for ad hoc communication

The simulation of smartphone-based DTN-MANETs further requires models for ad-hoc device-to-device communication. We employ the 802.11g [268] model from the ns-3 discrete-event network simulator for Internet systems [100], which is already implemented into the PEERFACTSIM.KOM platform [210]. The maximum transmission range is an essential parameter for simulations [250], which is a function of the signal path loss. Path loss occurs due to general signal attenuation, scattering, reflection at surfaces, and other influencing factors. Since ray trace models [94] of the city of Darmstadt are currently not available and their creation would be out of the scope of this thesis, we rely on an empirical propagation loss model to determine the maximum transmission range.

Usually, the log-distance model is used for macrocells like Global System for Mobile Communications (GSM), where one or both antennas are positioned at a higher level, for example, on a rooftop [173]. In the case of a DTN-MANET, however, both the sender and receiver radio are held by people walking on the ground. Here, obstacles such as buildings and trees play a much more important role by shadowing the signal or even blocking it completely. Ranges for device-to-device transmissions of up to 405 m, as measured by [61] in a rural area within line of sight, are uncommon in this kind of scenario [74], which was also confirmed by the field test analysis in Chapter 4. In our simulations, we are using the *Surrey University urban mobile-to-*

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[1] http://www.openstreetmap.org [Accessed July 1st, 2019]

mobile propagation model [124]. The model is based on measurements taken in London at a low height, and a frequency of 2.1 GHz close to our considered 2.4 GHz using 802.11g. The model offers two separate formulas for propagation loss at Line of Sight (LOS) and No Line of Sight (NLOS) conditions:

$$PL_{LOS} = 4.62 + P_0 - 2.24h_t - 4.9h_r + 29.6\log_{10} d \tag{5}$$

$$PL_{NLOS} = P_0 - 2h_r + 40\log_{10} d + C \tag{6}$$

$$C = \begin{cases} 0 & \textit{dense urban}(H_B > 18\text{m}) \\ -4 & \textit{suburban or urban}(H_B < 12\text{m}) \end{cases} \tag{7}$$

where h_t and h_r are the height of the transmitter and receiver, $P_0 = 20\log_{10}(^{4\pi}/_{\lambda})$ the reference free space loss to the distance d with the wavelength λ, and H_B the average building height. If no terrain data is available to determine whether a link is LOS or NLOS, the authors provide an approximation using the probability α that any given point within a reference distance is within LOS:

$$PL = \alpha PL_{LOS} + (1 - \alpha)PL_{NLOS} \tag{8}$$

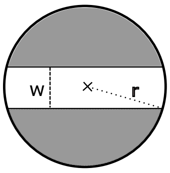


Figure 35: Street model used to calculate LOS probability α for the *Surrey University urban mobile-to-mobile propagation model* (reference range r, street width w) [72, 124].

For our experiments, we assume a dense urban area ($H_B > 18$m), equal receiver and transmitter antenna heights of 1.5 m [254], and a LOS probability of $\alpha = 0.104$. LOS probability α was estimated by calculating the fraction of a reference circle with a radius $r = 100$ m that lies within a street with a width $w = 30$ m and infinite length, while standing in the middle of the road (white area in Figure 35). This results in a maximum transmission range of 99.66 m that we use in our simulations, which also match the findings of the conducted field test in Chapter 4. To reflect real communicative behavior in the simulation, the effects of collisions caused by simultaneous transmissions need to be included. We model this behavior using the NIST error rate model taken from the ns-3 simulator [100].

If not stated otherwise, we use the simulation parameter setup shown in Table 1 to model the node behavior and communication characteristics to evaluate the different components of D2CS.KOM.

Table 1: Common D2CS.KOM evaluation setup.

Simulated Area $[\mathrm{m} \times \mathrm{m}]$	2000×2000
Map Section (OpenStreetMap)	Residential area in the city of Darmstadt
Max. Transmission Range $[\mathrm{m}]$	99.66, urban mobile-to-mobile propagation model [124]
WiFi Standard	802.11g [100]
Movement Speed $[\mathrm{m}/\mathrm{s}]$	$1.5 - 2.5$
Movement	Social movement [215] with 13 attraction points (parks)
Pause Time at Attraction Points $[\mathrm{min}]$	$15 - 20$
Exploration Probability [%]	20
Density $[\mathrm{nodes}/\mathrm{km}^2]$	25

6.1.3 *Evaluation Metrics*

The SIMONSTRATOR.KOM platform supports event- or time-based analyzers to log relevant system behavior to derive metrics for the evaluation of D2CS.KOM. The set of different metrics that we use for the evaluation of the different D2CS.KOM components are described in the following:

NODE LIFESPAN. For the evaluation of the resources allocation service as part of D2CS.KOM, we capture the number of active nodes in the network during the simulations. Nodes running out of energy switch to the OFFLINE state, not participating in the network anymore. We also look into the fraction of lifetime spent by nodes in the HEADING and the ROAMING state, as well as the average lifetime. From [93], we adopt the additional metrics *first node offline*, *half of the nodes offline* and *last node offline*.

RESOURCE METRICS. To capture the utilization of energy resources during simulations, we track the available amount of resources on the map over time. With the constant discovery and consumption of energy resources by the nodes, this metric provides valuable insights into the allocation capabilities of the different strategies used by the resource allocation service. Additionally a metric records the time of unsuccessful HEADING attempts, whenever a node reaches an already depleted energy resource.

RECALL. The recall is defined as the ratio of relevant receptions of a message over a defined set of message recipients. In the case of a message broadcast where all network nodes are part of the set of message recipients, a recall of 1.0 corresponds to successful network-wide propagation. In DTN-MANETs, the recall is typically influenced by the node density and mobility, as well as the Time to Live (TTL) of messages.

DELIVERY DELAY. The delayed message delivery is a common characteristic in DTN-MANETs. The metric measures the average time it took a message to arrive at its successfully reached recipients, via the DTN-MANET-specific store-carry-forward principle. It is recommended to always consider the delivery delay in combination with the recall metric, as the delivery delay alone has limited significance to assess the network communication capabilities.

Metric Plot Types

For the presentation of the evaluation results, we use time plots and box plots. We use time plots to investigate the temporal change of selected parameters or metrics during our simulations.

Box plots are a method to visually describe statistical data, and they provide information about the data distribution of the simulation results. Figure 36 shows the different parts of a box plot. The solid line inside the main box represents the median of the input data. The range from the lower to the upper bound of the box is called interquartile range, with the bounds representing the 25th percentile (lower quartile) and the 75th percentile (upper quartile). The two whiskers show the 2.5th percentile and the 97.5th percentile, meaning that 95 % of the results lie in between the whiskers. Values outside of the whiskers represent outliers and are represented as crosses. An additional marker with error bars on the left side of a box represents the mean of the means and the standard deviation of different simulation runs, using different seeds for the random number generation. If the marker is not shown, all results from the simulation runs are combined in one box plot. In our simulations, we rely on 10 different seeds per simulation setup.

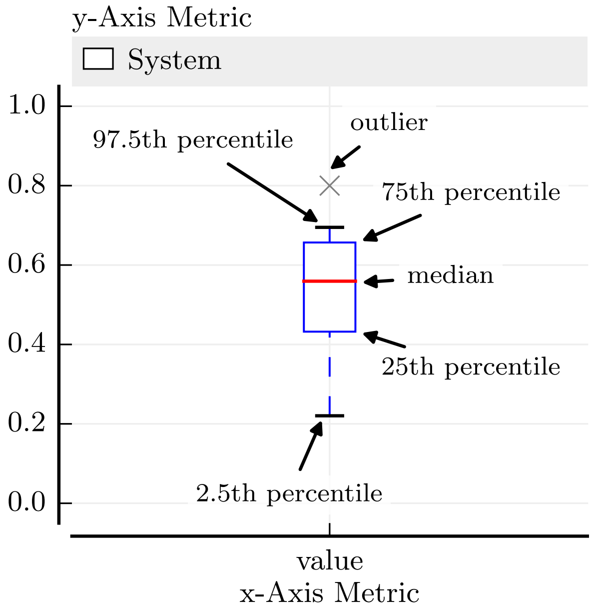


Figure 36: Box plot used in the evaluation.

6.2 IMPACT OF THE RESOURCE ALLOCATION SERVICE

In this section, we evaluate D2CS.KOM's resource allocation service and assess its impact on the lifetime of the post-disaster communication network. First, additionally to the common scenario setup presented in Table 1, we describe the utilized resource allocation service-specific simulation parameters in Section 6.2.1. After the scenario description, we present an example out of a full system parameter evaluation, presented in [72, 136, 138], for the determination of optimal service parameter settings in Section 6.2.2. In conclusion, we analyze the performance of the different resource allocation strategies in Section 6.2.3.

6.2.1 *Scenario Model*

Modelling energy consumption states ...

Besides the common movement and communication characteristics of the simulation scenario, the evaluation of the resource allocation service of D2CS.KOM requires additional features and parameters. First, we model a battery as an additional component to the mobile nodes, which limits the nodes' participation in the network. Based on the energy consumption calculations in Section 5.2, we model an abstraction of the nodes' maximum battery capacity with 14 400 ru (Resource Units) and the power consumption in the Roaming state as 1.0 ru/s and in the Heading state as 3.11 ru/s. Correspondingly, a fully charged node can communicate for 4 h (14 400 s) in Roaming state. For simplicity, the recharge process is assumed to be instantaneous. The initial node placement and battery charge level is defined by the simulation configuration, which are explained later in this section.

... and energy resources

The representation of energy resources, the Resource Demand Beacons (RDBs), in the Simonstrator.KOM platform are hosts with no movement capabilities, a battery component, and the communication behavior as explained in Section 5.2. New RDBs are generated over time at uniformly distributed random places, with a configurable energy capacity. During the simulation, one RDB per node is generated over time.

For the evaluation of the different resource allocation strategies, we propose two different scenarios (*s1*, *s2*) to examine their performance. The first scenario *s1* focuses on the *long term behavior* of the resource allocation with a constant appearance of new RDBs until the overall energy is depleted. We use the second scenario *s2* to explicitly study the system behavior under *over-competition*, when nearby nodes have demand for available energy resources at the same time.

Scenario 1: Long Term Behavior (s1)

This scenario is used to study the long term behavior of the post-disaster communication network to assess the influence of the different resource allocation strategies on the lifetime of the network. The nodes' start energy is distributed with a mean μ of 67 % (9648 ru), which is a typical average battery charge of a user's smartphone [71]. To hold the total amount of start resources equal each simulation run, we multiplied the number of nodes N with the mean and split this amount into buckets by drawing N times from a truncated normal distribution [217] with an upper bound

$\mu^{+} = 100\%$ and a lower bound $\mu^{-} = 10\%$ maximum battery capacity, and variance $\sigma^{2} = 0.1\mu$. Resources left over from the first distribution are allocated to the nodes proportional to their energy level, to ensure that all resources are distributed and no initial battery state is smaller than the lower bound.

Every two minutes, an RDB is randomly placed on the map, providing enough energy for two full battery recharges. In theory, the available energy of the RDBs in addition to the initial start energy of the nodes results in an average maximum running time of the nodes of 10 h 40 min 48 s if no additional energy in the HEADING state is consumed. This scenario reflects the beginning of a post-disaster situation where D2CS.KOM is utilized, and nodes try to discover and consume resources over time when they run out of energy. Considering this scenario, the number of nodes that simultaneously have a demand for energy greatly varies depending on the differences of the nodes' current energy state, the node density, as well as the number of available resources in close vicinity. The scenario helps to assess the benefit of cooperative resource allocation strategies compared to the non-cooperative baseline strategies. The described *long term* scenario-specific simulation parameters are summarized in Table 2, marked with *s1*.

Scenario 2: Over-Competition (s2)

The second scenario models a situation with high competition over limited energy resources for large crowds of people. All nodes start with an immediate demand for energy and are placed at the same location at the beginning of the simulation. We consider that all nodes have synchronized their *advertisement stores*, resulting in all nodes having the same knowledge about available energy resources. 50 nodes compete for one randomly placed resource per node, which can only serve 50 % of the maximum battery capacity. Such a scenario reflects the situation in which energy resources are suddenly available in a densely populated area, for example, provided by aid organizations [32, 235]. This scenario is used to demonstrate the benefit of strategies with the disclosure of the nodes' context, such as Ad Hoc On-demand Reservation Vector Auction (AORVA), where we expect a lower number of unsuccessful attempts to recharge at an RDB. The scenario-specific parameters for the *over-competition* scenario are also summarized in Table 2 marked with *s2*.

6.2.2 *Strategy Parameter Evaluation*

To be able to evaluate the different resource allocation strategies, we must first determine appropriate parameter values for the various strategies. Parameter values are, for example, the HEADING threshold, and the nodes' and RDBs' communication settings, such as the RDB announcement timer or the nodes resource reservation repetition interval. We have carried out a comprehensive system parameter evaluation in [136, 138] using the long term scenario *s1* from which we exemplary present the determination of optimal HEADING thresholds for the strategies *Greedy Selection* and *En Passant* in the following. The investigated parameter space of all considered

Table 2: Resource allocation evaluation setup for the long term scenario (s1) and the over-competition scenario (s2) in addition to Table 1.

Node Density [nodes/km^2]	s1: 25, s2: 12.5
Max. Simulation Duration [hours]	20
Max. Battery Capacity [*ru*]	14 400
Start Energy	s1: normal distributed, $\mu = 67\,\%$ s2: fixed $= 30\,\%$
Initial Node Placement	s1: random, s2: central
RDB Placement	random
RDB Generation Interval [*min*]	s1: 2, s2: immediately
Energy Amount per RDB [*ru*]	s1: 2 ×, s2: 0.5 × max. Bat. Cap.
Overall Energy [*ru*]	s1: 2 ×, s2: 0.5 × #Nodes × max. Bat. Cap.
Roaming Cost [ru/s]	1.0
Heading Cost [ru/s]	3.11

system- and strategy parameters are summarized in Table 3 and explained at the end of this section. Additional evaluation results are provided in Section A.3.

Determine the Heading *threshold*

The Heading threshold is an important parameter and needs to be determined individually for each selection strategy. The Heading threshold indicates the energy state when the resource allocation client initiates the resource selection process. For example, a Heading threshold of 0.3 results in the initiation of the selection process as soon as a node's energy level is below 30 % of the maximum battery capacity. Figure 37 and Figure 38 show the impact of the configured Heading threshold on a node's Roaming time for the *En Passant* and *Greedy Selection* strategies, respectively.

Since *En Passant* is an oblivious non-cooperative resource allocation strategy, it does not store or communicate any RDB information. Therefore, nodes may not be able to find an available RDB once they hit a low Heading threshold if no RDB is in the vicinity. This results in an overall poor utilization of available resources and a shorter lifetime and, consequently, Roaming time of the nodes. This effect can be observed when we apply a Heading threshold of 0.1 to *En Passant*. Half of the nodes run out of energy after 6 h 54 min with an average Roaming time of 7 h 39 min (median). In Figure 37 we can determine the optimal Heading threshold of 0.7 with regard to the average Roaming time, resulting in half of the nodes being offline after 8 h 48 min and an average Roaming time of 9 h 4 min (median). With the optimal Heading threshold for *En Passant*, nodes profit from the discovery of new resources for a longer time. A further increase of the Heading threshold decreases the Roaming time since nodes are heading more often to discovered resources and the amount of energy that can be consumed to reach a fully charged battery gets smaller. Nodes are not in the Heading state for distances beyond the communication range of the RDBs (100 m). Therefore, *En Passant* is the strategy with the shortest fraction of time spend in Heading.

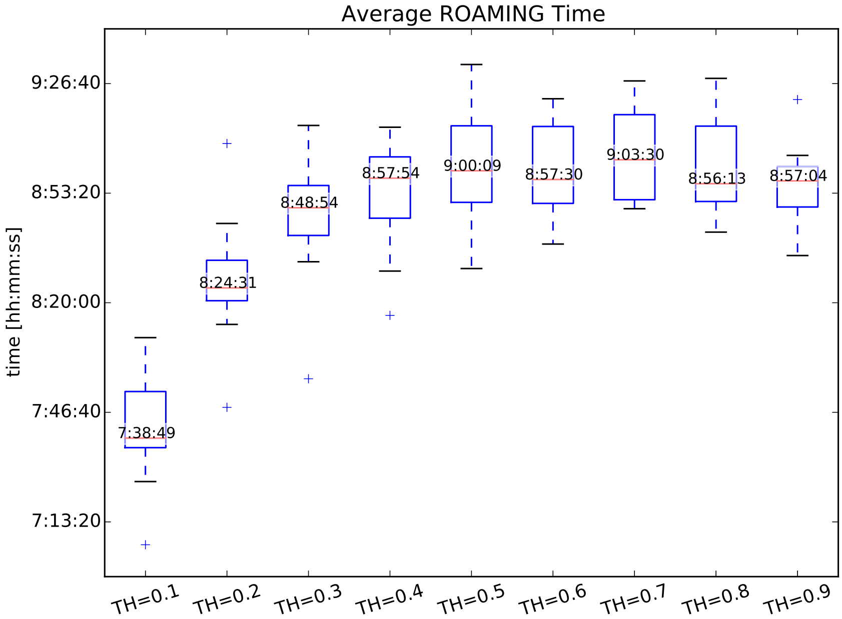


Figure 37: *En Passant Strategy*: Average total ROAMING time for different HEADING thresholds (TH) [138].

Figure 38 shows the HEADING threshold evaluation for the cooperative *Greedy Selection* strategy. In contrast to the behavior of *En Passant*, the ROAMING time of nodes decreases with thresholds higher than 0.2. This behavior is a result of the knowledge sharing between nodes, which enables them to select the most profitable RDB from a broader set of known resources, but at the same time it increases the competition, and the distances traveled while in the HEADING state. A low HEADING threshold of 0.2 is optimal for the *Greedy Selection* in the considered scenario. The threshold allows a sufficient lifetime (20 % battery equals 48 min lifetime in the ROAMING state) of the node to target another RDB after an unsuccessful HEADING attempt. Furthermore, if enough energy is available at a reached RDB, the amount of energy recharged is at least 80 % of the nodes maximum battery capacity, because of the HEADING threshold of 0.2. Recharging larger quantities of energy reduce the number of nodes having a demand for energy simultaneously since it takes longer until the nodes have a demand again. A high HEADING threshold results in nodes trying to recharge energy at RDBs more frequently, which results in more HEADING attempts and consequently in higher resource competition.

The determination of the best performing HEADING threshold for the different resource allocation strategies is used as an example to show how different system parameters are determined. The results of a comprehensive system evaluation are summarized in Table 3 and briefly described below. Additionally, we provide an extended evaluation of the influence of different resource allocation strategy parameter settings and an evaluation of the robustness of the resource allocation strategies against scenario characteristics fluctuations in Section A.3.

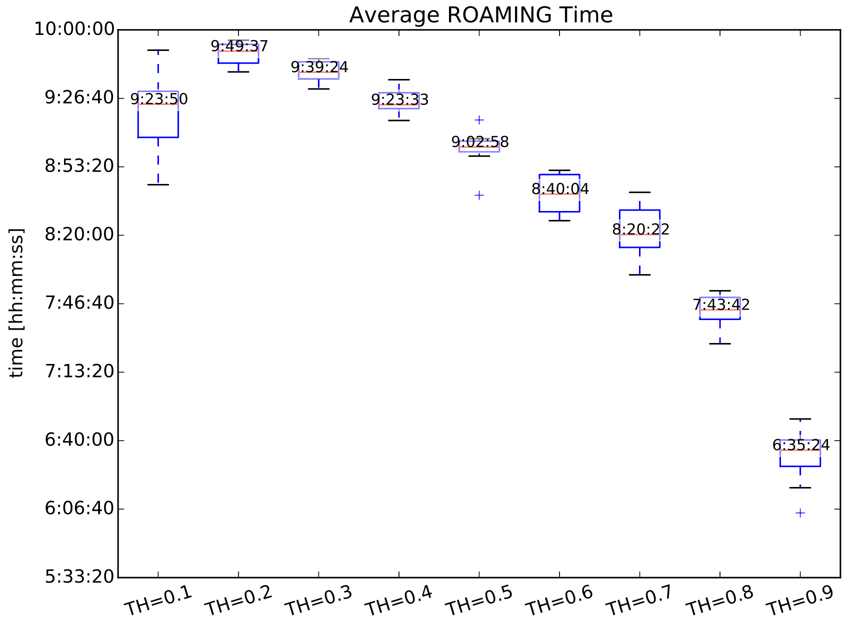


Figure 38: *Greedy Selection Strategy*: Average total ROAMING time for different HEADING thresholds (TH) [138].

The resource announcement timer defines the frequency of the resource advertisement distribution of the original RDBs and the forwarding nodes. Together with the reservation repetition interval of AORVA, these parameters are mainly responsible for the communication overhead of the resource allocation service. While the reduction of the protocol overhead is important, we still decide to have announcement intervals of resource information and reservations at a frequency of 5-10 seconds for the resource announcement timer and 5 seconds for the reservation repetition interval to also enable the information dissemination in sparse networks. The resulting communication overhead is limited by the TTL, to restrict the dissemination of data to a regional extent. Due to the movement speed of the nodes, frequencies lower than 5 seconds did not result in notable performance improvements of the resource allocation service (cf. Section A.3).

Optimizing the protocol overhead is not in the scope of this thesis. However, existing approaches [8, 189, 221], for example, piggybacking announcements during the neighborhood discovery procedure, can be added due to the design modularity of the resource allocation service and the overall D2CS.KOM.

The memory span and the reservation vector lifetime define the duration until RDB advertisements or resource reservations are no longer considered by the selection strategy anymore and are deleted from the node-storage. The system evaluation showed that 40 min is a suitable value for both parameters because it is a good compromise between neglecting information at an early stage and incorporating outdated information into the nodes decision making [136, 138].

Table 3: System parameters with the best performing (underlined) parameter values (cf. Section A.3) [136, 138].

Resource Announcement Timer [*s*]	5-10, 10-20, 20-40, 40-60
Memory Span [*min*]	1, 5, 10, 20, 40, 60, 80, 100
TTL [*hops*]	1, 2, 3, 4, 5, 6, 7, 8, 9
HEADING Threshold	
– Reservation Oracle	.1, .2, .3, .4, .5, .6, .7, .8, .9
– En Passant	.1, .2, .3, .4, .5, .6, .7, .8, .9
– Greedy Selection	.1, .2, .3, .4, .5, .6, .7, .8, .9
– AORVA	.1, .2, .3, .4, .5, .6, .7, .8, .9
AORVA Reservation Vector Lifetime [*min*]	1, 2, 4, 5, 10, 20, 30, 40, 80, 120
AORVA Reservation Repetition Interval [*s*]	1, 2, 3, 4, 5, 7, 10, 12, 15, 20, 30

Understanding the system behavior

The system evaluation was used to determine the best performing setting of the parameters that influence the distribution of knowledge, the nodes recharge behavior, and the storage duration of resource- and decision-advertisements. We have shown that different forms of communication, represented by cooperative and non-cooperative resource allocation strategies, result in different suitable parameters values for the different strategies. A non-cooperative strategy like *En Passant*, for example, needs to allocate known resources at an early stage to provide the longest ROAMING time for the individual nodes (cf. Figure 37). In contrast to cooperative strategies, such as *Greedy selection*, it is beneficial for nodes to recharge with less energy remaining. This way, nodes consume higher portions of energy, which consequently decrease over-competition, since fewer recharge attempts per node are necessary.

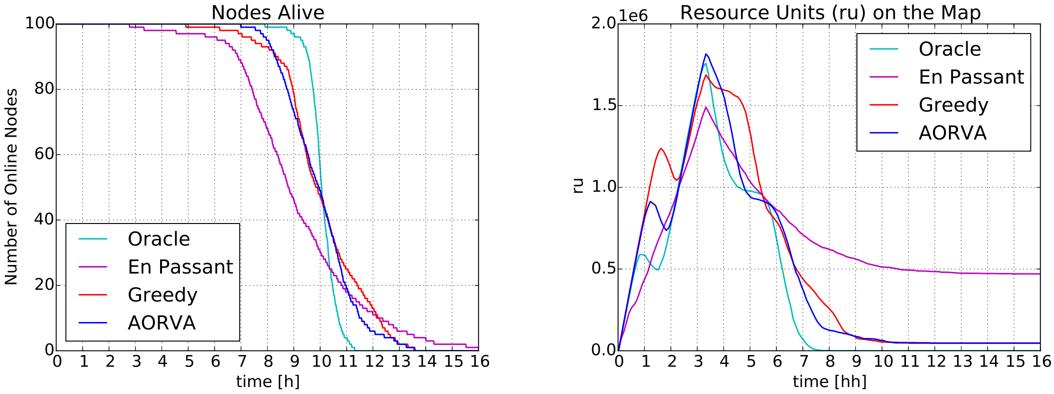
The determined parameters from Table 3 are further used in the next section to compare and evaluate the performance of the different resource allocation strategies considering the two scenarios described in Section 6.2.1.

6.2.3 *Evaluation and Comparison of Resource Allocation Strategies*

The overall goal of D2CS.KOM's resource allocation service is to maintain a high node density in the network. The service's resource allocation strategies attempt to keep as many nodes up and running for as long as possible, to support the communication capabilities of the DTN-MANET. A resource allocation strategy achieves this by assigning as many available resources as possible to the nodes, while at the same time avoiding unsuccessful attempts to recharge. If a node's charging attempt cannot be successful, for example, if another node reaches the RDB faster or the RDB is already depleted, it should be aborted as quickly as possible to avoid wasting energy caused by the higher energy consumption in the HEADING state. First we are going to investigate these characteristics of the different allocation strategies (cf. Section 5.2.3) for the long term scenario *s1* (cf. Section 6.2.1).

Figure 39a shows the number of nodes supplied with energy over time for the two baseline strategies *Oracle* and *En Passant*, as well as for the cooperative strategies *Greedy Selection* and AORVA. *En Passant* is used as the lower baseline without the utilization of any communication for the resource allocation. *Oracle* is used as an upper baseline based on the availability of global network knowledge. As expected, *Greedy Selection* and AORVA perform in between these baselines in terms of keeping nodes supplied with energy, while allocating almost all available resources (cf. Figure 39b). The overall nodes alive graph in Figure 39a and the resource utilization characteristics in Figure 39b of *Greedy Selection* and AORVA are similar. Having a more detailed look into the result values from Figure 39a, the reservations used by AORVA have a prominent advantage. AORVA delays the point in time when the first node runs out of energy to 7:00 h compared to 4:55 h when using *Greedy Selection* an improvement of more than 42 %. The *first node offline* metric is particularly essential in the considered post-disaster scenario because each network participant can potentially be at risk and should, therefore, be able to call for help at any time. In comparison, the first node runs out of energy after 2:47 h using *En Passant* and 7:55 h using the global knowledge *Oracle*. Maintaining a high node density is crucial for the communication capabilities of the network and the applied services for emergency response efforts. It is undesirable to have only a fraction of nodes supplied with energy for a long time, as it appears in the last hours of the simulations when *En Passant* or *Greedy Selection* is used. In [138] we have extensively evaluated the effects of the networks node density on the communication capabilities in scenario *s1*. It follows that a successful data exchange between arbitrary locations is no longer feasible when more than 50 % of the nodes run out of energy.

Strategy performance comparison

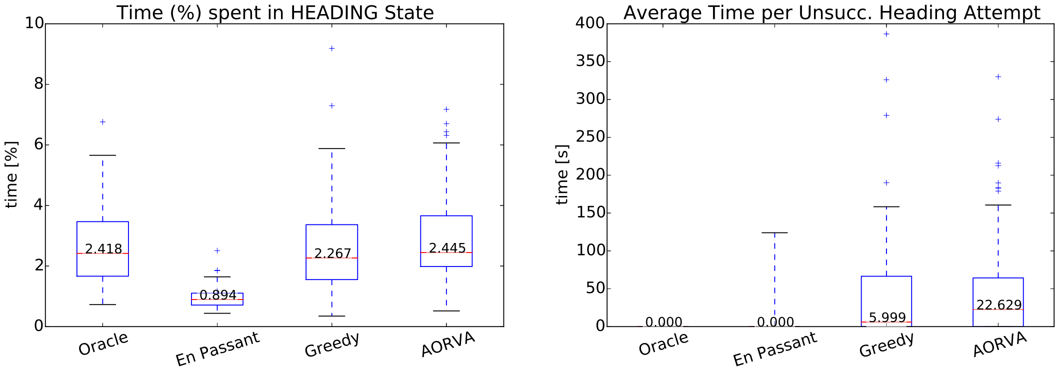


(a) Number of nodes alive.

(b) Available resource units.

Figure 39: Performance over time of the different resource allocation strategies using the *Long Term Behavior* scenario *s1* [136].

To have a more detailed view on the strategy's effects on the behavior of the nodes, we investigate the percentage of the nodes' total lifetime spent in the HEADING state in Figure 40a. Here, the HEADING time consists of the successful and unsuccessful attempts to recharge at an RDB. Dependent on the applied resource allocation strategy, we show the average time it took nodes to realize that an attempt will be unsuccessful in Figure 40b. In the worse case, the attempts are canceled on arrival at the RDBs' locations. In the best case there are no unsuccessful Heading attempts, for example, achieved by the *Oracle* strategy with global knowledge. Except of *En Passant*, all other



(a) Percentage of lifetime spent in the Heading state.

(b) Average time per unsuccessful Heading attempt.

Figure 40: Performance of the different resource allocation strategies using the *Long Term Behavior* scenario *s1* [136].

strategies have a similar share of time that nodes spend in the Heading state. Besides *En Passant*, Figure 40a shows that 2.267 % - 2.445 % of the nodes lifetime is necessary to allocate resources among the nodes in the given scenario. As already discussed in the evaluation of the system in Section 6.2.2, only nearby resources can be consumed by nodes using *En Passant*. Therefore, the chances of simultaneous competition for the same RDB is low. Even in the occurrence of competition, the time spent in the unsuccessful Heading state (cf. Figure 40b) is insignificantly small.

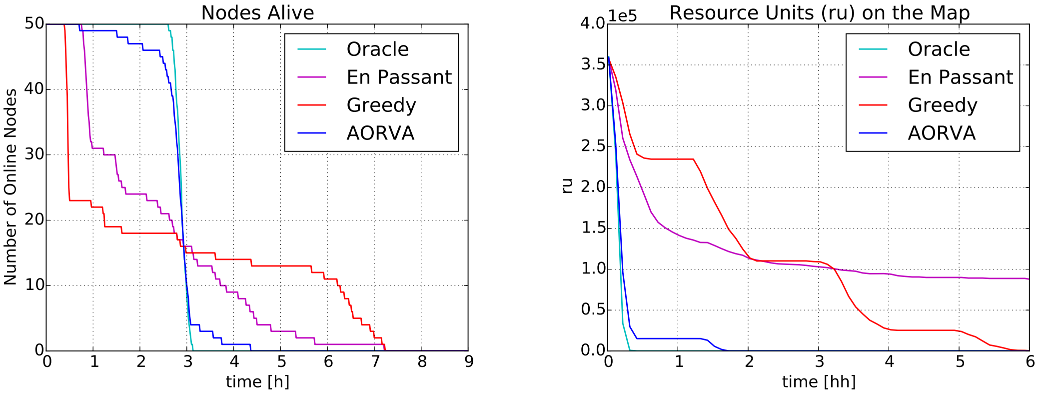
Maintain high node density

AORVA achieves to prolong the time until the first nodes run out of energy significantly compared to *Greedy Selection*. AORVA also maintains an overall higher node density for a longer time, which can be observed in Figure 39a for the time window 5.5 h to 8 h. The longer a high node density in the network can be maintained, consequently nodes spend a larger percentage of their total lifetime in the Heading state (cf. Figure 40a). As a consequence, AORVA is also resulting in longer unsuccessful Heading attempts as shown in Figure 40b. The reason that AORVA's reservations requests cannot always avoid long Heading attempts and potentially unsuccessful attempts is due to the separated network communication islands. These network separations are leading to nodes heading to the same resource from different directions, not being able to exchange their reservation requests.

With the evaluation of the *Long Term Behavior* scenario *s1*, we successfully showed that the cooperative resource allocation strategies *Greedy Selection* and AORVA can achieve a fully decentralized allocation of energy resources to prolong the lifetime of the communication network to maintain a high node density for as long as possible. AORVA's strength, compared to *Greedy Selection*, is the exchange of resource reservations with neighboring nodes to reduce over-competition. To analyze the impact of situations with high competition, we are evaluating the different resource allocation strategies in the *Over-Competition* scenario *s2*, whose settings are described in Section 6.2.1.

High demand for limited resources

In the *Over-Competition* scenario *s2*, we evaluate how the different strategies can cope with over-competition in combination with the scarcity of available resources. We investigate if a consensus about the allocation of resource between nodes can be achieved to maintain post-disaster communication as long as possible, even in extreme situations. As previously discussed and summarized in Table 2, all nodes in *s2* start at the same location, having direct demand for energy and the same knowledge about all resources in the scenario. Since *En Passant* is not capable of storing any information about RDBs, only resources in direct communication range are known at the beginning. Figure 41a show the results of the average lifetime of the nodes for the different strategies. The advantages of AORVA's resource reservations are evident in this scenario. AORVA supports a faster allocation of energy resources and consequently maintains a much higher node density for a longer time, compared to *En Passant* and *Greedy Selection*. Due to the high node density at the start of the scenario, AORVA utilizes the communication capabilities to achieve an *Oracle*-alike local agreement of the allocation of the RDBs. Figure 41b shows that AORVA and *Oracle* can allocate almost all resources immediately and have a similar share of time the nodes are in the HEADING state (cf. Figure 42a). Additionally, Figure 42b shows that the good connectivity in the network enables AORVA to cancel unsuccessful HEADING attempts much earlier (1.3 s), compared to the long-term scenario *s1* (22.6 sec).

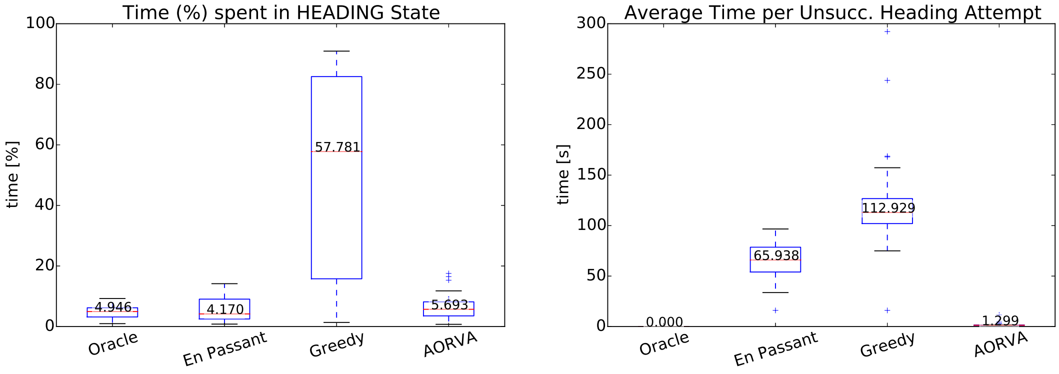


(a) Number of nodes alive.

(b) Available resource units.

Figure 41: Performance over time of the different resource allocation strategies using the *Over-Competition* scenario *s2* [136].

Greedy Selection is not able to cope with the over-competition situation and performs even worse than *En Passant*. *En Passant* does not utilize any kind of communication or cooperation between the nodes and is not able to allocate almost 25 % of the available resources, which remain undiscovered (cf. Figure 41b). The poor performance of the resource allocation by *Greedy Selection* is a clear indicator that knowledge-sharing without any coordination, cooperation or consensus can have significant negative effects on the overall capabilities of the network and consequently on the post-disaster communication. Without the disclosure of the nodes HEADING decisions, *Greedy Selection* results in a massive increase of the time spent in the HEADING state (cf. Figure 42a). Nodes are continuously heading to the same RDBs over and over again, spending almost 58 % of their lifetime in the HEADING state before they go offline. Due to the same movement patterns during the HEADING phase driven by the *Greedy Selection* strategy, information about depleted RDBs are distributed only very locally. This results in long HEADING attempts, shown in Figure 42b, because nodes only abort non-profitable HEADING attempts shortly before reaching the RDB.



(a) Percentage of lifetime spent in the HEADING state.

(b) Average time per unsuccessful HEADING attempt.

Figure 42: Performance of the different resource allocation strategies using the *Over-Competition* scenario *s2* [136].

Reduce unsuccessful attempts

A closer look at the result values used for Figure 41a show that AORVA can extend the *first node offline* metric to 44:28 min compared to 24:50 min using *Greedy Selection*. The global knowledge approach *Oracle* further extends this time to 2:38 h, reaching a near-optimal resource allocation since all resources are utilized and all nodes are running out of energy almost simultaneously. Since the *Oracle* strategy is not applicable in DTN-MANETs due to the lack of global network knowledge, AORVA achieves a comparable allocation of resources in the considered scenario.

Overall, we successfully demonstrated the decentralized resource allocation in DTN-MANETs to prolong the network's lifetime while maintaining a high node density. Taking advantage of the communication capabilities of the DTN-MANET, AORVA outperforms the other strategies significantly in distributing scarce energy resources in post-disaster scenarios without the support of any central infrastructure. With communication-based cooperation of the nodes, AORVA is especially beneficial in dense networks with high chances of competition, as shown in our evaluations. Simply applying communication-based resource allocation strategies do not necessarily result in better resource allocation. With *Greedy Selection* in scenario *s2*, we demonstrated that unsuitable strategies result in the fast collapse of the communication network, even though the strategy performed well in other scenarios. AORVA always supports the network capabilities independently of the current network situation. The proposed resource allocation service as part of D2CS.KOM successfully supports DTN-MANETs in the presence of available energy resources by improving the lifetime and the communication capability of the individual nodes.

6.3 IMPACT OF MESSAGE PRIORITIZATION

Understanding the impact of message prioritization

The goal of this evaluation is to assess the impact of message prioritization in DTN-MANETs, which is described in Section 5.3 while considering the specific dynamics of the post-disaster communication characteristics. Our architecture (cf. Section 5.3.2) is used to observe the interactions between different prioritization algorithms and the communication behavior in DTN-MANETs. As described at the beginning of this chapter, we use the common simulation setup and parameter settings summarized in Table 1. We extend this setup with routing and workload components, which are necessary for the evaluation of the D2CS.KOM prioritization after we evaluate the influence of different prioritization algorithms.

6.3.1 *Scenario Model*

Compared to the evaluation of the resource allocation service of D2CS.KOM in Section 5.2, a communication workload and message routing need to be included in the simulation scenario to evaluate the impact of message prioritization. The additional simulation parameters are summarized in Table 4 and will be explained in the following.

Table 4: Simulation parameters in addition to Table 1, necessary for the evaluation of the message prioritization.

Simulation duration [hours]	3.5
Routing protocol	*Epidemic Routing* [267]
Beaconing interval [sec]	15
Maximum sending capacity per node [msgs/minute]	10
Message generation distribution per node	cf. Figure 43
Message types (in prioritization order)	*Emergency, Warning, Alive*
Message addressing	Broadcast
Message TTL [min]	12
Prioritization algorithms	*None, Static, Adaptive*
Message trend window size [min]	20

Based on prior knowledge-sharing, we use *Epidemic Routing* [267] as the DTN-MANET routing protocol in our simulations. With *Epidemic Routing* two nodes first exchange their *summary vectors* to determine the messages unknown, before exchanging new messages. Additionally, each node maintains a cache of nodes it has already exchanged data with to avoid unnecessary *summary vector* exchanges in the future. The cache and message storage of the nodes are assumed to be unlimited, due to the sufficient storage capacity of common smartphones [142]. The protocol uses a beaconing interval of 15 s for the neighborhood discovery procedure. To reflect the insufficient bandwidth in the post-disaster communication network, the capacity of the DTN-MANET is limited in terms of the number of messages each node is capable of sending in a specific time period. This way, we can directly control the scarcity of communication resources by defining a workload that results in the number of messages being created by the nodes. Each node can send 10 messages every minute, and nodes are generating messages of different types following the message type workload distribution shown in Figure 43. To mimic the post-disaster communication characteristics, we vary the frequency of the three different message types *Emergency*, *Warning* and *Alive* over time as discussed in Section 5.3.1.

Limited network resources

Post-disaster workload

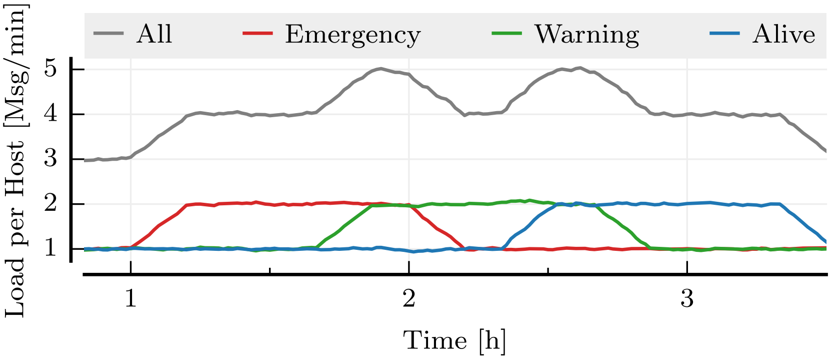


Figure 43: Number of generated messages for different message types for each node over time [140].

Messages have a TTL of 12 minutes and are sent out as broadcast messages, with the goal to reach as many network participants as possible. We have deliberately chosen a short TTL, to demonstrate and visualize the impact of the different prioritization mechanisms on the message propagation more explicitly. We compare three different prioritization mechanisms: *None*, *Static*, and *Adaptive*, as described in Section 5.3. For the *Adaptive* prioritization, we use a 20 minute window size to detect message trends based on the generated and received messages by a node.

None, Static, and Adaptive prioritization

For simplicity, all generated messages have the same size in our simulations – however, the size of a message is an important factor for the message prioritization under network limitations, especially when considering low-bandwidth and long-range communication links to interconnect communication islands. Therefore, we additionally conducted a Line of Sight (LOS) field test experiment with long-range communication devices to demonstrate the positive effects of message-size data prioritization (cf. Section 5.4). By favoring smaller messages over larger messages for the utilization of a 4 km long communication link with an available bandwidth of 1 kB/s, we showed that the delivery delay of prioritized messages was reduced to less than one minute compared to one hour if no prioritization was applied. The interested reader can find detailed information and results of the experiment in [135].

6.3.2 *Evaluation of Prioritization Algorithms*

Prioritized message propagation

The goal of message prioritization is to enable communication in resource-restricted and overloaded DTN-MANETs. We are considering the recall of the broadcast message propagation as an indicator of the performance of the DTN-MANET. Figure 44 shows the achieved recall for the three different prioritization algorithms *None*, *Static* and *Adaptive*. Unsurprisingly the box-plots show that the recall is similar for the three different message types if no prioritization (*None*) is applied. On average, messages reach approximately 65 % of the network nodes, with more than 75 % of all messages reach at least half of the network participants. The results show the saturation of the DTN-MANET communication capacity and the overload situation, while older messages are less forwarded by the nodes because new messages are inserted on top of their message storage. This behavior limits the propagation of older messages in the network and therefore, the achievable recall.

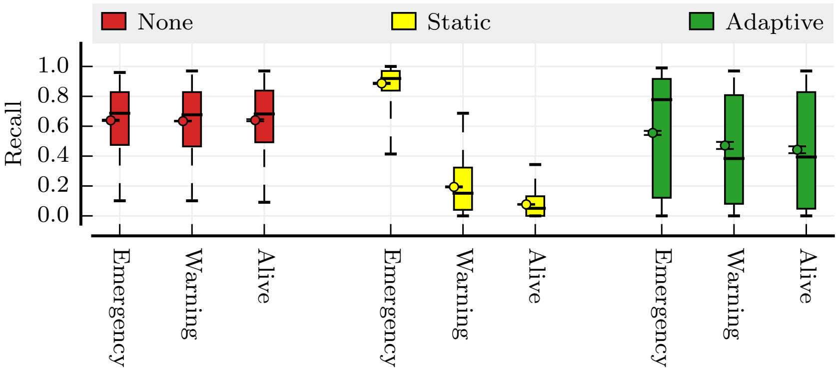


Figure 44: Recall for the different prioritization algorithms *None*, *Static*, and *Adaptive* [140].

Prioritization order

The *Static* prioritization algorithm reorders the node's message storage with a predefined prioritization order. Messages of the type *Emergency* are assigned with the highest priority, then the type *Warning* and the lowest priority have messages of the type *Alive*. The impact of the *Static* prioritization on the message recall is significant, as favored messages counteract the network saturation effect described earlier. This results in a weakened propagation of low-priority messages. High prioritized messages reach a mean recall of 0.9, with more than 75 % of messages reach at least 80 % of all nodes. These recall values for the prioritized message type also shows that the communication capabilities of the DTN-MANET can disseminate messages network-wide via the store-carry-forward principle made possible by the movement of the nodes. As already mentioned, this recall amplification comes with the costs of a low recall below 0.2 for messages with lower priority. These messages cannot spread in the network since all available communication capacities are occupied. To gather more insight into the actual impact of the *Static* prioritization on the DTN-MANET, we need to analyze the network performance of the message dissemination over time. Figure 45 shows the recall of the individual messages a colored dots throughout the simulation scenario. With this additional information, we can deduct that *Static* prioritization favors duplicates and outdated information of high prioritized messages over newer and potentially more relevant messages of other types. Even though there are less high prioritized *Emergency* messages generated by the network nodes after approximately 2.5 hours (cf. Figure 28), they still significantly interfere with the propagation of other message types.

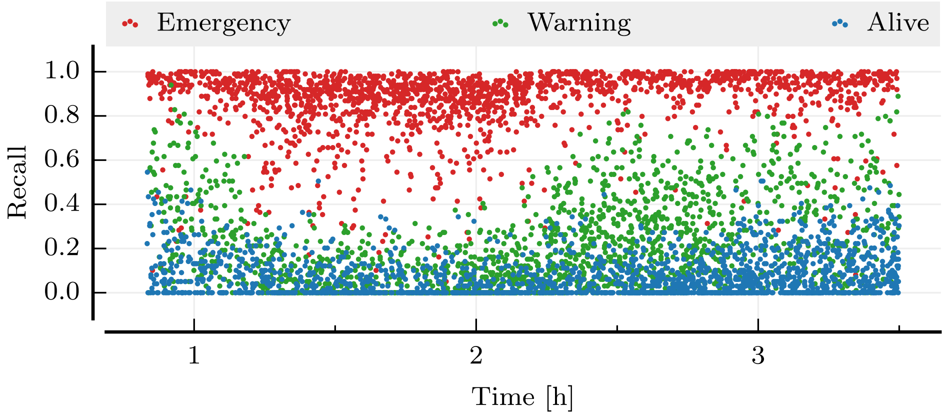


Figure 45: *Static Prioritization*: Recall per individual message [140].

This impact can be observed in Figure 46, which shows the average message load of the individual nodes for the different types. The illustrated load is subdivided in messages that the nodes are willing to send (WS) and messages that were actually sent (AS) by the nodes regarding the maximal sending capacity of ten messages per minute. For the overall simulation duration, the number of *Emergency* messages that the node is willing to send, exceeds the nodes sending capacity (*Emergency* (WS)) and only a few new messages of other types are forwarded. This observation confirms the identified impact of long-living duplicates of high prioritized messages when *Static* prioritization is utilized.

Overloaded network conditions

The *Adaptive* algorithm performs in between the two other prioritization approaches with highly skewed recall values for the different message types, as shown in Figure 44. This is a result of the changing prioritization order defined by each node, based on the detected message trends in the DTN-MANET data flow. To understand the impact of the *Adaptive* prioritization on DTN-MANET, we also need to look at the more detailed communication characteristics over time.

If we look at the individual message recall in Figure 47 and the stored messages that the nodes are willing to send (WS) and were actually sent (AS) in Figure 48 we can clearly see that the message type with the highest recall values and the utilized

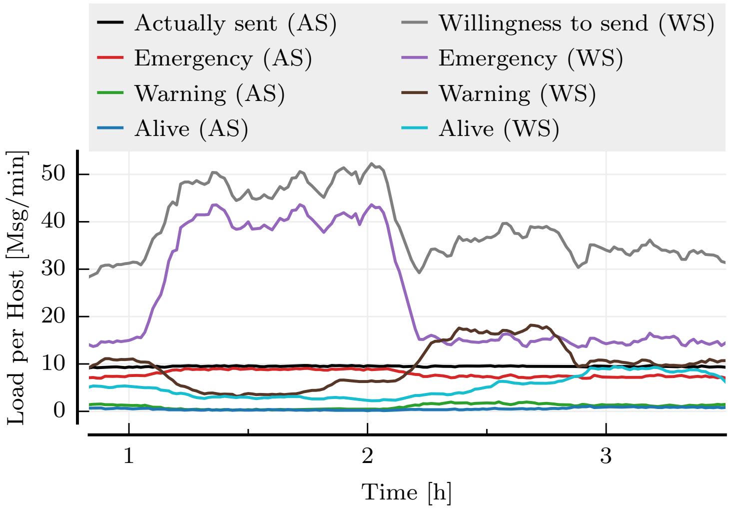


Figure 46: *Static Prioritization*: Message load over time [140].

bandwidth of the nodes follows the applied workload (cf. Figure 43) with the time-shifted message type trends.

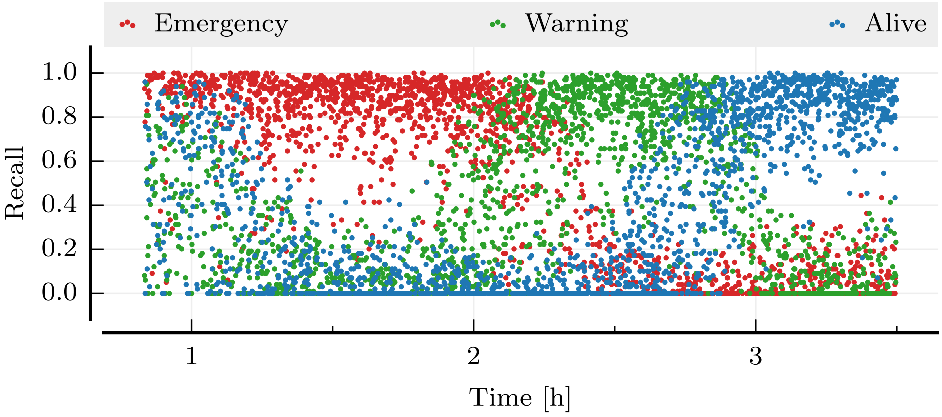


Figure 47: *Adaptive Prioritization*: Recall per individual message [140].

Adapt to communication behavior

Additionally, *Emergency* messages have the highest recall in the first hour of the simulations because nodes fall back to the static prioritization order if two or more message type have the same rank. This occurs because the different message types are generated equally at the beginning of the simulation (cf. Figure 43), and the amount of spread messages and generated duplicates in the network are still low.

The ability of the *Adaptive* prioritization to correctly detect message trends in the networks data flow in a decentralized fashion, results in undesired impacts on the communication capabilities of the DTN-MANET. It can be observed that *Adaptive* prioritization prevents critical information (such as *Emergency* messages) to be spread in the network when other message trends are currently detected and prioritized by

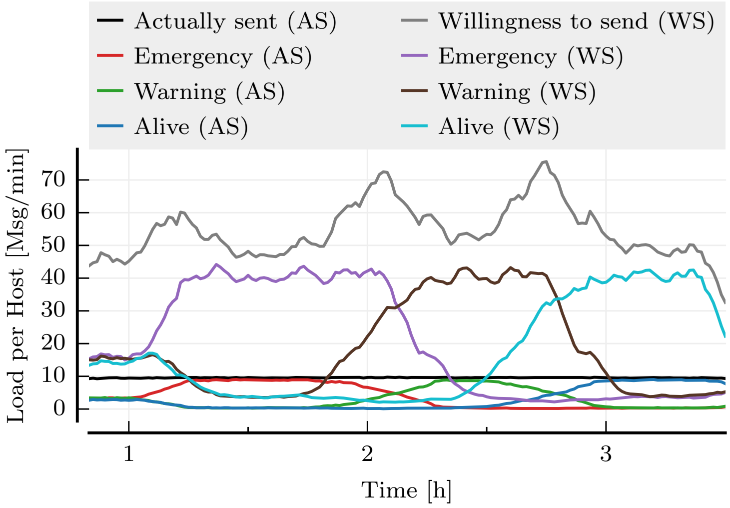


Figure 48: *Adaptive Prioritization*: Message load over time [140].

the nodes. Figure 48 reveals an increased amount of the overall buffered messages (WS) by the nodes compared to the *Static* prioritization in Figure 46. The increase of buffered messages per node results from the fact that the DTN-MANET nodes are not able to reach a consensus of the prioritization order based on the trending message types. Most likely different prioritization orders are calculated based on the generated messages in the node's nearby region, and therefore a higher amount of messages are spread in the network, while fewer duplicates are generated. The applied 20 minute time window for the detection of trending message types can also be recognized in Figure 48 as the delay until the most common message type in the traffic is prominently visible in the buffered (WS) and actually sent (AS) messages.

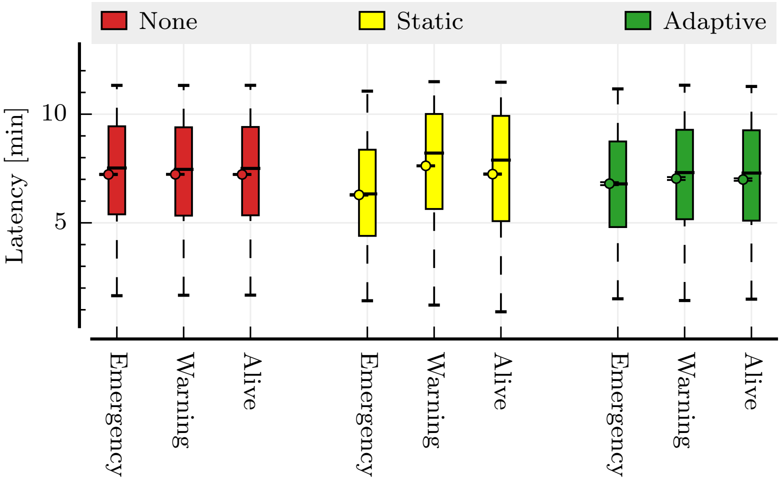


Figure 49: Message latency for the different prioritization algorithms *None*, *Static* and *Adaptive* [140].

Regarding the influence of the different prioritization algorithms on the message dissemination latency, shown in Figure 49, we can observe that the algorithms only have a minor impact on the data dissemination speed and that in some cases the dissemination of the messages requires the full TTL. As expected, no difference in the message delay is observable with no prioritization applied. Only *Static* prioritization achieves a reduced message latency for the highest prioritized message type compared to the two other prioritization algorithms. At the same time, the delay of the other message types is worsened compared to the other algorithms. As already mentioned, favoring typical messages in resource-constrained and overloaded communication networks always results in a trade-off, for example, by penalizing the propagation or delaying other messages.

In this evaluation, we studied the implications of messages prioritization in resource restricted DTN-MANETs for post-disaster communication as part of D2CS.KOM. Based on the findings of the conducted field test and a survey of post-disaster communication characteristics in Chapter 4, we evaluated our proposed prioritization architecture. Our architecture allows prioritization algorithms to access scenario-specific meta-information, such as the message type, provided by the respective mobile application, potentially including further contextual information. The architecture includes three different example prioritization algorithms to gather insights into the potential dependencies and potentially undesired interactions between prioritization and the DTN-MANET communication capabilities. We showed that the *Static* prioritization leads to the delay of urgent message types that are trending in the network and instead amplifying the propagation of outdated or duplicate information. On the contrary, when the prioritization algorithm supports the detection of message trends in the data flow, it prevents the propagation of urgent messages, which do not correspond to the majority of the created messages in the network. These findings result in the necessity for further research on adaptive and scenario-specific prioritization algorithms. These should consider type-, content- or context-specific TTLs to reduce the occupied network capacities caused by outdated message duplicates.

The proof of concept evaluation successfully demonstrates the usefulness of our prioritization architecture, which decouples the message storage and its manipulation from the utilized DTN-MANET routing protocol, to assess the impact of different prioritization mechanisms, and to develop new suitable prioritization mechanisms for the specific needs of post-disaster communication.

6.4 IMPACT OF UAV-BASED SUPPORT STRATEGIES

The goal of this evaluation is to showcase the various possibilities of UAV support strategies in DTN-MANETs, one of the core functionalities of D2CS.KOM. Via simulations, we assess the capabilities of UAV-based support strategies for various post-disaster DTN-MANET scenarios to ensure an efficient and adequate deployment of UAVs depending on the current situation. After a short description of the integration of the UAV functionality in our simulation framework, we are conducting simulations in two representative scenarios. First, we compare the support capabilities of the different support strategies, described in Section 5.4, using an urban simulation scenario with different degrees of ground node movement between different communication islands. The second part of the evaluation focuses on the data ferry strategy in an exact replication of the conducted field test, based on Chapter 4. In this scenario, we are investigating the effect of different numbers of utilized UAVs and message TTLs on the DTN-MANET communication performance. We determine the adequate number of deployed UAVs, which are necessary to deliver messages within their TTL to the overall network. Here, the number of UAVs reflect the saturation point at which the additional utilization of more UAVs no longer yields to a significant performance gain.

6.4.1 *Scenario Model*

Replication of UAV behavior

To be able to evaluate the support strategies, we needed to ensure the replication of UAV behavior in our simulation platform. We extended the SIMONSTRATOR.KOM simulation platform by the following required UAV components based on an extensive state-of-the-art study in [141]: *i)* actuators such as different motors and rotors, *ii)* battery and energy consumption states, *iii)* an autopilot using a three-dimensional movement model, and *iv)* a strategy controller that allows the realization of specific behavioral patterns, like the presented support strategies or the return flight maneuver to the base-station when the battery runs out of energy. Together with the communication and sensor functionalities inherited from the DTN-MANET nodes, the combination of these components can be used to entirely configure and simulate a realistic representation of UAVs within our simulation platform. Besides the possibility to simulate UAVs, we included the simulation of a base-station that provides the necessary infrastructure for the battery recharging or battery replacement and landing pads for the UAVs. A detailed description of the design of the simulation platform consisting of all UAV components, their interactions, and configurations can be found in [141].

Urban Scenario with Communication Islands

The parameters for the urban simulation scenario are summarized in Table 5 in addition to the basic simulation parameter settings in Table 1. In an inter-city environment (4 km^2), 100 DTN-MANET nodes move as pedestrians on walkways and choose one out of five important locations, such as a market place or a hospital, as their next target. These locations represent the center of the different communication islands, while the pause time determines the duration nodes stay at these locations. The pause time is mainly responsible for the inter-island communication achieved by the DTN-MANET itself. With shorter pause times, the message transfer between communication islands improves, while longer pause times result in the isolation of the communication islands. In this scenario, we are investigating three different pause time values (∞ results in no movement, 5–300 min and 60–300 min) to simulate

Isolated communication islands

different degrees of inter-island movement within the DTN-MANET. In the network, every ten seconds, a random node generates a broadcast message with a TTL of 30 minutes, which should reach as many nodes as possible. As in any simulation in this thesis, we use 10 different seeds for each simulation to alternate the movement and the workload generation.

UAV capabilities

Acquired from the state-of-the-art analysis in [141], the simulated UAVs can operate 20–25 min, achieve a maximum speed of 15 m/s and operate in 30 m height. For the simulations, we apply battery replacement, which takes 60 s instead of recharging. The relay mesh strategy can utilize up to 200 UAVs, while they operate in a 150 m distance to each other in the air. This distance ensures that every DTN-MANET node is always in reach of at least one UAV. The data ferry strategy maximizes the number of UAVs simultaneously in the air while guaranteeing a replacement UAV at the base station at all times. UAVs leave the base station in such a way that they are evenly distributed over the flight path. For the data exchange, UAVs hover for 30 s over the center of each communication island, whose locations are known in advance.

Table 5: Simulation parameters for the urban scenario in addition to Table 1, necessary for the UAV support strategy evaluation.

Simulated Time [hours]	5
Movement	Social movement [215] with 5 communication islands
Pause Time at POI [min]	∞ (no movement), 5 − 300, 60 − 300
Message TTL [min]	30
UAV Flight Time [min]	20 − 25
UAV Speed [m/s]	15
UAV Flight Altitude [meter]	30
UAV Battery Replacement [sec]	60
Network Workload	1 broadcast message every 10 seconds
Relay Mesh Strategy	200 UAVs, 150 meter mesh distance
Data Ferry Strategy	10 UAVs, 30 seconds hover time

Replication of the Field Test Scenario

Repeat the field test in simulations

The second simulation scenario is a replication of the conducted field test described in Chapter 4. Figure 50 shows a screenshot of the simulation visualization of the field test area, the DTN-MANET nodes, and the three different villages. The scenario contains the underlying map of the field test area and the movement patterns of 119 participants between the three different villages. Based on the recorded movement traces during the field test, nodes need approximately 12 min to walk from Village B to Village C and 50–70 min to walk from Village C to Village A since there are no direct walking paths between them.

Flight time between villages

As indicated in Figure 50, UAVs fly directly between villages on the shortest paths. This results in flight durations of 45 s between Village B and Village C, 4.4 min between B and A, 4.1 min between A and C and 18 s between Village C and the base-

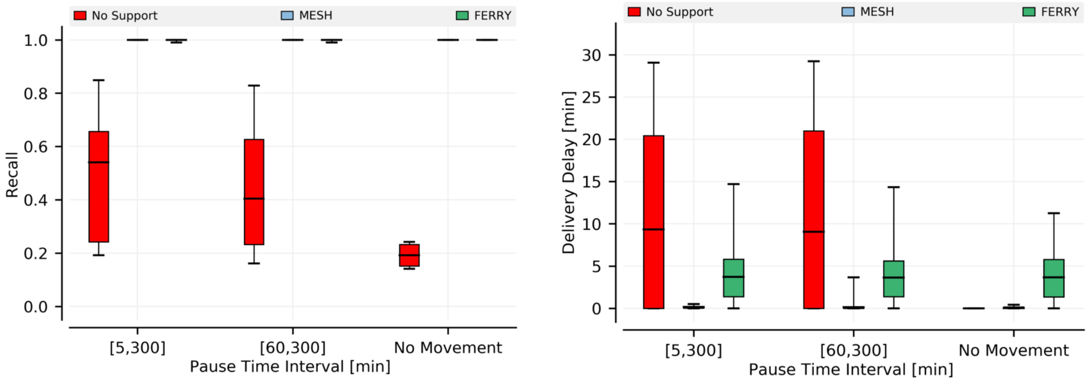
Figure 50: The field test environment from Chapter 4 with an additional UAV base station located near Village C and nodes as black dots (OpenStreetMap) [141].

station. The communication workload in the network generated by the DTN-MANET nodes is considered to be the same as in the urban scenario (cf. Table 5). In the field test scenario, we are solely focusing on the evaluation of the data ferry strategy with varying number of available UAVs (0 to 20) and different TTLs (10, 30 and 60 minutes) for the broadcast messages, since the applicability of the mesh relay strategy is only given with a much higher number of available UAVs. Since the resulting flight time to visit all three villages in combination with the additional hover time consumes more than 53 % of the UAV's battery capacity, UAVs are not able to complete more than one cycle in the given scenario. UAVs return to the base-station after visiting Village C, B and A consecutively, for a 60 s battery replacement procedure.

6.4.2 *Evaluation of UAV-based Support Strategies*

First, we evaluate the different support strategies applying the urban scenario to compare the strategies with each other and demonstrate the potential of UAV support for DTN-MANET communication. The evaluation results for the urban simulation scenario are shown in Figure 51 containing the recall and delivery delay without any UAV support (No Support), for the relay mesh strategy (MESH) and the data ferry strategy (FERRY). The x-axis shows the variations of different pause times, influencing the node movement between the communication islands.

It can be observed that the unsupported DTN-MANET is behaving as expected, regarding the recall values in Figure 51a, comparable to the recorded data from the real field test in Chapter 4. With higher node pause times at the five different communication islands, the recall of the message propagation drops. This behavior is caused by fewer encounters and message exchanges with other nodes until a point where messages are only distributed in the communication island of origin with almost no delivery delay. While simulating five different communication islands, the message recall increases on average by 0.2 if the messages are reaching a new island. The simulation results demonstrate that it is impossible with the unsupported DTN-MANET to a reach all communication islands to achieve network-wide message dissemination within a message TTL of 30 min.



(a) Recall. (b) Delivery delay.

Figure 51: Performance of the DTN-MANET without UAV support compared to the relay mesh strategy and the message ferry strategy [141].

High recall with UAV support ...

The relay mesh strategy achieves a perfect recall and very low delivery delays independent of the nodes pause times. In some cases, the message delay can take several minutes caused by packet collision during the message propagation in a dense communication island.

... and fast message delivery

The data ferry strategy is taking advantage of the fast movement of the UAVs to distribute messages between intermittent communication islands while utilizing only a fraction of the required number of UAVs compared to the relay mesh strategy. The data ferry strategy is also able to propagate all messages to all DTN-MANET nodes in almost any cases within their message TTL. Since the UAVs' maximum movement speed is limited to 15 m/s, the resulting message delay is, with a median value of below 5 min, higher compared to the relay mesh strategy while still improving the delay significantly compared to the unsupported DTN-MANET. When nodes move between islands, it occurs that some isolated nodes cannot be reached by the data ferries. This is a result of the shortest path movement of the UAVs, which not necessarily matches the nodes' movement that is bound to the underlying map. The time to deliver or receive messages of these nodes increases, until they either reach a communication island, are in the range of a UAV or meet other nodes in between communications islands.

We conclude that the relay mesh strategy outperforms the data ferry strategy in terms of the support performance of the DTN-MANET communication on the ground in both recall and delivery delay. Since the relay mesh strategy is evaluated to show the best possible communication support regardless of the necessary number of utilized UAVs, the strategy is over-supporting the considered area, especially in sparsely frequented areas where no communication is taking place. As the number of utilized UAVs is mainly responsible for the whole support system's costs in acquisition and maintenance, it also influences the amount of the required infrastructure at the base-station such as the required landing pads, charging stations or the required power sources. The efficient utilization of UAVs is, therefore, an essential aspect for suitable communication support strategies. In contrast, the data ferry strategy requires only 10 compared to 200 UAVs for the same area and focuses explicitly on the movement-based data dissemination between communication islands. For practical real-world applications, the efficient and adequate utilization of available UAVs is essential. Therefore, we want to obtain the performance gain per additionally utilized UAV on the DTN-MANET, regarding the recall and the message delay.

In the next step, we evaluate the message ferry strategy using the field test replication, including three different communication islands, while alternating the number of deployed UAVs and different message TTLs.

Impact of the number of UAVs ...

... and the message TTL

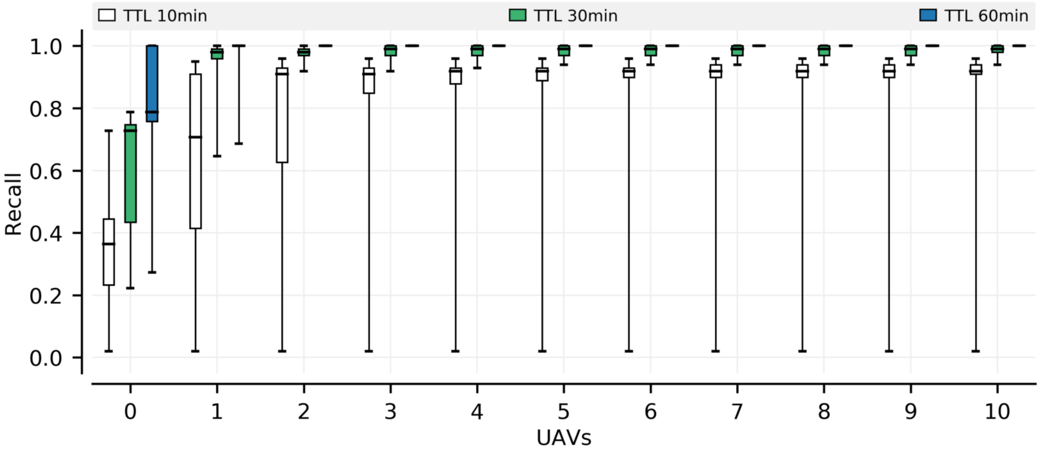
Figure 52 presents the results for the recall and the message delay, for up to 10 data ferries. Even though we analyzed the support potential for up to 20 UAVs, more than 10 UAVs resulted in no further noticeable changes and are not displayed in Figure 52. With no UAVs support, it can be observed that the movement of the nodes themselves is not sufficient for network-wide data dissemination if low message TTLs are applied. The limited data dissemination caused by a 10 min TTL again comes along with very low message delays inside the communication island of the message origin, as already observed in the urban scenario (cf. Figure 51b). With an increasing message lifetime the inter-island communication improves, resulting in a median recall value of 0.7 and 0.8 with a 30 min and 60 min TTL, respectively.

The operation of only a single UAV already results in a major improvement of the achieved recall values independent of the applied TTL. Especially with a TTL of 30 and 60 min, an almost optimal recall value can be achieved. The delivery delay at the same time slightly increases for the two lower TTL values, since more nodes are now reached through the movement of the UAV that needs approximately 12 min for a round-trip between the three communication islands including the hovering phase and battery replacement. At the same time, the delay of messages with a TTL of 60 min improves slightly with the utilization of one UAV, since the data dissemination already achieves a median recall value of approximately 0.8 solely by the movement of the nodes on the ground.

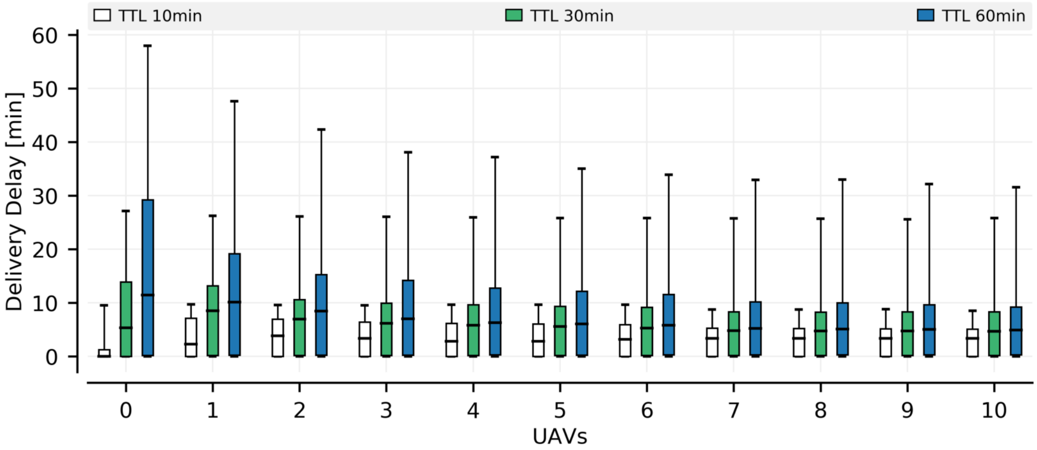
For the considered scenario, the additional deployment of more than one UAV consecutively increases the recall while reducing the message delay with decreasing intensity. The decreasing influence of the communication capability improvements by additional UAVs is caused by the fixed flight route, since more UAVs only result in higher frequencies of islands overflights while the round-trip time stays the same. More UAVs lead to a saturation of the support capabilities and represents the preferable number of utilized UAVs for meaningful, sufficient, and adequate application of the support strategy.

Required support strategy parameters

The ability to determine, for example, the UAV saturation point, can further be used to design and plan UAV-based communication support systems for specific scenarios and application areas. If the locations of the communication islands as well as the message TTL are known to the UAV operators, simulations scenarios, as presented in this section, can determine the required support strategy parameters. Taking the field test replication as an example, 2 UAVs are sufficient to achieve the



(a) Recall.



(b) Delivery delay.

Figure 52: Performance for an increasing number of UAVs with message TTLs of 10, 30 and 60 minutes [141].

highest recall when a 60 min TTL is applied in the DTN-MANET. Additional UAVs result in lower message delays up to the utilization of 7 UAVs, achieving a message delay of less than 10 min for approximately 75 % of the overall generated messages. Furthermore, simulation results can be used to identify possible improvements for UAV-based support strategies. For example, by observing the lower whiskers in Figure 52 of the recall values for a TTL of 10 min we can see that the TTL is not sufficient for the given scenario and the considered area, no matter how many UAVs are utilized. It happens that nodes generate messages outside of a communication island and never meet other DTN-MANET nodes or UAVs before the messages expire. This observation shows, one the hand, that the message TTL should be configured depending on the area of the disaster communication network and, on the other hand, shows potential improvements of more sophisticated UAV-based communication support strategies. The proposed UAV simulation platform and the different simulation scenarios are at this moment a perfect foundation for further research focusing on, for example, the detection and integration of isolated DTN-MANET nodes in the post-disaster communication network.

In this evaluation, we successfully demonstrated the positive impact and the high support capabilities by utilizing UAVs to bridge intermittent communication islands to enable inter-island communication. We considered different scenarios to showcase the impact of the UAV support strategies in different environments. One of the scenarios was a replication of the performed field test (cf. Chapter 4), allowing us to evaluate how using varying numbers of UAVs impacts the DTN-MANET communication on the ground. The evaluation results of the two example support strategies, relay mesh, and data ferry, further demonstrate the diverse application possibilities dependent on the available UAVs and the considered disaster area. Simulation results also serve as an indicator for the specification of suitable message TTL values. The TTL should be kept as low as possible and still provide high recall values to limit the number of message duplications and to eliminate outdated copies, reducing the nodes buffer occupancy and the overall load in the network.

Overall, the results of the evaluation presented in this chapter show the positive impact of D2CS.KOM on post-disaster communication by improving upon decentralized, infrastructure-independent communication. We evaluated the three core components of D2CS.KOM that allow the system to *i)* facilitate and allocate available resources, *ii)* support information selection and prioritization, and *iii)* provide communication support strategies. The results will be summarized and discussed in the next chapter before we conclude the thesis.

7

SUMMARY, CONCLUSIONS, AND OUTLOOK

Communication is key for successful emergency response and disaster relief efforts. At the same time, communication systems are often unavailable or overloaded during and after a disaster, as a consequence of infrastructure failures. Providing dedicated and scenario-specific infrastructure-independent communication systems is essential to support and utilize the self-help and coordination potential of the affected population. In this chapter, we summarize our work, highlight the main contributions, and discuss potential future work.

7.1 SUMMARY OF THE THESIS

In Chapter 1, we described how modern societies are dependent on critical infrastructures and highlighted the significant challenges which arise when communication technologies are unavailable due to infrastructure failures. We explained the intention behind the usage of smartphone-based Delay Tolerant and Mobile Ad Hoc Networks (DTN-MANETs) to create infrastructure-independent post-disaster communication networks, as described in Chapter 2. We studied and discussed existing mechanisms that address the dynamics and characteristics of DTN-MANETs in the absence of Critical Infrastructures (CIs) in combination with disaster-specific user behavior in Chapter 3. Based on our study of disaster reports, we identified three essential scenario-specific aspects: *i)* prolonging the network lifetime, *ii)* overcoming network resource restrictions, and *iii)* enabling network-wide data dissemination. In the following, we summarize our contributions and discuss how they address the identified scenario-specific challenges.

7.1.1 *Contributions*

Large-scale field test

To quantify the scenario-specific characteristics of DTN-MANETs in post-disaster scenarios, we planned and conducted a large-scale field test, as discussed in Chapter 4. We evaluated the recordings from the field test to prove the real-world applicability of DTN-MANETs and to gain insights into user behavior, focusing on the users' utilization of the communication system and their social interactions. In Chapter 5 we introduced the Decentralized Disaster Communication System (D2CS.KOM) that extends conventional DTN-MANETs with disaster-specific mechanisms to: *i)* facilitate and allocate available resources, *ii)* support information selection and prioritization, and *iii)* provide communication support strategies.

D2CS.KOM

We focused on the distribution of energy resources to prolong the lifetime of the individual communication nodes and consequently of the overall DTN-MANET, in a fully decentralized manner. We designed, analyzed, and evaluated the impact of dif-

Resource allocation strategies

ferent cooperative and non-cooperative allocation strategies on the DTN-MANET's lifetime and communication capabilities. We propose a cooperative resource allocation strategy, named Ad Hoc On-demand Reservation Vector Auction (AORVA), that communicates via the DTN-MANET to propagate and reveal the nodes' states and decisions to communication neighbors. With this information exchange, we avoid over-competition in the network and reduce unsuccessful charging attempts.

Prioritization architecture

To tackle the scenario-specific combination of high and at the same time continuously changing communication demands after a disaster, we proposed a prioritization architecture. As part of D2CS.KOM, the prioritization architecture allows us to identify and favor disaster-relevant messages in the network. Within our architecture, we implemented static and adaptive prioritization algorithms and analyzed their impact on the communication network under scenario-specific workloads.

UAV-based support strategies

Since network-wide communication in DTN-MANETs is hindered by potentially insufficient node movement, we studied the support capabilities of UAVs on the communication capabilities of DTN-MANETs. We demonstrated the versatile application of UAV support in two different strategies and presented their impact on the network performance in both, an urban scenario and in the field test replication.

7.1.2 *Conclusions*

Disaster models

We conducted an extensive analysis of the sensor and network data recorded in the field test to assess disaster-specific user behavior including communication characteristics and to confirm our assumptions based on reports of past disasters. We identified challenges for post-disaster communication that were successfully addressed by D2CS.KOM. We extracted user and communication parameters from the field test recordings and transferred them to our simulation platform, thus reproducing the users' behavior. This was necessary to evaluate the applicability, impacts, and limitations of D2CS.KOM under realistic conditions. Therefore, we integrated the aforementioned components into our simulation framework to evaluate the overall system. In our evaluations, we successfully showed that the decentralized resource allocation in DTN-MANETs prolongs the nodes' lifetime and, consequently, the lifetime of the overall network. Our proposed allocation strategy AORVA successfully utilizes the communication capabilities of the network and can allocate scarce energy resources in post-disaster networks without the support of any central infrastructure. By prolonging the communication possibilities of the affected population, we make a significant contribution to the disaster relief efforts.

Prolonging the network lifetime

Overcome network resource restrictions

In addition, we showed the implications of message prioritization in resource restricted DTN-MANETs when different disaster services, such as *SOS messages* or *I'm alive notifications*, were used by the network participants. We evaluated our proposed prioritization architecture that utilizes scenario-specific meta-information of the disaster workload, such as the most trending message type. Our evaluation results demonstrated the dependency between different message prioritization algorithms and the DTN-MANET communication capabilities. We identified undesired interactions of prioritization mechanisms that can detect message trends in the constantly changing communication demands in the network compared to a static prioritization approach. The prioritization architecture improves the message propagation of disaster-relevant messages by reducing the network capacities occupied by outdated or irrelevant messages.

To ensure network-wide dissemination, we studied the applicability of UAV-based communication support strategies on intermittent post-disaster DTN-MANETs. UAVs significantly improve the communication capabilities of the DTN-MANET by allowing messages to reach more network nodes and by reducing the delay until messages reach their destination. We investigated the different effects of varying numbers of UAVs, based on a simulation model derived from the field test, which allows the design and evaluation of efficient scenario-specific support strategies.

Enable network-wide data dissemination

7.2 OUTLOOK

Our results build the foundation for further research in the area of post-disaster communication. We provide the ability to represent and simulate communication networks in post-disaster scenarios, including node behavior and node interactions, based on generalized findings from a large-scale field test. Such simulations allow the verification of new and existing approaches to identify their effect on the communication, and to assess their applicability in infrastructure-independent post-disaster communication networks. To further improve the post-disaster representation, more findings from the field test measurement can complement the simulation platform, such as realistic representations of post-disaster communication workloads or the integration and generalization of social media activities [92] during disasters.

Post-disaster communication workloads

In this thesis, we demonstrated the significant impact of the utilization of UAVs on the communication capabilities in DTN-MANETs. UAV-based communication support is, therefore, a promising field of research, with high potential for further improvements for infrastructure-independent communication networks. To enable reactions to network changes, UAVs or DTN-MANET nodes on the ground could monitor the current network state in a decentralized fashion [168, 201, 211, 245, 247]. Access to additional information about the network state can be used by the UAVs in various potential ways: *i)* to optimize the UAVs' flight routes and react to network changes, *ii)* to detect and support isolated DTN-MANET nodes, *iii)* to implement UAV-based message prioritization, or *iv)* to detect new energy resources to support resource allocation strategies.

Adaptive UAV-based support strategies

The findings and methods outlined in this thesis incite new and exciting research questions, many of which are now to be tackled in the LOEWE funded Research Center *emergenCITY* – the resilient and digital city. The cooperation with global partners and a team of interdisciplinary researchers ensures that this field of study will continue to develop and evolve.

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BIBLIOGRAPHY

[1] Ejaz Ahmed and Hamid Gharavi. "Cooperative Vehicular Networking: A Survey." In: *IEEE Transactions on Intelligent Transportation Systems* 19.3 (2018), pp. 996–1014.

[2] Amro Al-Akkad, Leonardo Ramirez, Alexander Boden, Dave Randall, and Andreas Zimmermann. "Help Beacons: Design and Evaluation of an Adhoc Lightweight S.O.S. System for Smartphones." In: *CHI*. Toronto, Ontario, Canada: ACM, 2014, pp. 1485–1494.

[3] Ian F Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. "Wireless Sensor Networks: A Survey." In: *Computer networks* 38.4 (2002), pp. 393–422.

[4] Marwan Albahar. "Cyber Attacks and Terrorism: A Twenty-first Century Conundrum." In: *Science and engineering ethics* (2017), pp. 1–14.

[5] David E Alexander. "Social Media in Disaster Risk Reduction and Crisis Management." In: *Science and engineering ethics* 20.3 (2014), pp. 717–733.

[6] Hassan Haes Alhelou, Mohamad Esmail Hamedani-Golshan, Takawira Cuthbert Njenda, Pierluigi Siano, et al. "A Survey on Power System Blackout and Cascading Events: Research Motivations and Challenges." In: *Energies* 12.4 (2019), pp. 1–28.

[7] Salman Ali, Junaid Qadir, and Adeel Baig. "Routing Protocols in Delay Tolerant Networks - A Survey." In: *2010 6th International Conference on Emerging Technologies (ICET)*. IEEE. 2010, pp. 70–75.

[8] Virgil Del Duca Almeida, André B. Oliveira, Daniel F. Macedo, and José Marcos S. Nogueira. "Performance Evaluation of MANET and DTN Routing Protocols." In: *Proceedings of the IFIP Wireless Days (WD)*. 2012.

[9] Flor Álvarez, Lars Almon, Patrick Lieser, Tobias Meuser, Yannick Dylla, Björn Richerzhagen, Matthias Hollick, and Ralf Steinmetz. "Conducting a Large-scale Field Test of a Smartphone-based Communication Network for Emergency Response." In: *Proceedings of the 13th Workshop on Challenged Networks*. ACM. 2018, pp. 3–10.

[10] Flor Álvarez, Max Kolhagen, and Matthias Hollick. "Sea of Lights: Practical Device-to-Device Security Bootstrapping in the Dark." In: *2018 IEEE 43rd Conference on Local Computer Networks (LCN)*. Chicago, USA, Oct. 2018.

[11] Bo An, Victor Lesser, David Irwin, and Michael Zink. "Automated Negotiation with Decommitment for Dynamic Resource Allocation in Cloud Computing." In: *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1*. International Foundation for Autonomous Agents and Multiagent Systems. 2010, pp. 981–988.

[12] Lin Liangxun Wu Naigeng Cai Anan and Zhuang Xudong. "Disaster and Emergency Response of the Cryogenic Freezing Rain and Snow Weather in Guangdong in 2008 [J]." In: *Meteorological Monthly* 5 (2009), p. 005.

[13] Alex M Andrew. "Another Efficient Algorithm for Convex Hulls in Two Dimensions." In: *Information Processing Letters* 9.5 (1979), pp. 216–219.

[14] Carmela Aquino. *After the Quake: Mobile Internet Use Soars in Wake of Japan Crisis*. Mar. 2011. URL: `http://www.comscore.com/Insights/Blog/After-the-Quake-Mobile-Internet-Use-Soars-in-Wake-of-Japan-Crisis` (Last accessed on July 1st, 2019).

[15] Nils Aschenbruck, Raphael Ernst, Elmar Gerhards-Padilla, and Matthias Schwamborn. "BonnMotion: A Mobility Scenario Generation and Analysis Tool." In: *Proceedings of the 3rd international Conference on Simulation Tools and Techniques (SIMUTools)*. Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering (ICST). 2010, p. 51.

[16] Nils Aschenbruck and E Gerhards-Padilla. "A Survey on Mobility Models for Performance Analysis in Tactical Mobile Networks." In: *Journal of Telecommunications and Information Technology* 2 (2008), pp. 54–61. ISSN: 13891286.

[17] Nils Aschenbruck, Elmar Gerhards-Padilla, Michael Gerharz, Matthias Frank, and Peter Martini. "Modelling Mobility in Disaster Area Scenarios." In: *MSWiM*. Chania, Crete Island, Greece: ACM, 2007, pp. 4–12.

[18] Nils Aschenbruck, Aarti Munjal, and Tracy Camp. "Trace-based Mobility Modeling for Multi-hop Wireless Networks." In: *Computer Communications* 34.6 (2011), pp. 704–714. ISSN: 01403664.

[19] Muhammad Ashar, Hirohiko Suwa, Yutaka Arakawa, and Keiichi Yasumoto. "Priority Medical Image Delivery Using DTN for Healthcare Workers in Volcanic Emergency." In: *Scientific Phone Apps and Mobile Devices* 2.1 (2016), pp. 1–9.

[20] Daniel Ayala, Ouri Wolfson, Bo Xu, Bhaskar DasGupta, and Jie Lin. "Parking in Competitive Settings: A Gravitational Approach." In: *IEEE MDM*. 2012.

[21] Daniel Ayala, Ouri Wolfson, Bo Xu, Bhaskar Dasgupta, and Jie Lin. "Parking Slot Assignment Games." In: *ACM SIGSPATIAL GIS*. 2011.

[22] Öztas Basak, Tolga Kurt, and Emin Anarim. "A Survey of Social Based Mobility Models for Ad Hoc Networks." In: *2011 2nd International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace and Electronic Systems Technology, Wireless VITAE 2011* (2011).

[23] Lars Baumgärtner, Stefan Kohlbrecher, Juliane Euler, Tobias Ritter, Milan Stute, Christian Meurisch, Max Mühlhäuser, Matthias Hollick, Oskar von Stryk, and Bernd Freisleben. "Emergency Communication in Challenged Environments via Unmanned Ground and Aerial Vehicles." In: *IEEE* (2017).

[24] I Safak Bayram, George Michailidis, Ioannis Papapanagiotou, and Michael Devetsikiotis. "Decentralized Control of Electric Vehicles in a Network of Fast Charging Stations." In: *IEEE GLOBECOMM*. 2013.

[25] BBK. *Sozialwissenschaftliche Evaluation der Feldübung*. Jan. 2018. URL: `https://smarter-projekt.de/wp-content/uploads/2018/01/2018-01-23-Evaluation-der-Feld%C3%BCbung.pdf` (Last accessed on July 1st, 2019).

[26] Michael Behrisch, Laura Bieker, Jakob Erdmann, and Daniel Krajzewicz. "SUMO–Simulation of Urban Mobility." In: *Proceedings of the third International Conference on Advances in System Simulation (SIMUL)*. Vol. 42. 2011.

[27] Assia Belbachir, Juan-Antonio Escareno, Elsa Rubio, and Humberto Sossa. "Preliminary Results on UAV-based Forest Fire Localization Based on Decisional Navigation." In: *Research, Education and Development of Unmanned Aerial Systems (RED-UAS), 2015 Workshop on*. IEEE. 2015, pp. 377–382.

[28] Peter J Bennett, Kenichi Soga, Ian Wassell, Paul Fidler, Keita Abe, Yusuke Kobayashi, and Martin Vanicek. "Wireless Sensor Networks for Underground Railway Applications: Case Studies in Prague and London." In: *Smart Structures and Systems* 6.5-6 (2010), pp. 619–639.

[29] Shreyansh P Bhatt, Hemant Purohit, Andrew Hampton, Valerie Shalin, Amit Sheth, and John Flach. "Assisting Coordination During Crisis: A Domain Ontology Based Approach to Infer Resource Needs from Tweets." In: *Proceedings of the 2014 ACM conference on Web science*. ACM. 2014, pp. 297–298.

[30] Suman Bhattacharjee, Souvik Basu, Siuli Roy, and Sipra Das Bit. "Best-effort Delivery of Emergency Messages in Post-disaster Scenario with Content-based Filtering and Priority-enhanced PRoPHET over DTN." In: *Proceedings of the COMSNETS*. 2016.

[31] Mitchell Bingemann. *Telstra says it's ready for the next Black Saturday*. 2009. URL: `%5Curl%7Bhttp://www.theaustralian.com.au/business/technology/telco-says-its-ready-for-the-next-black-saturday/news-story/f48e065f14fa8614f2a18165c9b279b8%7D` (Last accessed on July 1st, 2019).

[32] Chris Bosak. *Duracell program brings power to natural disaster sites*. Oct. 2017. URL: `https://www.newstimes.com/business/article/Duracell-program-brings-power-to-natural-disaster-12275646.php#item-85307-tbla-8` (Last accessed on July 1st, 2019).

[33] Klaus Brouwers. *Guide for Emergency Preparedness and Correct Action in Emergency Situations*. German Federal Office of Civil Protection and Disaster Assistance (BBK). 2015.

[34] Raymond C Browning, Emily A Baker, Jessica A Herron, and Rodger Kram. "Effects of Obesity and Sex on the Energetic Cost and Preferred Speed of Walking." In: *Journal of applied physiology* (2006).

[35] Sonja Buchegger and J-Y Le Boudec. "Nodes Bearing Grudges: Towards Routing Security, Fairness, and Robustness in Mobile Ad Hoc Networks." In: *Parallel, Distributed and Network-based Processing, 2002. Proceedings. 10th Euromicro Workshop on*. IEEE. 2002, pp. 403–410.

[36] John Burgess, Brian Gallagher, David Jensen, and Brian Neil Levine. "MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks." In: *Proceedings of the IEEE INFOCOM*. 2006.

[37] Regin Cabacas and In-ho Ra. "CMP: A Context Information-based Routing Scheme with Energy-based Message Prioritization for Delay Tolerant Networks." In: *International Journal of Fuzzy Logic and Intelligent Systems* 14.4 (2014), pp. 295–304.

[38] Sergio Cabrero, Roberto Garcia, Xabiel G Paneda, and David Melendi. "Understanding Opportunistic Networking for Emergency Services: Analysis of One Year of GPS Traces." In: *MobiCom CHANTS*. Paris, France: ACM, 2015, pp. 31–36.

[39] Mario Cagalj, Srdjan Capkun, and J-P Hubaux. "Key agreement in peer-to-peer wireless networks." In: *Proceedings of the IEEE* 94.2 (2006), pp. 467–478.

[40] Murat Caliskan, Andreas Barthels, Björn Scheuermann, and Martin Mauve. "Predicting Parking Lot Occupancy in Vehicular Ad Hoc Networks." In: *IEEE Vehicular Technology Conference (VTC)*. IEEE, 2007, pp. 277–281.

[41] Tracy Camp, Jeff Boleng, and Vanessa Davies. "A Survey of Mobility Models for ad hoc Network Research." In: *Wireless communications and mobile computing* 2.5 (2002), pp. 483–502.

[42] Andrew T Campbell, Shane B Eisenman, Nicholas D Lane, Emiliano Miluzzo, Ronald A Peterson, Hong Lu, Xiao Zheng, Mirco Musolesi, Gahng-Seop Ahn, et al. "The Rise of People-centric Sensing." In: *IEEE Internet Computing* 4 (2008), pp. 12–21.

[43] Daniel Camps-Mur, Andres Garcia-Saavedra, and Pablo Serrano. "Device-to-device Communications with Wi-Fi Direct: Overview and Experimentation." In: *IEEE wireless communications* 20.3 (2013), pp. 96–104.

[44] Srdjan Capkun, Jean-Pierre Hubaux, and Levente Buttyan. "Mobility Helps Peer-to-peer Security." In: *IEEE Transactions on Mobile Computing* 5.1 (2006), pp. 43–51.

[45] Cornelia Caragea, Adrian Silvescu, and Andrea H Tapia. "Identifying Informative Messages in Disaster Events using Convolutional Neural Networks." In: *International Conference on Information Systems for Crisis Response and Management*. 2016, pp. 137–147.

[46] Aaron Carroll and Gernot Heiser. "The Systems Hacker's Guide to the Galaxy." In: *Proc. of APSYS* (2013).

[47] Eunjoon Cho, Seth A Myers, and Jure Leskovec. "Friendship and Mobility: User Movement in Location-based Social Networks." In: *Proceedings of the 17th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD)*. ACM. 2011, pp. 1082–1090.

[48] Soudip Roy Chowdhury, Muhammad Imran, Muhammad Rizwan Asghar, Sihem Amer-Yahia, and Carlos Castillo. "Tweet4act: Using Incident-Specific Profiles for Classifying Crisis-Related Messages." In: *Proceedings of the ISCRAM*. 2013.

[49] Ann Coffin and John Morrall. "Walking Speeds of Elderly Pedestrians at Crosswalks." In: *Transportation Research Record: Journal of the Transportation Research Board* (1995), pp. 63–67. ISSN: 0361-1981.

[50] Louise K Comfort, Kilkon Ko, and Adam Zagorecki. "Coordination in Rapidly Evolving Disaster Response Systems: The Role of Information." In: *American Behavioral Scientist* 48.3 (2004), pp. 295–313.

[51] Marco Conti, Chiara Boldrini, Salil S Kanhere, Enzo Mingozzi, Elena Pagani, Pedro M Ruiz, and Mohamed Younis. "From MANET to People-centric Networking: Milestones and Open Research Challenges." In: *Computer Communications* 71 (Nov. 2015), pp. 1–21.

[52] Marco Conti and Silvia Giordano. "Mobile ad hoc Networking: Milestones, Challenges, and new Research Directions." In: *IEEE Communications Magazine* 52.1 (Jan. 2014), pp. 85–96.

[53] Elizabeth M Daly and Mads Haahr. "Social Network Analysis for Routing in Disconnected Delay-tolerant MANETs." In: *Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing*. ACM. 2007, pp. 32–40.

[54] Kai Daniel, Bjoern Dusza, Andreas Lewandowski, and Christian Wietfeld. "AirShield: A System-of-systems MUAV Remote Sensing Architecture for Disaster Response." In: *Systems conference, 2009 3rd Annual IEEE*. IEEE. 2009, pp. 196–200.

[55] Louis De Alessi. "Toward an Analysis of Postdisaster Cooperation." In: *The American Economic Review* 65.1 (1975), pp. 127–138.

[56] Mathijs Michiel De Weerdt, Enrico H Gerding, Sebastian Stein, Valentin Robu, and Nicholas R Jennings. "Intention-Aware Routing to Minimise Delays at Electric Vehicle Charging Stations." In: *International Joint Conference on Artificial Intelligence (IJCAI)*. AAAI Press, 2013, pp. 83–89.

[57] Thierry Delot, Nicolas Cenerario, Sergio Ilarri, and Sylvain Lecomte. "A Cooperative Reservation Protocol for Parking Spaces in Vehicular Ad Hoc Networks." In: *ACM MobiCASE*. 2009.

[58] Rajvardhan Somraj Deshmukh and Michael Zink. "An Information Centric Networking Approach for Sensor to Vehicular Network Communication in Disasters." In: *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*. IEEE. 2017, pp. 227–234.

[59] Thomas Dietrich, Silvia Krug, and Armin Zimmermann. "A Discrete Event Simulation and Evaluation Framework for Multi UAV System Maintenance Processes." In: *Systems Engineering Symposium (ISSE), 2017 IEEE International*. IEEE. 2017, pp. 1–6.

[60] Shuo Ding. "A Survey on Integrating MANETs with the Internet: Challenges and Designs." In: *Computer Communications* 31.14 (2008), pp. 3537–3551.

[61] Bernhard Distl and Franck Legendre. "Are Smartphones Suited for DTN Networking? A Methodological Reardown of Smartphones' WiFi Performance." In: *International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*. IEEE, 2015, pp. 90–95.

[62] Michael Doering, Sven Lahde, Johannes Morgenroth, and Lars Wolf. "IBR-DTN: An Efficient Implementation for Embedded Systems." In: *MobiCom CHANTS*. San Francisco, California, USA: ACM, 2008, pp. 117–120.

[63] Paul Earle, Daniel Bowden, and Michelle Guy. "Twitter Earthquake Detection: Earthquake Monitoring in a Social World." In: *Annals of Geophysics* (2012).

[64] Wolfgang Effelsberg, Ralf Steinmetz, and Thorsten Strufe. "Benchmarking Peer-to-Peer Systems." In: *Lecture Notes in Computer Science* 7847 (2013).

[65] Daniel Ehrhard. "Entwicklung und Evaluation von Funkbrücken zwischen Ad-hoc-Netzcluster bei Katastrophenereignissen." Bachelor Thesis. TU Darmstadt, 2016.

[66] Milan Erdelj and Enrico Natalizio. "UAV-assisted Disaster Management: Applications and Open Issues." In: *2016 international conference on computing, networking and communications (ICNC)*. IEEE. 2016, pp. 1–5.

[67] Milan Erdelj, Osamah Saif, Enrico Natalizio, and Isabelle Fantoni. "UAVs that Fly Forever: Uninterrupted Structural Inspection Through Automatic UAV Replacement." In: *Ad Hoc Networks* (2017).

[68] Jovilyn Therese B Fajardo, Keiichi Yasumoto, and Minoru Ito. "Content-based Data Prioritization for Fast Disaster Images Collection in Delay Tolerant Network." In: *Mobile Computing and Ubiquitous Networking (ICMU), 2014 Seventh International Conference on*. IEEE. 2014, pp. 147–152.

[69] Federal Emergency Management Agency. *FEMA App*. 2017. URL: `http://www.fema.gov/mobile-app` (Last accessed on July 1st, 2019).

[70] Emad Felemban, Adil A Sheikh, and Muhammad Asif Manzoor. "Improving Response Time in Time Critical Visual Sensor Network Applications." In: *Ad Hoc Networks* 23 (2014), pp. 65–79.

[71] Denzil Ferreira, Anind K Dey, and Vassilis Kostakos. "Understanding Human-Smartphone Concerns: A Study of Battery Life." In: *IEEE PerCom*. 2011.

[72] Tim Feuerbach. "Allocation Strategies for Physical Energy-Resources in Ad-hoc Networks." Master Thesis (Best Thesis of the Year 2017). TU Darmstadt, 2016.

[73] Charles E Fritz and Eli S Marks. “The NORC Studies of Human Behavior in Disaster.” In: *Journal of Social Issues* 10.3 (1954), pp. 26–41.

[74] Gregor Gaertner. “Understanding Link Quality in 802.11 Mobile Ad Hoc Networks.” In: *IEEE Internet Computing* 8.1 (2004), pp. 55–60.

[75] Rossano Gaeta and Matteo Sereno. “Generalized Probabilistic Flooding in Unstructured Peer-to-peer Networks.” In: *IEEE Transactions on Parallel and Distributed Systems* 22.12 (2011), pp. 2055–2062.

[76] Maria Gallucci. “Rebuilding Puerto Rico’s Power Grid: The Inside Story.” In: *IEEE Spectrum* (2018).

[77] Huiji Gao, Geoffrey Barbier, Rebecca Goolsby, and Daniel Zeng. *Harnessing the Crowdsourcing Power of Social Media for Disaster Relief*. Tech. rep. Arizona State Univ Tempe, 2011.

[78] Tia Gao and David White. “A Next Generation Electronic Triage to Aid Mass Casualty Emergency Medical Response.” In: *Engineering in Medicine and Biology Society,EMBS’06. 28th Annual International Conference*. IEEE. 2006.

[79] Paul Gardner-Stephen, Romana Challans, et al. “The Serval Mesh: A Platform for Resilient Communications in Disaster & Crisis.” In: *Global Humanitarian Technology Conference (GHTC), 2013 IEEE*. IEEE. 2013, pp. 162–166.

[80] Paul Gardner-Stephen, Romana Challans, Jeremy Lakeman, Andrew Bettison, Patrick Lieser, Ralf Steinmetz, Flor Alvarez, and Matthew Lloyd. “Productizing Humanitarian Telecommunications Research: A Case Study of the Serval Mesh Extender.” In: *Global Humanitarian Technology Conference (GHTC), 2017 IEEE*. IEEE. 2017, pp. 1–10.

[81] Stephen M George, Wei Zhou, Harshavardhan Chenji, Myounggyu Won, Yong Oh Lee, Andria Pazarloglou, Radu Stoleru, and Prabir Barooah. “DistressNet: A Wireless Ad Hoc and Sensor Network Architecture for Situation Management in Disaster Response.” In: *IEEE Communications Magazine* 48.3 (2010).

[82] Ibrahim Ghafir, Jibran Saleem, Mohammad Hammoudeh, Hanan Faour, Vaclav Prenosil, Sardar Jaf, Sohail Jabbar, and Thar Baker. “Security Threats to Critical Infrastructure: The Human Factor.” In: *The Journal of Supercomputing* (2018), pp. 1–17.

[83] A Malcolm Gill and Scott L Stephens. “Scientific and Social Challenges for the Management of Fire-prone Wildland–urban Interfaces.” In: *Environmental Research Letters* 4 (2009).

[84] Katsuichiro Goda, Takashi Kiyota, et al. “The 2015 Gorkha Nepal Earthquake: Insights from Earthquake Damage Survey.” In: *Frontiers in Built Environment* 1 (2015), p. 8.

[85] David Gomez, Ana M Bernardos, Javier I Portillo, Paula Tarrio, and Jose R Casar. "A Review on Mobile Applications for Citizen Emergency Management." In: *International Conference on Practical Applications of Agents and Multi-Agent Systems*. Springer. 2013, pp. 190–201.

[86] Cyril Goutte and Eric Gaussier. "A Probabilistic Interpretation of Precision, Recall and F-score, with Implication for Evaluation." In: *European Conference on Information Retrieval*. Springer. 2005, pp. 345–359.

[87] Christoph Groneberg, Vitali Heidt, Thomas Knoch, and Jutta Helmerichs. "Analyse internationaler Bevölkerungsschutz-Apps." In: *Bevölkerungsschutz-Magazin*. 2017.

[88] Yixin Gu, Mi Zhou, Shengli Fu, and Yan Wan. "Airborne WiFi Networks Through Directional Antennae: An Experimental Study." In: *Wireless Communications and Networking Conference (WCNC), 2015 IEEE*. IEEE. 2015, pp. 1314–1319.

[89] Amit Kumar Gupta, Indrajit Bhattacharya, Partha Sarathi Banerjee, Jyotsna Kumar Mandal, and Animesh Mukherjee. "DirMove: Direction of Movement Based Routing in DTN Architecture for Post-disaster Scenario." In: *Wireless Networks* 22.3 (2016), pp. 723–740.

[90] Zygmunt J Haas, Joseph Y Halpern, and Li Li. "Gossip-based Ad Hoc Routing." In: *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*. Vol. 3. IEEE. 2002, pp. 1707–1716.

[91] Zygmunt J Haas and Marc R Pearlman. "The Performance of Query Control Schemes for the Zone Routing Protocol." In: *IEEE/ACM Transactions on networking* 9.4 (2001), pp. 427–438.

[92] Shane Errol Halse, Rob Grace, Jess Kropczynski, and Andrea Tapia. "Simulating Real-time Twitter Data from Historical Datasets." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2019.

[93] MJ Handy, Marc Haase, and Dirk Timmermann. "Low Energy Adaptive Clustering Hierachy with Deterministic Cluster head Selection." In: *IEEE International Conference on Mobile and Wireless Communications Networks (WiMob)*. IEEE, 2002, pp. 368–372.

[94] Thomas Hänel, Alexander Bothe, and Nils Aschenbruck. "RaLaNS—A Ray Launching Based Propagation Loss Model for ns-3." In: *2015 International Conference and Workshops on Networked Systems (NetSys)*. IEEE. 2015, pp. 1–7.

[95] John C Harsanyi. "Games with Incomplete Information Played by "Bayesian" Players, I-III Part I. The Basic Model." In: *Management Science* 14.3 (1967), pp. 159–182.

[96] Samira Hayat, Evşen Yanmaz, and Raheeb Muzaffar. "Survey on Unmanned Aerial Vehicle Networks for Civil Applications: A Communications Viewpoint." In: *IEEE Communications Surveys & Tutorials* 18.4 (2016), pp. 2624–2661.

[97] Bingshun He, Xianlong Huang, Meihong Ma, Qingrui Chang, Yong Tu, Qing Li, Ke Zhang, and Yang Hong. "Analysis of Flash Flood Disaster Characteristics in China from 2011 to 2015." In: *Natural Hazards* 90.1 (2018), pp. 407–420.

[98] Erik Aufder Heide. "Common Misconceptions about Disasters: Panic, the "Disaster Syndrome," and Looting." In: *The First 72 Hours: A Community Approach to Disaster Preparedness* 337 (2004).

[99] Wendi Rabiner Heinzelmann, Joanna Kulik, and Hari Balakrishnan. "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks." In: *ACM/IEEE MobiCom*. 1999.

[100] Thomas R Henderson, Mathieu Lacage, George F Riley, Craig Dowell, and Joseph Kopena. "Network Simulations with the ns-3 Simulator." In: *SIGCOMM demonstration* 14.14 (2008), p. 527.

[101] Guido R Hiertz, Jörg Habetha, Peter May, E Weib, Rajesh Bagul, and Stefan Mangold. "A Decentralized Reservation Scheme for IEEE 802.11 ad hoc Networks." In: *IEEE PIMRC*. Vol. 3. IEEE. 2003, pp. 2576–2580.

[102] Ralf D Hofmann. "Smart Operation of a Mobile Network in Event of Disaster." In: *Telecommunications Energy Conference, 2008. INTELEC 2008. IEEE 30th International*. IEEE. 2008, pp. 1–5.

[103] Mohammadmajid Hormati, Ferhat Khendek, Roch Glitho, and Fatna Belqasmi. "Differentiated QoS for Overlay-based Disaster Response Systems." In: *Proceedings of the IEEE International Conference on Communications Workshops (ICC)*. 2014.

[104] Theus Hossmann, Franck Legendre, Paolo Carta, Per Gunningberg, and Christian Rohner. "Twitter in Disaster Mode: Opportunistic Communication and Distribution of Sensor Data in Emergencies." In: *Proceedings of the 3rd Extreme Conference on Communication: The Amazon Expedition*. ACM. 2011, p. 1.

[105] Muhammad Imran, Shady Elbassuoni, Carlos Castillo, Fernando Diaz, and Patrick Meier. "Extracting Information Nuggets from Disaster-Related Messages in Social Media." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2013.

[106] Facebook Inc. *Facebook Safety Check*. 2014. URL: `https://www.facebook.com/about/crisisresponse/` (Last accessed on July 1st, 2019).

[107] Google Inc. *Google Person Finder*. 2019. URL: `https://google.org/personfinder/global` (Last accessed on July 1st, 2019).

[108] Federal Office for Information Security, Federal Office of Civil Protection, and Disaster Assistance. *Critical Infrastructures – Introduction and Motivation*. 2017. URL: `https://www.kritis.bund.de/SubSites/Kritis/EN/introduction/introduction_node.html` (Last accessed on July 1st, 2019).

[109] European Telecommunications Standards Institute. "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions." In: ETSI TR 102 638, V1.1.1 (2009).

[110] Philippe Jacquet, Paul Muhlethaler, Thomas Clausen, Anis Laouiti, Amir Qayyum, and Laurent Viennot. "Optimized Link State Routing Protocol for Ad Hoc Networks." In: *Multi Topic Conference, 2001. IEEE INMIC 2001*. IEEE. 2001, pp. 62–68.

[111] Zhigang Jin, Jia Wang, Sainan Zhang, and Yantai Shu. "Epidemic-based Controlled Flooding and Adaptive Multicast for Delay Tolerant Networks." In: *2010 7th International Conference on Ubiquitous Intelligence & Computing and 7th International Conference on Autonomic & Trusted Computing*. IEEE. 2010, pp. 191–194.

[112] David B Johnson, David A Maltz, Josh Broch, et al. "DSR: The Dynamic Source Routing Protocol for Multi-hop Wireless Ad Hoc Networks." In: *Ad hoc networking* 5 (2001), pp. 139–172.

[113] Jennifer Johnson, Elizabeth Basha, and Carrick Detweiler. "Charge Selection Algorithms for Maximizing Sensor Network Life with UAV-based Limited Wireless Recharging." In: *2013 IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing*. IEEE. 2013, pp. 159–164.

[114] Jamal Nazzal Al-Karaki. "Infrastructureless Wireless Networks: Cluster-based Architectures and Protocols." PhD thesis. Iowa State University Capstones, 2004.

[115] Dmytro Karamshuk, Chiara Boldrini, Marco Conti, and Andrea Passarella. "Human Mobility Models for Opportunistic Networks." In: *IEEE Communications Magazine* 49.12 (2011), pp. 157–165.

[116] Fabian Kaup. "Measurement and Modeling of WiFi ad hoc-based Communication in Mobile Peer-to-Peer Networks using Smartphones." Diploma thesis. TU Darmstadt, 2012.

[117] Stephen Kelly, Xiubo Zhang, and Khurshid Ahmad. "Mining Multimodal Information on Social Media for Increased Situational Awareness." In: *Proceedings of the 14th International Conference on Information Systems for Crisis Response And Management*. 2017.

[118] Peter J Kennedy. "Mobile Phone Amber Alert Notification System and Method." US Patent 7,228,121. 2007.

[119] Maurice J Khabbaz, Chadi M Assi, and Wissam F Fawaz. "Disruption-tolerant Networking: A Comprehensive Survey on Recent Developments and Persisting Challenges." In: *IEEE Communications Surveys & Tutorials* 14.2 (2011), pp. 607–640.

[120] Bakul Khanna, Jason Redi, Prithwish Basu, and Ram Ramanathan. "Disrupted Adaptive Routing: Gossip-based Routing in Delay-tolerant Networks." In: *MILCOM 2013-2013 IEEE Military Communications Conference*. IEEE. 2013, pp. 1099–1104.

[121] Ponthai Klinsompus and Natawut Nupairoj. "Critical Message Scheduling for Disaster Response and Recovery Phases." In: *Proceedings of the International Conference on Information and Communication Technology Convergence (ICTC)*. 2015.

[122] Xianshu Kong, Hazel Everett, and Godfried Toussaint. "The Graham Scan Triangulates Simple Polygons." In: *Pattern Recognition Letters* 11.11 (1990), pp. 713–716.

[123] Alisa Kongthon, Choochart Haruechaiyasak, Jaruwat Pailai, and Sarawoot Kongyoung. "The Role of Twitter during a Natural Disaster: Case Study of 2011 Thai Flood." In: *Proceedings of PICMET: Technology Management for Emerging Technologies*. 2012.

[124] Konstantinos Konstantinou, Shaoli Kang, and Costas Tzaras. "A Measurement-based Model for Mobile-to-mobile UMTS Links." In: *Proceedings of the Vehicular Technology Conference (VTC)*. 2007.

[125] Kenji Koshiyama. "Sheltering Status a Year After the Multiple Disaster in Fukushima." In: *Resettlement Challenges for Displaced Populations and Refugees*. Springer, 2019, pp. 153–162.

[126] Venkatachary Sampath Kumar, Jagdish Prasad, and Ravi Samikannu. "A Critical Review of Cyber Security and Cyber Terrorism–threats to Critical Infrastructure in the Energy Sector." In: *International Journal of Critical Infrastructures* 14.2 (2018), pp. 101–119.

[127] Olaf Landsiedel, Federico Ferrari, and Marco Zimmerling. "Chaos: Versatile and Efficient All-to-All Data Sharing and In-Network Processing at Scale." In: *ACM Sensys*. 2013.

[128] Alexandru Lavric and Valentin Popa. "Internet of Things and LoRa™ Powpower Wide-area Networks: A Survey." In: *2017 International Symposium on Signals, Circuits and Systems (ISSCS)*. IEEE. 2017, pp. 1–5.

[129] Thorne Lay, Hiroo Kanamori, et al. "The Great Sumatra-Andaman Earthquake of 26 december 2004." In: *Science* 308 (2005), pp. 1127–1133.

[130] Jennifer Leaning and Debarati Guha-Sapir. "Natural Disasters, Armed Conflict, and Public Health." In: *New England Journal of Medicine* 369.19 (2013), pp. 1836–1842.

[131] Jeremie Leguay, Timur Friedman, and Vania Conan. "Evaluating Mobility Pattern Space Routing for DTNs." In: *arXiv preprint cs/0511102* (2005).

[132] Li Li, Xiaoxiong Zhong, and Yang Qin. "A Secure Routing Based on Social Trust in Opportunistic Networks." In: *Communication Systems (ICCS), 2016 IEEE International Conference on*. IEEE. 2016, pp. 1–6.

[133] Xu Li, Dongning Guo, Huarui Yin, and Guo Wei. "Drone-assisted Public Safety Wireless Broadband Network." In: *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*. IEEE. 2015, pp. 323–328.

[134] Patrick Lieser, Alaa Alhamoud, Hosam Nima, Björn Richerzhagen, Sanja Huhle, Doreen Böhnstedt, and Ralf Steinmetz. "Situation Detection based on Activity Recognition in Disaster Scenarios." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2018, pp. 1–17.

[135] Patrick Lieser, Flor Alvarez, Paul Gardner-Stephen, Matthias Hollick, and Doreen Böhnstedt. "Architecture for Responsive Emergency Communications Networks." In: *Global Humanitarian Technology Conference (GHTC), 2017 IEEE*. IEEE. 2017, pp. 1–9.

[136] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, Tobias Meuser, Björn Richerzhagen, and Ralf Steinmetz. "Collaborative Decentralized Resource Reservation for Emergency Communication Networks." In: *Proceedings of the 43rd IEEE Conference on Local Computer Networks (LCN)*. IEEE, 2018, pp. 1–9.

[137] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, The An Binh Nguyen, Björn Richerzhagen, Doreen Böhnstedt, and Ralf Steinmetz. "Decentralized Resource Allocation in Mobile Networks." In: *Demonstrations of the 42nd IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2017, pp. 1–3.

[138] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, Leonhard Nobach, Doreen Böhnstedt, and Ralf Steinmetz. "Take it or Leave it: Decentralized Resource Allocation in Mobile Networks." In: *Proceedings of the 42st IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2017, pp. 1–8.

[139] Patrick Lieser, Nils Richerzhagen, Michal Lipinski, Clemens Krug, Tobias Meuser, Björn Richerzhagen, and Ralf Steinmetz. "Decentralized Disaster Area Detection in Mobile Networks." In: *Demonstrations of the 43rd IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2018, pp. 1–3.

[140] Patrick Lieser, Nils Richerzhagen, Simon Luser, Björn Richerzhagen, and Ralf Steinmetz. "Understanding the Impact of Message Prioritization in Post-Disaster Ad Hoc Networks." In: *Proc. International Conference on Networked Systems (NetSys)*. ACM. 2019, pp. 1–8.

[141] Patrick Lieser, Julian Zobel, Björn Richerzhagen, and Ralf Steinmetz. "Simulation Platform for Unmanned Aerial Systems in Emergency Ad Hoc Networks." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM), awarded with the Best Student Paper Award*. 2019, pp. 1–15.

[142] Suejong Lim. *Average Storage Capacity in Smartphones to Cross 80GB by End-2019*. Mar. 16, 2019. URL: `https://www.counterpointresearch.com/average-storage-capacity-smartphones-cross-80gb-end-2019/` (Last accessed on July 1st, 2019).

[143] Anders Lindgren, Avri Doria, et al. “Probabilistic Routing in Intermittently Connected Networks.” In: *ACM SIGMOBILE mobile computing and communications review* 7 (2003), pp. 19–20.

[144] Mengjuan Liu, Yan Yang, and Zhiguang Qin. “A Survey of Routing Protocols and Simulations in Delay-tolerant Networks.” In: *International Conference on Wireless Algorithms, Systems, and Applications*. Springer. 2011, pp. 243–253.

[145] Daniel F Lorenz, Katja Schulze, and Martin Voss. “Emerging Citizen Responses to Disasters in Germany. Disaster Myths as an Impediment for a Collaboration of Unaffiliated Responders and Professional Rescue Forces.” In: *Journal of Contingencies and Crisis Management* 26.3 (2018), pp. 358–367.

[146] Xin Lu, Linus Bengtsson, and Petter Holme. “Predictability of Population Displacement after the 2010 Haiti Earthquake.” In: *Proceedings of the National Academy of Sciences of the United States of America*. Vol. 109. 29. 2012, pp. 11576–81.

[147] Faisal Luqman. “TRIAGE: Applying Context to Improve Timely Delivery of Critical Data in Mobile Ad Hoc Networks for Disaster Response.” In: *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2011 IEEE International Conference on*. IEEE. 2011.

[148] Faisal Luqman and Martin L Griss. “Leveraging Mobile Context for Effective Collaboration and Task Management in Disaster Response.” In: (2010).

[149] Faisal Luqman, Feng-Tso Sun, Heng-Tze Cheng, Senaka Buthpitiya, and Martin Griss. “Prioritizing Data in Emergency Response based on Context, Message Content and Role.” In: *Proceedings of the International Conference on Wireless Technologies for Humanitarian Relief (ACWR)*. 2011.

[150] Paige Maas, Shankar Iyer, Andreas Gros, Wonhee Park, Laura McGorman, and et al. Chaya Nayak. “Facebook Disaster Maps: Aggregate Insights for Crisis Response and Recovery.” In: *Proceedings of the 16th International Conference on Information Systems for Crisis Response And Management*. 2019.

[151] Consolee Mbarushimana and Alireza Shahrabi. “Comparative Study of Reactive and Proactive Routing Protocols Performance in Mobile Ad Hoc Networks.” In: *21st International Conference on Advanced Information Networking and Applications Workshops (AINAW'07)*. Vol. 2. IEEE. 2007, pp. 679–684.

[152] Florence McAtee, Sathya Narayanan, and Geoffrey G. Xie. “Performance Analysis of Message Prioritization in Delay Tolerant Networks.” In: *Proceedings of the IEEE Military Communications Conference (MILCOM)*. 2012.

[153] James Mclinn. *Major Power Outages in the US, and around the World*. Tech. rep. IEEE Reliability Society, 2009.

[154] Arvind Merwaday and Ismail Guvenc. “UAV Assisted Heterogeneous Networks for Public Safety Communications.” In: *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*. IEEE. 2015, pp. 329–334.

[155] Christian Meurisch, Stefan Wullkotte, Stefan Niemczyk, Florian Kohnhäuser, Max Mühlhäuser, et al. "NICER911: Ad-hoc Communication and Emergency Services Using Networking Smartphones and Wireless Home Routers." In: *Proceedings of the 18th ACM International Symposium on Mobile Ad Hoc Networking and Computing*. ACM. 2017, p. 33.

[156] Tobias Meuser, Daniel Bischoff, Ralf Steinmetz, and Björn Richerzhagen. "Simulation Platform for Connected Heterogeneous Vehicles." In: *Proceedings of the International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS)*. SCITEPRESS, May 2019.

[157] Shima Mohseni, Rosilah Hassan, Ahmed Patel, and Rozilawati Razali. "Comparative Review Study of Reactive and Proactive Routing Protocols in MANETs." In: *4th IEEE International Conference on Digital Ecosystems and Technologies*. IEEE. 2010, pp. 304–309.

[158] Osnat Mokryn, Dror Karmi, Akiva Elkayam, and Tomer Teller. "Help Me: Opportunistic Smart Rescue Application and System." In: *Ad Hoc Networking Workshop (Med-Hoc-Net), 2012 The 11th Annual Mediterranean*. IEEE. 2012, pp. 98–105.

[159] Simon Morgenthaler, Torsten Braun, Zhongliang Zhao, Thomas Staub, and Markus Anwander. "UAVNet: A Mobile Wireless Mesh Network Using Unmanned Aerial Vehicles." In: *Globecom Workshops (GC Wkshps), 2012 IEEE*. IEEE. 2012, pp. 1603–1608.

[160] Atsushi Mori, Hiraku Okada, Kentaro Kobayashi, Masaaki Katayama, and Kenichi Mase. "Construction of a Node-combined Wireless Network for Large-scale Disasters." In: *Consumer Communications and Networking Conference (CCNC), 2015 12th Annual IEEE*. IEEE. 2015, pp. 219–224.

[161] Scott Morton, Ruben D'Sa, and Nikolaos Papanikolopoulos. "Solar Powered UAV: Design and Experiments." In: *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*. IEEE. 2015, pp. 2460–2466.

[162] John Moteff, Claudia Copeland, and John Fischer. "Critical Infrastructures: What Makes an Infrastructure Critical?" In: Library of Congress Washington DC Congressional Research Service. 2003.

[163] Mohammad Mozaffari, Walid Saad, Mehdi Bennis, and Mérouane Debbah. "Mobile Unmanned Aerial Vehicles (UAVs) for Energy-efficient Internet of Things Communications." In: *arXiv preprint arXiv:1703.05401* (2017).

[164] Mirco Musolesi and Cecilia Mascolo. "Designing Mobility Models Based on Social Network Theory." In: *SIGMOBILE Mobile Computing Communications Review* 11.3 (July 2007), pp. 59–70.

[165] Adnan Nadeem and Michael P Howarth. "An Intrusion Detection & Adaptive Response Mechanism for MANETs." In: *Ad Hoc Networks* 13 (2014), pp. 368–380.

[166] Ladimer S Nagurney. "Advances in Disaster Communications: Broadband Systems for First Responders." In: *International Conference on Dynamics of Disasters*. Springer. 2017, pp. 135–156.

[167] Kamesh Namuduri, Serge Chaumette, Jae H Kim, and James PG Sterbenz. *UAV Networks and Communications*. Cambridge University Press, 2018.

[168] Soumendra Nanda and David Kotz. "Mesh-Mon: A Multi-radio Mesh Monitoring and Management System." In: *Computer Communications* 31.8 (2008), pp. 1588–1601.

[169] Dhanalakshmiand Natarajan and Alli P. Rajendran. "AOLSR: Hybrid Ad Hoc Routing Protocol Based on a Modified Dijkstra's Algorithm." In: *EURASIP Journal on Wireless Communications and Networking* 2014.1 (2014).

[170] Samuel C Nelson, Albert F Harris Iii, and Robin Kravets. "Event-driven, Role-based Mobility in Disaster Recovery Networks." In: *MobiCom CHANTS*. Montreal, Quebec, Canada: ACM, 2007, pp. 27–34.

[171] Dat Tien Nguyen, Shafiq Joty, Muhammad Imran, Hassan Sajjad, and Prasenjit Mitra. "Applications of Online Deep Learning for Crisis Response Using Social Media Information." In: *Proceedings of the International Workshop on Social Web for Disaster Management (SWDM)*. 2016.

[172] The An Binh Nguyen. "Quality-aware Tasking in Mobile Opportunistic Networks - Distributed Information Retrieval and Processing utilizing Opportunistic Heterogeneous Resources." PhD thesis. 2018.

[173] Petros Nicopolitidis, Mohammad Salameh Obaidat, Georgios I Papadimitriou, and Andreas S Pomportsis. *Wireless Networks*. John Wiley & Sons, 2003.

[174] *NINA - Die Warn-App des BBK*. 2013. URL: `https://www.bbk.bund.de/DE/NINA/Warn-App_NINA.html` (Last accessed on July 1st, 2019).

[175] Shuji Nishikawa, Osamu Uchida, and Keisuke Utsu. "Introduction of a Tracking Map to a Web Application for Location Recording and Rescue Request." In: *Proceedings of ISCRAM Asia Pacific 2018: Innovating for Resilience – 1st International Conference on Information Systems for Crisis Response and Management Asia Pacific.* 2018.

[176] Hiroki Nishiyama, Masaya Ito, and Nei Kato. "Relay-by-smartphone: Realizing Multihop Device-to-device Communications." In: *IEEE Communications Magazine* 52.4 (2014), pp. 56–65.

[177] Masaru Nohara. "Impact of the Great East Japan Earthquake and Tsunami on Health, Medical Care and Public Health Systems in Iwate Prefecture, Japan, 2011." In: *Western Pac Surveill Response J* 2 (2011).

[178] Gerard P O'Reilly, David J Houck, Eunyoung Kim, Thomas B Morawski, DD Picklesimer, and Huseyin Uzunalioglu. "Infrastructure Simulations of Disaster Scenarios." In: *Telecommunications Network Strategy and Planning Symposium. NETWORKS 2004, 11th International*. IEEE. 2004, pp. 205–210.

[179] Gerard O'Reilly, Ahmad Jrad, Ramesh Nagarajan, Theresa Brown, and Stephen Conrad. "Critical Infrastructure Analysis of Telecom for Natural Disasters." In: *Telecommunications Network Strategy and Planning Symposium, 2006. NETWORKS 2006. 12th International*. IEEE. 2006, pp. 1–6.

[180] Thomas D O'Rourke. "Critical infrastructure, Interdependencies, and Resilience." In: *BRIDGE-Washington-National Academy of Engineering-* 37.1 (2007), p. 22.

[181] Cathal O'Connor. "Foreign Humanitarian Assistance and Disaster-relief Operations: Lessons Learned and Best Practices." In: *Naval War College Review* 65.1 (2012), pp. 152–160.

[182] Alexandra Olteanu, Carlos Castillo, Fernando Diaz, and Sarah Vieweg. "CrisisLex: A Lexicon for Collecting and Filtering Microblogged Communications in Crises." In: *Proceedings of the International AAAI Conference on Web and Social Media (ICWSM)*. 2014.

[183] Martin J. Osborne. *An Introduction to Game Theory*. New York: Oxford University Press, 2009.

[184] Leysia Palen and Kenneth M Anderson. "Crisis Informatics—New Data for Extraordinary Times." In: *Science* 353.6296 (2016), pp. 224–225.

[185] Leysia Palen and Sophia B Liu. "Citizen Communications in Crisis: Anticipating a Future of ICT-supported Public Participation." In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM. 2007, pp. 727–736.

[186] Raghav Pant, Scott Thacker, Jim W Hall, David Alderson, and Stuart Barr. "Critical Infrastructure Impact Assessment due to Flood Exposure." In: *Journal of Flood Risk Management* 11.1 (2018), pp. 22–33.

[187] Raphaël Paris and Wassmer. "Tsunamis as Geomorphic Crises: Lessons from the December 26, 2004 Tsunami in Lhok Nga, West Banda Aceh (Sumatra, Indonesia)." In: *Geomorphology* 104 (2009), pp. 59–72.

[188] Donald J Patterson. "Haitian Resiliency: A Case Study in Intermittent Infrastructure." In: *First Monday* 20.8 (2015).

[189] Guangyu Pei, Mario Gerla, and Tsu-Wei Chen. "Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks." In: *2000 IEEE International Conference on Communications. ICC 2000. Global Convergence Through Communications. Conference Record*. Vol. 1. IEEE. 2000, pp. 70–74.

[190] Charles E. Perkins and Elizabeth M. Royer. "Ad-hoc On-Demand Distance Vector Routing." In: *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*. 1997, pp. 90–100.

[191] Charles E Perkins and Pravin Bhagwat. "Highly Dynamic Destination-sequenced Distance-vector Routing (DSDV) for Mobile Computers." In: *ACM SIGCOMM computer communication review*. Vol. 24. 4. ACM. 1994, pp. 234–244.

[192] Thomas Petermann, Harald Bradke, Arne Lüllmann, Maik Poetzsch, and Ulrich Riehm. *Was bei einem Blackout geschieht*. Berlin: edition sigma, 2011.

[193] Larry L Peterson and Bruce S Davie. *Computer networks: a systems approach*. Elsevier, 2007.

[194] Pouyan Pourbeik, Prabha S Kundur, and Carson W Taylor. "The Anatomy of a Power Grid Blackout-Root Causes and Dynamics of recent major Blackouts." In: *IEEE Power and Energy Magazine* 4.5 (2006), pp. 22–29.

[195] Uppara Prathap, P Deepa Shenoy, KR Venugopal, and Lalit M Patnaik. "Wireless Sensor Networks Applications and Routing Protocols: Survey and Research Challenges." In: *2012 International Symposium on Cloud and Services Computing*. IEEE. 2012, pp. 49–56.

[196] Franco P. Preparata and Se June Hong. "Convex Hulls of Finite Sets of Points in Two and Three Dimensions." In: *Communications of the ACM* 20.2 (1977), pp. 87–93.

[197] Hua Qin and Wensheng Zhang. "Charging Scheduling with Minimal Waiting in a Network of Electric Vehicles and Charging Stations." In: *ACM VANET*. 2011.

[198] Yan Qu, Chen Huang, Pengyi Zhang, and Jun Zhang. "Microblogging after a Major Disaster in China: A Case Study of the 2010 Yushu Earthquake." In: *Proceedings of the ACM Conference on Computer Supported Cooperative Work (CSCW)*. 2011.

[199] Markus Quaritsch, Robert Kuschnig, Hermann Hellwagner, Bernhard Rinner, A Adria, and U Klagenfurt. "Fast Aerial Image Acquisition and Mosaicking for Emergency Response Operations by Collaborative UAVs." In: *Proceedings for the International ISCRAM Conference*. 2011, pp. 1–5.

[200] Ramya Raghavendra, Prashanth Aravinda Kumar Acharya, Elizabeth M Belding, and Kevin C Almeroth. "Antler: A Multi-tiered Approach to Automated Wireless Network Management." In: *Proceedings of the Workshops of the International Conference on Computer Communications (INFOCOM)*. IEEE. 2008, pp. 1–6.

[201] Krishna N Ramachandran, Elizabeth M Belding-Royer, and KC AImeroth. "DAMON: A Distributed Architecture for Monitoring Multi-hop Mobile Networks." In: *2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004*. IEEE. 2004, pp. 601–609.

[202] Ram Ramanathan, Richard Hansen, Prithwish Basu, Regina Rosales-Hain, and Rajesh Krishnan. "Prioritized Epidemic Routing for Opportunistic Networks." In: *Proceedings of the International MobiSys Workshop on Mobile Opportunistic Networking (MobiOpp)*. 2007.

[203] Federica Ranghieri and Mikio Ishiwatari. *Learning from Megadisasters: Lessons from the Great East Japan Earthquake*. Washington, DC: World Bank, 2014.

[204] International Federation of Red Cross and Red Crescent Societies. *"What is a disaster?"* 2019. URL: `http://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/what-is-a-disaster/` (Last accessed on July 1st, 2019).

[205] Daniel G Reina, Sergio L Toral, Federico Barrero, Nik Bessis, and Eleana Asimakopoulou. "Evaluation of Ad Hoc Networks in Disaster Scenarios." In: *2011 third international conference on intelligent networking and collaborative systems*. IEEE. 2011, pp. 759–764.

[206] Guillaume Rémy, Sidi-Mohammed Senouci, François Jan, and Yvon Gourhant. "SAR Drones: Drones for Advanced Search and Rescue Mission." In: *Journées Nationales des Communications dans les Transports* (2013).

[207] Christian Reuter, Amanda Lee Hughes, and Marc-Andre Kaufhold. "Social Media in Crisis Management: An Evaluation and Analysis of Crisis Informatics Research." In: *International Journal of Human–Computer Interaction* 34.4 (2018), pp. 280–294.

[208] Christian Reuter, Marc Kaufhold, Inken Leopold, and Hannah Knipp. "KATWARN, NINA, or FEMA? Multi-Method Study On Distribution, Use, and Public Views on Crisis Apps." In: *25th European Conference on Information Systems (ECIS)*. 2017.

[209] Björn Richerzhagen. *Mechanism Transitions in Publish/Subscribe Systems: Adaptive Event Brokering for Location-based Mobile Social Applications*. Springer, 2018.

[210] Björn Richerzhagen, Dominik Stingl, Julius Rückert, and Ralf Steinmetz. "Simonstrator: Simulation and Prototyping Platform for Distributed Mobile Applications." In: *Proceedings of the 8th International Conference on Simulation Tools and Techniques (SIMUTools)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Aug. 2015, pp. 99–108.

[211] Nils Richerzhagen. "Transitions in Monitoring and Network Offloading - Handling Dynamic Mobile Applications and Environments." PhD thesis. 2019.

[212] Nils Richerzhagen, Roland Kluge, Björn Richerzhagen, Patrick Lieser, Boris Koldehofe, Ioannis Stavrakakis, and Ralf Steinmetz. "Better Together: Collaborative Monitoring for Location-based Services." In: *Proceedings of the 19th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, June 2018, pp. 1–9.

[213] Nils Richerzhagen, Patrick Lieser, Björn Richerzhagen, Boris Koldehofe, Ioannis Stavrakakis, and Ralf Steinmetz. "Change as Chance: Transition-enabled Monitoring for Dynamic Networks and Environments." In: *Proceedings of the 14th Wireless On-demand Network systems and Services Conference (WONS)*. IEEE/IFIP, Feb. 2018, pp. 1–8.

[214] Nils Richerzhagen, Björn Richerzhagen, Boris Koldehofe, and Ralf Steinmetz. "Towards Transitions between Role Assignment Schemes: Enabling Adaptive Offloading in Challenged Networks." In: *Proceedings of the 12th Workshop on Challenged Networks (CHANTS) co-located with 23rd Annual International Conference on Mobile Computing and Networking (MobiCom)*. ACM, Oct. 2017, pp. 1–6.

[215] Nils Richerzhagen, Björn Richerzhagen, Dominik Stingl, and Ralf Steinmetz. "The Human Factor: A Simulation Environment for Networked Mobile Social Applications." In: *Networked Systems (NetSys)*. IEEE. 2017, pp. 1–8.

[216] Nils Richerzhagen, Björn Richerzhagen, Michael Walter, Dominik Stingl, and Ralf Steinmetz. "Buddies, not Enemies: Fairness and Performance in Cellular Offloading." In: *Proceedings of the 17th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, June 2016, pp. 1–9.

[217] Christian P. Robert. "Simulation of Truncated Normal Variables." In: *Statistics and Computing* 5.2 (1995), pp. 121–125.

[218] Sebastian Rohde, Markus Putzke, and Christian Wietfeld. "Ad Hoc Self-healing of OFDMA Networks Using UAV-based Relays." In: *Ad Hoc Networks* 11.7 (2013), pp. 1893–1906.

[219] Ahmed Safwat, Hossam Hassanein, and Hussein Mouftah. "Power-Aware Fair Infrastructure Formation for Wireless Mobile Ad Hoc Communications." In: *IEEE GLOBECOM*. 2001.

[220] Takeshi Sakaki, Makoto Okazaki, and Yutaka Matsuo. "Earthquake Shakes Twitter Users: Real-time Event Detection by Social Sensors." In: *Proceedings of the 19th international conference on World wide web*. ACM. 2010, pp. 851–860.

[221] Ehssan Sakhaee, Tarik Taleb, Abbas Jamalipour, Nei Kato, and Yoshiaki Nemoto. "A Novel Scheme to Reduce Control Overhead and Increase Link Duration in Highly Mobile Ad Hoc Networks." In: *2007 IEEE Wireless Communications and Networking Conference*. IEEE. 2007, pp. 3972–3977.

[222] Subir Kumar Sarkar, Tiptur Gangaraju Basavaraju, and C Puttamadappa. *Ad Hoc Mobile Wireless Networks: Principles, Protocols, and Applications*. CRC Press, 2016.

[223] Jürgen Scherer, Saeed Yahyanejad, Samira Hayat, Evsen Yanmaz, Torsten Andre, Asif Khan, Vladimir Vukadinovic, Christian Bettstetter, Hermann Hellwagner, and Bernhard Rinner. "An Autonomous Multi-UAV System for Search and Rescue." In: *Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use*. ACM. 2015, pp. 33–38.

[224] Sebastian Schildt, Johannes Morgenroth, Wolf-Bastian Pöttner, and Lars Wolf. "IBR-DTN: A Lightweight, Modular and Highly Portable Bundle Protocol Implementation." In: *Electronic Communications of the EASST* 37 (2011).

[225] Milan Schmittner and Matthias Hollick. “Xcastor: Secure and Scalable Group Communication in Ad Hoc Networks.” In: *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2016 IEEE 17th International Symposium on A*. IEEE. 2016, pp. 1–6.

[226] Aaron Schulman and Neil Spring. “Pingin’ in the Rain.” In: *Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference*. ACM. 2011, pp. 19–28.

[227] Matthias Schulz, Daniel Wegemer, and Matthias Hollick. “DEMO: Using NexMon, the C-based WiFi Firmware Modification Framework.” In: *ACM WiSec 2016*. Darmstadt, Germany: ACM, July 2016, pp. 213–215.

[228] Dominik Schürmann, Julian Timpner, and Lars Wolf. “Cooperative Charging in Residential Areas.” In: *IEEE ITS*. 2016.

[229] Jan Seedorf, Dirk Kutscher, and Fabian Schneider. “Decentralised Binding of Self-certifying Names to Real-world Identities for Assessment of Third-party Messages in Fragmented Mobile Networks.” In: *Computer Communications Workshops (INFOCOM WKSHPS), 2014 IEEE Conference on*. IEEE. 2014, pp. 416–421.

[230] Muthukumar Selvi and B Ramakrishnan. “Prioritized and Secured Data Dissemination Technique in VANET Based on Optimal Blowfish Algorithm and Signcryption Method.” In: *International Journal of Computer Networks and Applications (IJCNA)* 2.4 (2015), pp. 165–172.

[231] Dong-Jun Seo, Branko Kerkez, Michael Zink, Nick Fang, Jean Gao, and Xinbao Yu. “iSPUW: A Vision for Integrated Sensing and Prediction of Urban Water for Sustainable Cities.” In: *International Conference on Dynamic Data-Driven Environmental Systems Science*. Springer. 2014, pp. 68–78.

[232] Elhadi M Shakshuki, Nan Kang, and Tarek R Sheltami. “EAACK—A Secure Intrusion-detection System for MANETs.” In: *IEEE transactions on industrial electronics* 60.3 (2013), pp. 1089–1098.

[233] Jian Shen, Sangman Moh, and Ilyong Chung. “A Priority Routing Protocol Based on Location and Moving Direction in Delay Tolerant Networks.” In: *IEICE Transactions on Information and Systems* E93D.10 (2010), pp. 2763–2775.

[234] Wenlong Shen, Weisheng Hong, Xianghui Cao, Bo Yin, Devu Manikantan Shila, and Yu Cheng. “Secure Key Establishment for Device-to-device Communications.” In: *arXiv preprint arXiv:1410.2620* (2014).

[235] Jiuh-Biing Sheu. “An Emergency Logistics Distribution Approach for Quick Response to Urgent Relief Demand in Disasters.” In: *Transportation Research Part E: Logistics and Transportation Review* 43.6 (2007).

[236] Liu Shu, Zhang Li, and Zhu Zhengyuan. “Moving Towards Reality.” In: - (2010), pp. 1–23.

[237] David M Simpson. "Non-institutional Sources of Assistance Following a Disaster: Potential Triage and Treatment Capabilities of Neighborhood-based Preparedness Organizations." In: *Prehospital and disaster medicine* 15.4 (2000), pp. 73–80.

[238] Xuan Song, Quanshi Zhang, Yoshihide Sekimoto, Teerayut Horanont, Satoshi Ueyama, and Ryosuke Shibasaki. "Modeling and Probabilistic Reasoning of Population Evacuation During Large-scale Disaster." In: *Proceedings of the 19th ACM SIGKDD international conference on Knowledge discovery and data mining*. ACM. 2013, pp. 1231–1239.

[239] Xuan Song, Quanshi Zhang, Yoshihide Sekimoto, and Ryosuke Shibasaki. "Prediction of Human Emergency Behavior and their Mobility Following Large-scale Disaster." In: *Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery and data mining*. ACM. 2014, pp. 5–14.

[240] Patric R Spence, Kenneth A Lachlan, Xialing Lin, and Maria del Greco. "Variability in Twitter Content Across the Stages of a Natural Disaster: Implications for Crisis Communication." In: *Communication Quarterly* 63.2 (2015), pp. 171–186.

[241] Thrasyvoulos Spyropoulos, Konstantinos Psounis, and Cauligi S. Raghavendra. "Spray and Wait: An Efficient Routing Scheme for Intermittently Connected Mobile Networks." In: *Proceedings of the ACM SIGCOMM Workshop on Delay-tolerant Networking*. 2005.

[242] Ioannis Stavrakakis and Evangelia Kokolaki. "Managing Competition for (Public) Resources in Human-centric Networked Environments." In: *International Conference on Computing, Networking and Communications*. 2015.

[243] Ralf Steinmetz and Klaus Wehrle. "What Is This "Peer-to-Peer" About?" In: *Peer-to-peer systems and applications*. Springer, 2005, pp. 9–16.

[244] James PG Sterbenz, David Hutchison, Egemen K Çetinkaya, Abdul Jabbar, Justin P Rohrer, Marcus Schöller, and Paul Smith. "Resilience and Survivability in Communication Networks: Strategies, Principles, and Survey of Disciplines." In: *Computer Networks* 54.8 (2010), pp. 1245–1265.

[245] Dominik Stingl, Christian Gross, Leonhard Nobach, Ralf Steinmetz, and David Hausheer. "BlockTree: Location-aware Decentralized Monitoring in Mobile Ad Hoc Networks." In: *38th Annual IEEE Conference on Local Computer Networks*. IEEE. 2013, pp. 373–381.

[246] Dominik Stingl, Christian Gross, Julius Rückert, Leonhard Nobach, Aleksandra Kovacevic, and Ralf Steinmetz. "Peerfactsim.KOM: A Simulation Framework for Peer-to-peer Systems." In: *Proceedings of the International Conference on High Performance Computing and Simulation (HPCS)*. IEEE. July 2011, pp. 577–584.

[247] Dominik Stingl, Reimond Retz, Bjorn Richerzhagen, Christian Gross, and Ralf Steinmetz. “Mobi-G: Gossip-based Monitoring in Manets.” In: *Proceedings of the Network Operations and Management Symposium (NOMS)*. IEEE. 2014, pp. 1–9.

[248] Milan Stute, Max Maass, Tom Schons, and Matthias Hollick. “Reverse Engineering Human Mobility in Large-scale Natural Disasters.” In: *MSWiM*. Miami, Florida, USA: ACM, 2017, pp. 219–226.

[249] Piotr Szczurek, Bo Xu, Ouri Wolfson, Jie Lin, and Naphtali Rishe. “Learning the Relevance of Parking Information in VANETs.” In: *ACM VANET*. 2010.

[250] Mineo Takai, Jay Martin, and Rajive Bagrodia. “Effects of Wireless Physical Layer Modeling in Mobile Ad Hoc Networks.” In: *Proceedings of the 2nd ACM International Symposium on Mobile Ad hoc Networking & Computing*. 2001.

[251] Yordphol Tanaboriboon. “Analysis of Pedestrian Movements in Bangkok.” In: *Transportation Research Record* 1294 (1991), pp. 52–56. ISSN: 0309051002.

[252] Andrew S Tanenbaum et al. “Computer Networks, 4-th Edition.” In: *ed: Prentice Hall* (2003).

[253] *The American National Red Cross - Contact Loved Ones*. 2019. URL: `https://www.redcross.org/get-help/disaster-relief-and-recovery-services/contact-and-locate-loved-ones.html` (Last accessed on July 1st, 2019).

[254] Qinglin Tian, Zoran Salcic, I Kevin, Kai Wang, and Yun Pan. “An Enhanced Pedestrian Dead Reckoning Approach for Pedestrian Tracking Using Smartphones.” In: *2015 IEEE Tenth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*. IEEE. 2015, pp. 1–6.

[255] Chai K. Toh, Hiroshi Cobb, and David A. Scott. “Performance Evaluation of Battery-life-Aware Routing Schemes for Wireless Ad Hoc Networks.” In: *IEEE ICC*. 2001.

[256] Joseph Trainor, Lauren Barsky, and Manuel Torres. “Disaster Realities in the Aftermath of Hurricane Katrina: Revisiting the Looting Myth.” In: (2006).

[257] Edgar Marko Trono, Yutaka Arakawa, Morihiko Tamai, and Keiichi Yasumoto. “DTN Mapex: Disaster Area Mapping Through Distributed Computing over a Delay Tolerant Network.” In: *Mobile Computing and Ubiquitous Networking (ICMU), 2015 Eighth International Conference on*. IEEE. 2015, pp. 179–184.

[258] Hayley Tsukayama. *Facebook’s Paris Safety Check, by the numbers*. Nov. 2015. URL: `https://www.washingtonpost.com/news/the-switch/wp/2015/11/16/facebooks-paris-safety-check-by-the-numbers/` (Last accessed on July 1st, 2019).

[259] Ian L Turner, Mitchell D Harley, and Christopher D Drummond. “UAVs for Coastal Surveying.” In: *Coastal Engineering* 114 (2016), pp. 19–24.

[260] S Patel Tushar, M Panchal Mayur, N Ladumor Dhara, I Patel Ankit, and P Desai Piyusha. “A Classification and Mobility Metrics of Various Mobility Models.” In: *Research Journal of Engineering Sciences* 2.1 (2013), pp. 40–44.

[261] Noriki Uchida, Noritaka Kawamura, Kazuo Takahata, Yoshitaka Shibata, and Norio Shiratori. "Proposal of Data Triage Methods for Disaster Information Network System Based on Delay Tolerant Networking." In: *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2013 Eighth International Conference on*. IEEE. 2013, pp. 15–21.

[262] Yusuf S. Uddin, David M. Nicol, Tarek F. Abdelzaher, and Robin H. Kravets. "A Post-disaster Mobility Model for Delay Tolerant Networking." In: *Winter Simulation Conference*. Austin, Texas: WSC, 2009, pp. 2785–2796.

[263] Yusuf Sarwar Uddin, Hongyan Wang, Fatemeh Saremi, Guo-Jun Qi, Tarek Abdelzaher, and Thomas Huang. "PhotoNet: A Similarity-Aware Picture Delivery Service for Situation Awareness." In: *Proccedings of the IEEE 32nd Real-Time Systems Symposium*. 2011.

[264] Asanga Udugama, Jens Dede, Anna Förster, Vishnupriya Kuppusamy, Koojana Kuladinithi, Andreas Timm-Giel, and Zeynep Vatandas. "My Smartphone Tattles: Considering Popularity of Messages in Opportunistic Data Dissemination." In: *Future Internet* 11.2 (2019), p. 29.

[265] US Senate. "Hurricane Katrina: A Nation Still Unprepared." In: *Rep. to the Committee on Homeland Security and Government Affairs, Washington, DC* (2006).

[266] Arifumi Utani, Teruhiro Mizumoto, and Takashi Okumura. "How Geeks Responded to a Catastrophic Disaster of a High-tech Country: Rapid Development of Counter-disaster Systems for the Great East Japan Earthquake of March 2011." In: *Proceedings of the Special Workshop on Internet and Disasters*. ACM. 2011, p. 9.

[267] Amin Vahdat and David Becker. *Epidemic Routing for Partially-Connected Ad Hoc Networks*. Tech. rep. CS-200006. Duke University, 2000.

[268] Dimitris Vassis, George Kormentzas, Angelos Rouskas, and Ilias Maglogiannis. "The IEEE 802.11 g Standard for High Data Rate WLANs." In: *IEEE network* 19.3 (2005), pp. 21–26.

[269] Marcel Verst. "Design of a Disaster Mobility Model Based on Real-world Movement Traces." Master Thesis. TU Darmstadt, 2018.

[270] William E Walsh and Michael P Wellman. "A Market Protocol for Decentralized Task Allocation." In: *IEEE MAS*. 1998, pp. 325–332.

[271] Cong Wang, Ji Li, Fan Ye, and Yuanyuan Yang. "Multi-Vehicle Coordination for Wireless Energy Replenishment in Sensor Networks." In: *IEEE IPDPS*. 2013.

[272] En Wang, Yong-Jian Yang, Jie Wu, and Wen-Bin Liu. "A Buffer Scheduling Method Based on Message Priority in Delay Tolerant Networks." In: *Journal of Computer Science and Technology* 31.6 (2016), pp. 1228–1245.

[273] Udi Weinsberg, Qingxi Li, Nina Taft, Athula Balachandran, Vyas Sekar, Gianluca Iannaccone, and Srinivasan Seshan. “CARE: Content Aware Redundancy Elimination for Challenged Networks.” In: *Proceedings of the ACM Workshop on Hot Topics in Networks (HotNets)*. 2017.

[274] Morten Wendelbo, Federica La China, et al. *The Crisis Response to the Nepal Earthquake: Lessons Learned*. 2016.

[275] John Whitbeck and Vania Conan. “HYMAD: Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks.” In: *Computer communications* 33.13 (2010), pp. 1483–1492.

[276] Joshua Whittaker, Katharine Haynes, et al. “Community Safety During the 2009 Australian’Black Saturday’Bushfires: An Analysis of Household Preparedness and Response.” In: *International Journal of Wildland Fire* 22 (2013), pp. 841–849.

[277] Evşen Yanmaz, Samira Hayat, Jürgen Scherer, and Christian Bettstetter. “Experimental Performance Analysis of Two-hop Aerial 802.11 Networks.” In: *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*. IEEE. 2014, pp. 3118–3123.

[278] Dave Yates and Scott Paquette. “Emergency Knowledge Management and Social Media Technologies: A Case Study of the 2010 Haitian Earthquake.” In: *Proceedings of the 73rd ASIS&T Annual Meeting on Navigating Streams in an Information Ecosystem-Volume 47*. American Society for Information Science. 2010, p. 42.

[279] Jie Yin, Sarvnaz Karimi, Andrew Lampert, Mark Cameron, Bella Robinson, and Robert Power. “Using Social Media to Enhance Emergency Situation Awareness.” In: *Twenty-Fourth International Joint Conference on Artificial Intelligence*. 2015.

[280] Jane Louie Fresco Zamora, Noriyuki Suzuki, Hiroaki Takemoto, Shigeru Kashihara, Yuzo Taenaka, and Suguru Yamaguchi. “Battery-saving Message Collection Method for Disrupted Communication Service Areas.” In: *IEEE CCNC*. 2014.

[281] Haibo Zhang. “What has China learnt from disasters? Evolution of the emergency management system after SARS, Southern Snowstorm, and Wenchuan Earthquake.” In: *Journal of Comparative Policy Analysis: Research and Practice* 14.3 (2012), pp. 234–244.

[282] Lide Zhang, Birjodh Tiwana, Zhiyun Qian, Zhaoguang Wang, Robert P Dick, Zhuoqing Morley Mao, and Lei Yang. “Accurate Online Power Estimation and Automatic Battery Behavior Based Power Model Generation for Smartphones.” In: *Proceedings of the eighth IEEE/ACM/IFIP international conference on Hardware/software codesign and system synthesis*. ACM. 2010, pp. 105–114.

[283] Zhensheng Zhang. “Routing in Intermittently Connected Mobile Ad Hoc Networks and Delay Tolerant Networks: Overview and Challenges.” In: *IEEE Communications Surveys & Tutorials* 8.1 (2006), pp. 24–37.

[284] Wenrui Zhao, Mostafa Ammar, and Ellen Zegura. "A Message Ferrying Approach for Data Delivery in Sparse Mobile Ad Hoc Networks." In: *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*. ACM. 2004, pp. 187–198.

[285] Yi Zhou, Nan Cheng, Ning Lu, and Xuemin Sherman Shen. "Multi-UAV-aided Networks: Aerial-ground Cooperative Vehicular Networking Architecture." In: *IEEE Vehicular Technology Magazine* 10.4 (2015), pp. 36–44.

A

APPENDIX

A.1 DISASTER REGION ANALYZING SERVICE (DRAS)

The Disaster Region Analyzing Service (DRAS) is a service that allows civilians to report observations of the disaster area to other civilians or organizations [139]. The service focuses on the area detection of the absence of the Information and Communication Technology (ICT), caused by, for example, a large power blackout, where the affected area of a blackout is often unknown to the infrastructure providers and citizens [226]. In this section, we describe a decentralized blackout area detection in DTN-MANETs that enables mobile devices to share their location history with neighboring nodes to determine the area affected by the blackout. This information can be used to support the affected population by providing information in which areas the ICT is still available. Additionally, the location history of the nodes can be used by organizations to conclude whether roads or paths are still passable and not destroyed or obstructed by the disaster. This information can be used, for example, to plan the dispatch of ambulances or other rescue vehicles.

Service Functionality

DRAS also considers the integration of detecting the absence of the ICT and switches to an ad hoc mode via the Wireless Fidelity (Wi-Fi) interface, when no cellular reception is available. For DRAS, the ad hoc mode is also called "disaster mode". The disaster mode features all DTN-MANET functionalities, for example, neighborhood discovery and direct message exchange. It is assumed that each mobile node has two communication interfaces, one for ad hoc communication (WiFi) and one for communication over the cellular network. Switching to the disaster mode occurs when a node no longer has contact with the ICT or receives messages from a neighboring node which is already in the disaster mode. If a node has contact with the cellular infrastructure again, it remains in a so-called hybrid mode for a short time, where both ad hoc and cellular communication is possible.

Nodes in disaster mode start tracking their movement while sharing their location history with neighboring nodes in communication range. Because nodes can exit and re-enter the blackout area, the location history can store two types of locations: "ICT-available" or "ICT-unavailable". A temporal sequence of the knowledge about the blackout area for a specific node was already displayed in Section 4.2 in Figure 9.

Disaster Region Recognition and Calculation

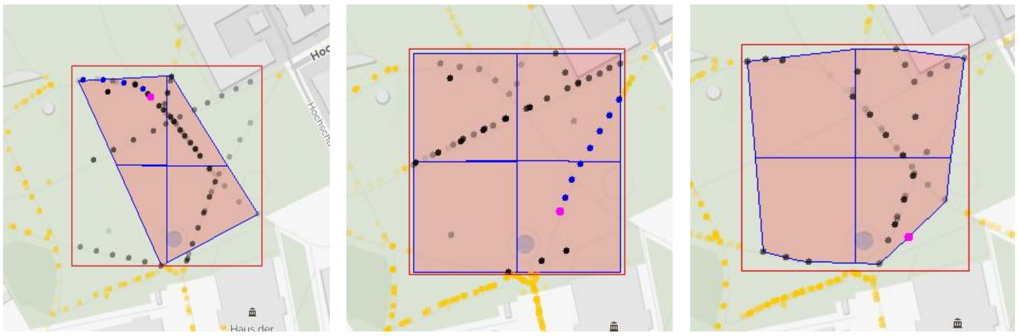
The recorded data includes information about the node's ID, the location's time stamp, latitude and longitude, and position status. The status indicates whether the infrastructure was available or not. Every node maintains its local location storage as the basis for the calculation of the affected area. The calculation of the blackout area is done by each node individually with the locations known to that particular node.

To calculate the blackout area from the logged and exchanged locations, three different algorithms have been implemented.

Corners. The *Corners* algorithm determines the northern-, southern-, western- ,and easternmost locations and constructs a quadrilateral with those locations as vertices, displayed in Figure 53a.

Bounding box. The *Bounding Box* algorithm extends the *Corners* algorithm. It takes the quadrilateral and draws the smallest, non-rotated rectangle around it, displayed in Figure 53b.

Andrew's monotone chain. The *Andrew's Monotone Chain* algorithm [13] constructs the convex hull of a set of 2-dimensional points. The *Andrew's Monotone Chain* algorithm computes the upper and lower hulls of a monotone chain of points, displayed in Figure 53c. Like the *Graham Scan* [122], it runs in $O(n\log - n)$ time due to the sort time. After that, it only runs in $O(n)$ time to compute the hull [196].



(a) Corners. (b) Bounding Box. (c) Andrew's Monotone Chain.

Figure 53: Different algorithms for the blackout area calculation based on the nodes shared location histories. The red bordered rectangle represents the blackout area (OpenStreetMap).

Depending on the size of the blackout area and the number of affected nodes, the number of stored locations on each node can get very large. Therefore, nodes only exchange unknown positions after broadcasting their knowledge in a three-way handshake manner to reduce the load on the DTN-MANET. Additionally, to reduce the network load, we provide the option *hull only* to broadcast only the locations which are relevant for the blackout area calculation. For *Andrew's Monotone Chain*, this results in only broadcasting the hull, and for the *Bounding Box* and *Corners* algorithm only the corners of the rectangle, respectively.

For the evaluation of DRAS, we are relying on the Simonstrator.KOM platform, described in Chapter 6. The evaluation scenario is equal to the evaluation setup described in Section 6.1, which is extended with the representation of the ICT infrastructure. The ICT infrastructure is represented as rectangular grid cells, which can be turned on and off dynamically. Figure 54 visualizes the dynamic ICT blackout area (red rectangles) throughout a simulation run.

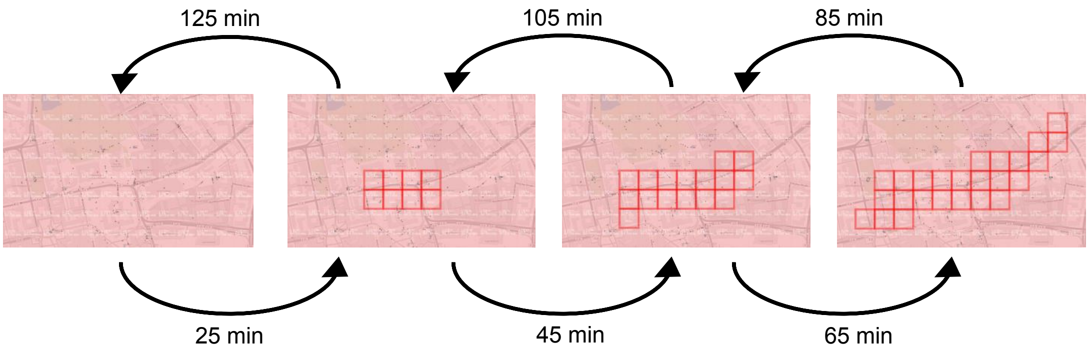
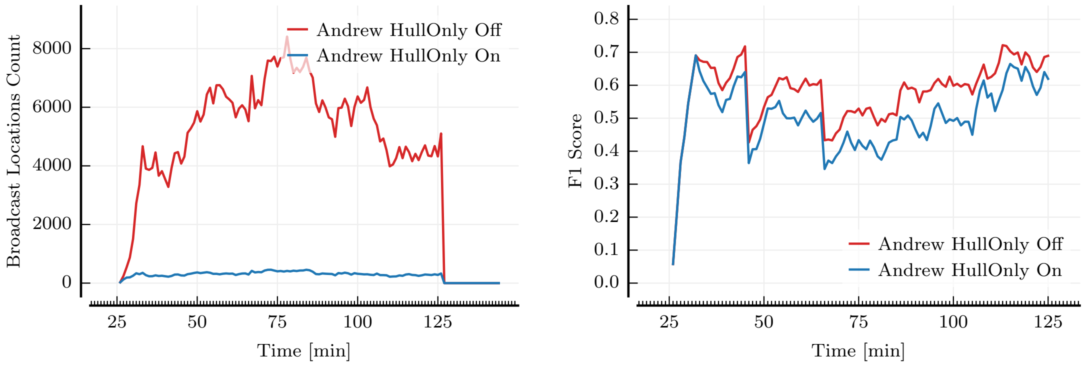


Figure 54: Dynamic change of the simulated blackout area. Rectangles with red borders represent the area with unavailable ICT (OpenStreetMap).

Figure 55a shows the number of exchanged locations by the network nodes, with and without the *hull only* option. The number of exchanged locations between the nodes can be reduced significantly.



(a) Location count.

(b) F1 score.

Figure 55: *Andrew's Monotone Chain*: Impact of the *hull only* option on the number of exchanged locations and the F1 score.

At the same time, Figure 55b shows that the performance (F1 Score) of the blackout area detection is slightly reduced when the *hull only* option is activated. When all available locations (without the *hull only* option) are exchanged between the communication nodes, an F1 Score between 0.43 and 0.72 can be achieved. The F1 score is the harmonic average of precision and recall [86]. Precision denotes the proportion of predicted positive cases that are correctly real positives and recall is the proportion of real positive cases that are correctly predicted positive. The F1 score reaches its best value at 1 when there is perfect precision and perfect recall. The sudden drops of the F1 score in Figure 55b at the 45 min and 65 min mark, are the result of the sudden increase of the simulated blackout area, displayed in Figure 54. For these sudden changes, the nodes need to gather new location information in the newly affected area to adapt to the dynamic scenario. Additionally, outdated stored locations should not be considered anymore.

This can be achieved by simply defining a maximum Time to Live (TTL), after that locations will not be considered anymore and are removed from the location storage on each node. Therefore, the configuration of the location TTL is important. If the TTL is set too low, information might expire before it has the chance to spread in the DTN-MANET. If the TTL is set too high, the number of stored locations will grow and more outdated locations will be taken into consideration to calculate the blackout area. This leads to increased computational cost, redundancy in high traffic areas, and possibly wrong results in low traffic areas.

To handle dynamic error corrections additionally to the TTL-based location timeouts, we introduce a so-called Location Consistency Check (LCC). During this check, each node iterates its stored locations and checks them for contradictions like an ICT-available location in the middle of a group of ICT-unavailable locations. In such a case, it is assumed that the freshest location (based on the TTL) is the more recent one and all locations of the opposite type in a defined radius around the freshest location are removed. Figure 56 shows the adaptations of a node's view on the blackout area when the size of the area suddenly changes.

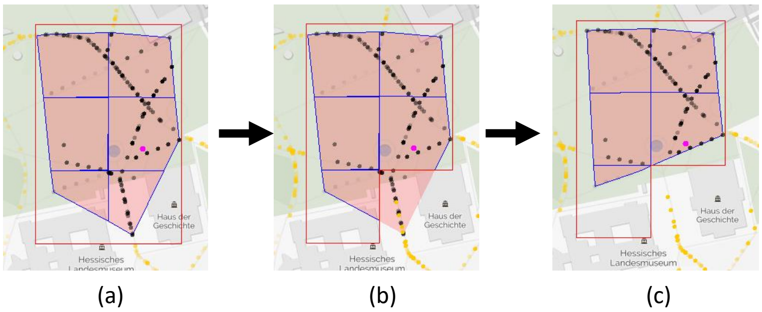
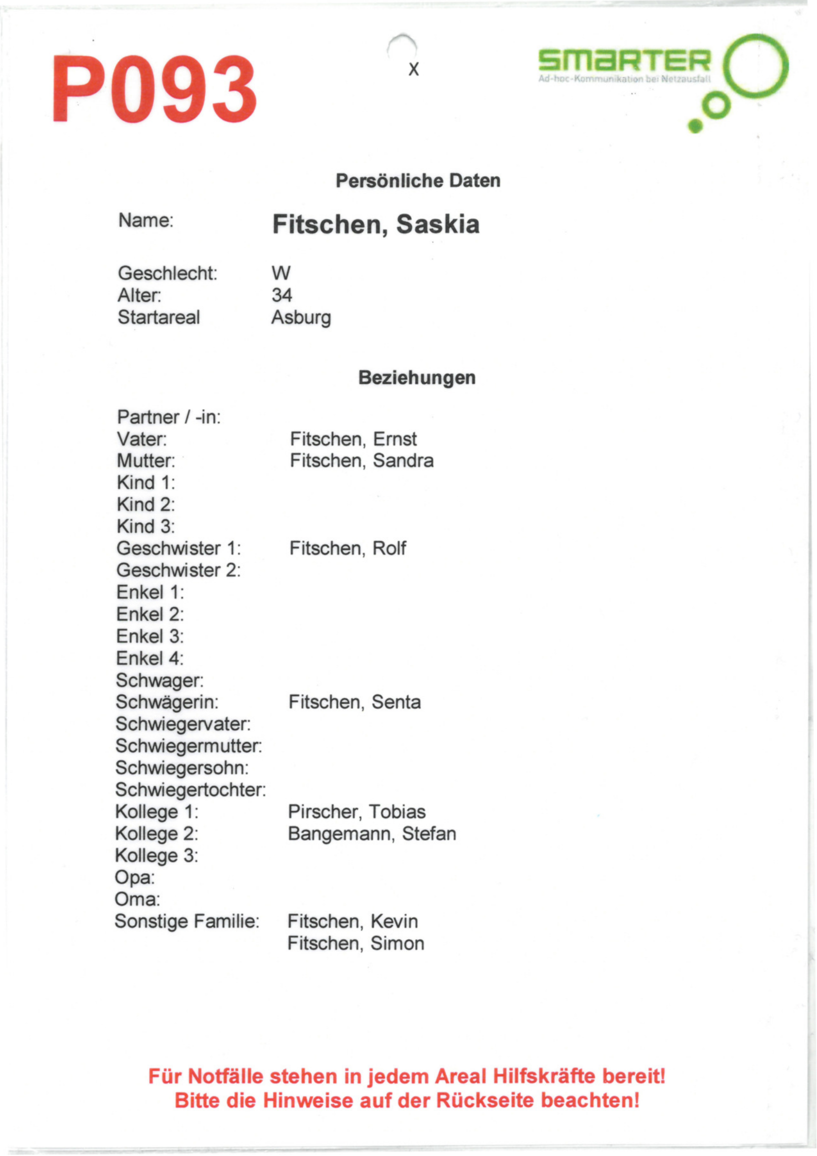


Figure 56: *Location Consistency Check (LCC)*: A node's view on the blackout area with a sudden change in the area size (a-b). The node adapts (c) to the change by detecting contradicting ICT-available (yellow) and ICT-unavailable (black) locations (OpenStreetMap).

In this section, we showed that DRAS can successfully detect and calculate the affected area of an ICT blackout to strengthen the situational awareness of the affected population. DRAS can cope with dynamic scenario changes and implements measures to reduce the resulting communication overhead of the service.

A.2 SED CARD EXAMPLE FROM THE FIELD TEST

In the conducted field test described in Chapter 4, 125 people participated to reflected the affected population of the disaster. Figure 57 and Figure 58 show a copy of an original *Sed Card* that was used during the field test. A *Sed Card* describes the attributes of a person with various information and tasks. The information about family and friends was also mirrored in the smartphone's contacts, which was handed out together with the *Sed Card*.



P093

x

SMARTER
Ad-hoc-Kommunikation bei Netzausfall

Persönliche Daten

Name: **Fitschen, Saskia**

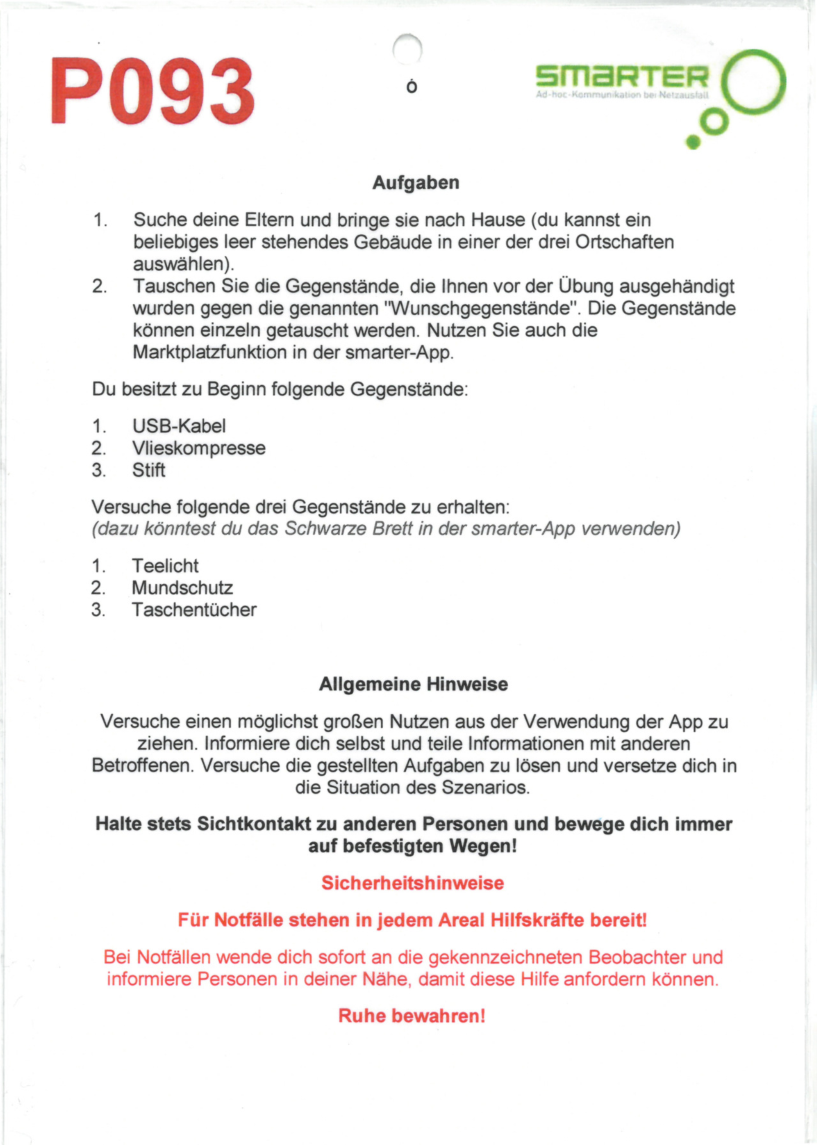
Geschlecht: W
Alter: 34
Startareal Asburg

Beziehungen

Partner / -in:
Vater: Fitschen, Ernst
Mutter: Fitschen, Sandra
Kind 1:
Kind 2:
Kind 3:
Geschwister 1: Fitschen, Rolf
Geschwister 2:
Enkel 1:
Enkel 2:
Enkel 3:
Enkel 4:
Schwager:
Schwägerin: Fitschen, Senta
Schwiegervater:
Schwiegermutter:
Schwiegersohn:
Schwiegertochter:
Kollege 1: Pirscher, Tobias
Kollege 2: Bangemann, Stefan
Kollege 3:
Opa:
Oma:
Sonstige Familie: Fitschen, Kevin
Fitschen, Simon

Für Notfälle stehen in jedem Areal Hilfskräfte bereit!
Bitte die Hinweise auf der Rückseite beachten!

Figure 57: Front-side of a *Sed Card* that was used during the field test, written in German. It includes information about the represented person including relatives and friends, a list of different tasks, and a list of desired items (cf. Figure 58).



P093

SMARTER
Ad-hoc-Kommunikation bei Netzausfall

Aufgaben

1. Suche deine Eltern und bringe sie nach Hause (du kannst ein beliebiges leer stehendes Gebäude in einer der drei Ortschaften auswählen).
2. Tauschen Sie die Gegenstände, die Ihnen vor der Übung ausgehändigt wurden gegen die genannten "Wunschgegenstände". Die Gegenstände können einzeln getauscht werden. Nutzen Sie auch die Marktplatzfunktion in der smarter-App.

Du besitzt zu Beginn folgende Gegenstände:

1. USB-Kabel
2. Vlieskompresse
3. Stift

Versuche folgende drei Gegenstände zu erhalten:
(dazu könntest du das Schwarze Brett in der smarter-App verwenden)

1. Teelicht
2. Mundschutz
3. Taschentücher

Allgemeine Hinweise

Versuche einen möglichst großen Nutzen aus der Verwendung der App zu ziehen. Informiere dich selbst und teile Informationen mit anderen Betroffenen. Versuche die gestellten Aufgaben zu lösen und versetze dich in die Situation des Szenarios.

Halte stets Sichtkontakt zu anderen Personen und bewege dich immer auf befestigten Wegen!

Sicherheitshinweise

Für Notfälle stehen in jedem Areal Hilfskräfte bereit!

Bei Notfällen wende dich sofort an die gekennzeichneten Beobachter und informiere Personen in deiner Nähe, damit diese Hilfe anfordern können.

Ruhe bewahren!

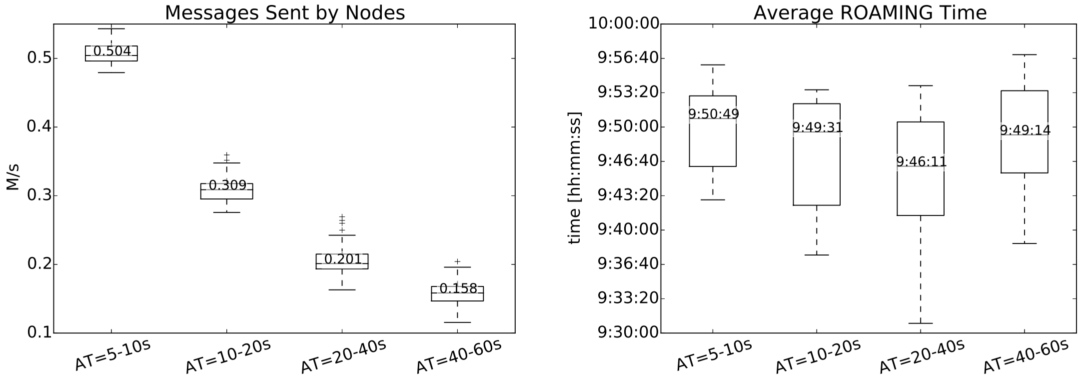
Figure 58: Back-side of a *Sed Card* in addition to Figure 57.

A.3 EXTENDED STUDY OF THE RESOURCE ALLOCATION SERVICE

This section provides additional results from the system and parameter evaluation of the resource allocation service as part of D2CS.KOM, as discussed in Section 5.2. The system parameter evaluation is necessary to understand the influence of different parameter settings on the overall system to determine suitable configuration setting for the different resource allocation strategies. The evaluation is conducted in the same setup described in Section 6.2, and the presented results provide detailed information about the parameters applied in Section 6.2.2. For the overall evaluation of the resource allocation service, we perform a twofold evaluation. First, we analyze the influence of strategy parameter settings, such as, the HEADING threshold as already presented in Section 6.2, the frequency of the nodes' resource announcements, and the message TTL. The second part of the evaluation focuses on the robustness of selected resource allocation strategies against scenario characteristic fluctuations. This evaluation includes an investigation of the influence of different Resource Demand Beacon (RDB) capacities and RDB generation intervals on the performance of the *En Passant* and *Greedy Selection* strategy.

Impact of the Nodes' Announcement Timer

Figure 59 shows the impact of the frequency in which nodes announce their knowledge about RDB advertisement to their neighborhood for cooperative resource allocation strategies such as *Greedy Selection*. This periodic messaging is responsible for the majority of the resource allocation service overhead, which is displayed in Figure 59a. For example, doubling the announcement interval from 5–10 s to 10–20 s results in a reduction of 39 % of the number of messages per second per node in the network. One might think that sending more announcements would lead to a better knowledge distribution in the network and, consequently, a better performance of the resource allocation service. However, Figure 59b shows that the announcement



(a) Message overhead. (b) Average total ROAMING time.

Figure 59: *Greedy Selection Strategy*: Impact of the frequency of different announcement timer (AT) values [138].

interval has only a small (at most 4 min) impact on the total average Roaming time per node when using the *Greedy Selection* strategy. While the reduction of the protocol overhead is important to consider, especially in resource-restricted post-disaster communication networks, a slight increase of the 0.2 messages send per second per node when applying an announcement timer of 5–10 s compared to 10–20 s is reasonable (cf. Figure 59a). More frequent resource announcements result in faster knowledge dissemination in the network, which is especially important in highly dynamic and mobile networks with sparse populations.

Impact of the Message TTL

Figure 60 shows the impact of different TTLs on the average total Roaming time while an announcement timer of 5–10 s was applied. Here the TTL defines the maximum hop count of a message. It can be seen that the TTL has no significant impact on the performance of the resource allocation service, since short TTLs are already compensated by the high frequency of newly generated resource advertisements by the nodes. In order to support the distribution of resources as good as possible, we have chosen a TTL of 7 hops in our evaluations throughout Section 6.2, since this TTL has reached the best median value.

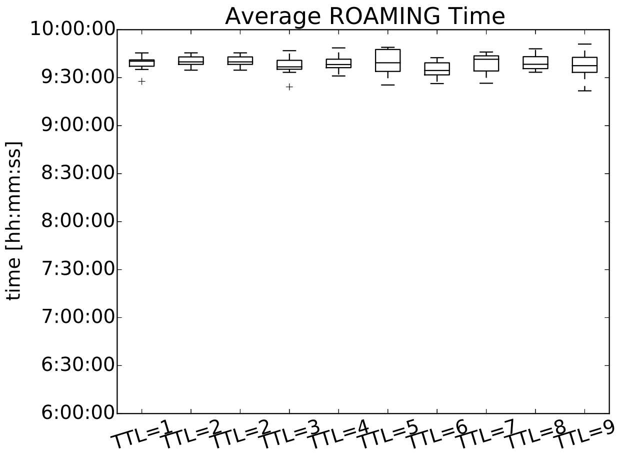
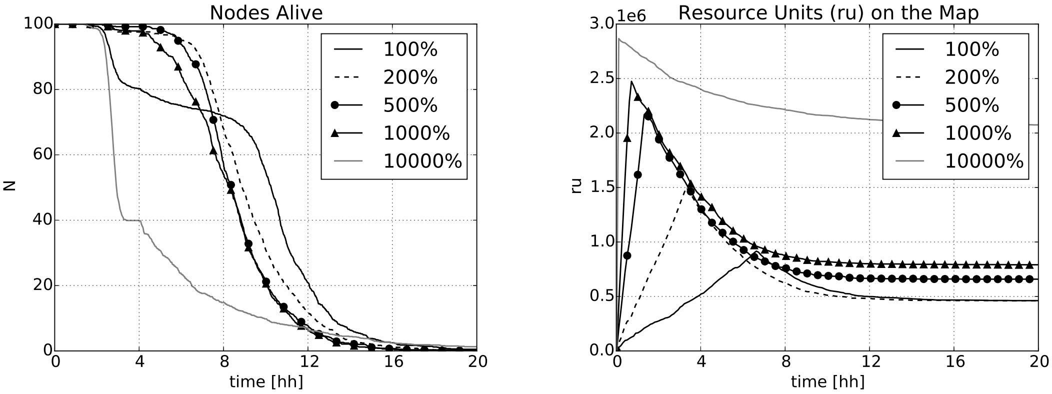


Figure 60: *Greedy Selection Strategy*: Average total Roaming time for different TTLs [138].

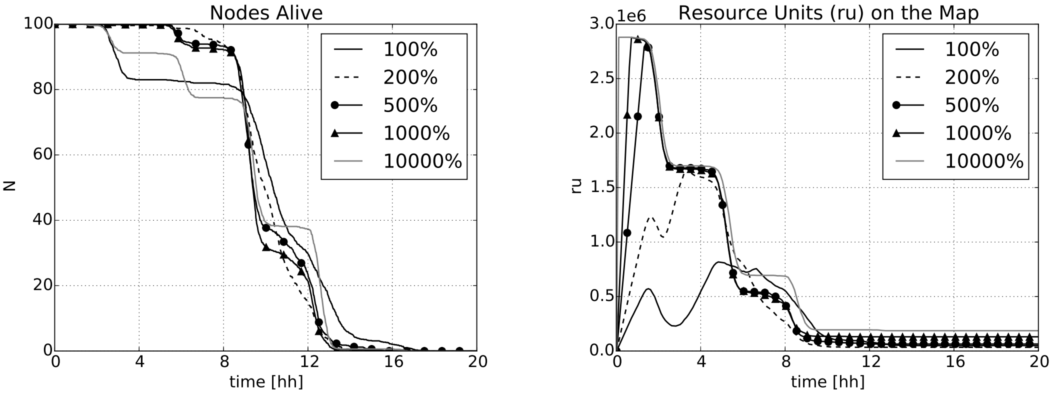
Impact of RDB Capacities and Generation Interval

To examine the robustness of the resource allocation service against scenario characteristic fluctuations, we investigate the impact of the resource amount per generated RDB. For five different resource amounts per RDB, Figure 61 shows the number of nodes alive over time and the amount of available resources in the simulated area. The overall amount of available resources in the evaluation is always the same, regardless of the different resource amounts per RDB. The RDB generation interval is set to 2 min, so that an increasing RDB resource amount results in a faster availability of the total amount of resources. An RDB resource amount of 100 %, with regard to a node's maximum battery capacity, all resources were made available by 200 different RDBs after approximately 6.66 h. An RDB resource amount of 10 000 % results in only two RDBs after 4 min. A lower number of RDBs consequently results in fewer nodes discovering them. In this case, the non-cooperative strategy *En Passant* performs poorly since the majority of nodes do not encounter one of the two RDBs and cannot recharge their battery. Figure 61a shows that less than 40 % of the nodes are alive after 4 h while most of the resources, held by the two RDBs, are not consumed in the end, as shown in Figure 61b. Independent of the amount of individual RDBs, *En Passant* is never able to utilize the overall available resources before all nodes are offline. In contrast, the cooperative strategy *Greedy Selection* demonstrates that the dissemination of resource advertisements enables nodes to be aware of the two different RDBs' locations, although they have not discovered them by themselves. This results in approximately 75 % consumed resources after 8 h (cf. Figure 61d). Nevertheless, some nodes never hear about available resources and go offline after approximately



(a) *En Passant Strategy.*

(b) *En Passant Strategy.*



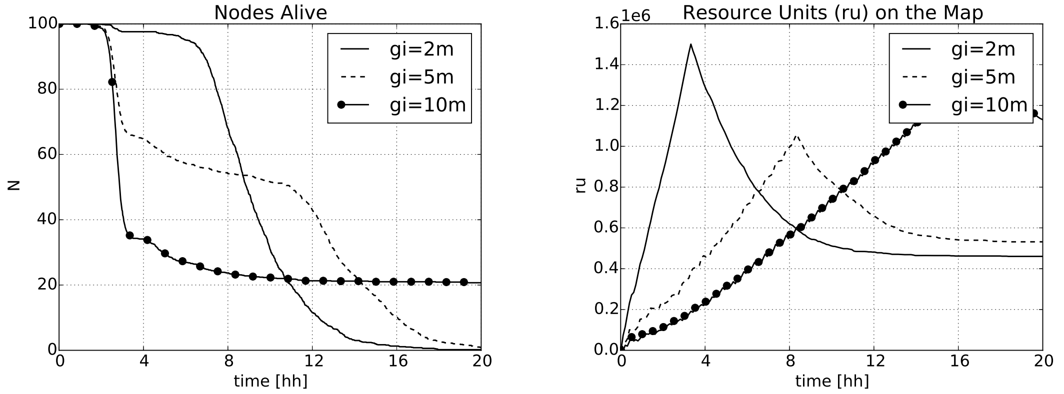
(c) *Greedy Selection Strategy.*

(d) *Greedy Selection Strategy.*

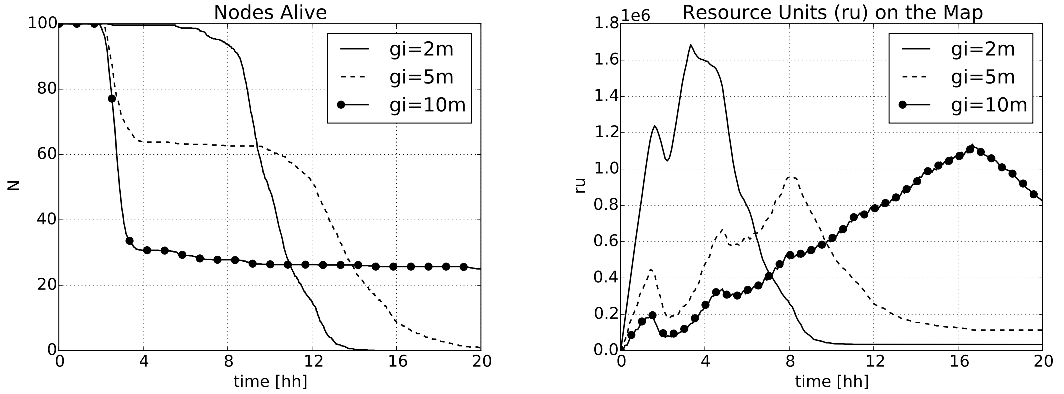
Figure 61: Nodes alive and available resources for different RDB resource amount (in % of the nodes' maximum battery capacity) [138].

3 h, which is visible as a sudden drop in Figure 61c. This results from the network partitioning caused by the nodes' individual movement patterns, which is a common characteristic for DTN-MANETs. Figure 61d highlights that, if knowledge is shared, almost all the RDBs are discovered and all the resources are consumed at the end of the simulation.

Both, *En Passant* and *Greedy Selection* benefit from a large number of RDBs as this makes the RDB discovery more likely and, additionally reduces the high competition of individual RDBs. However, with only 100 % battery capacity per RDB, the resource spawning is too slow and the available resource amount is too low to serve the resource demand of the nodes, resulting in nodes going offline without recharging at all. This is supported by the results for different generation intervals of RDBs in Figure 62, which determine the time until a new RDB spawns. With 200 % of a node's maximum battery capacity. When applying a generation interval of 5 min or 10 min, a large proportion of the nodes go offline before the 4 h mark.



(a) *En Passant Strategy.* (b) *En Passant Strategy.*



(c) *Greedy Selection Strategy.* (d) *Greedy Selection Strategy.*

Figure 62: Nodes alive and total amount of available resources for different RDB generation intervals (gi) [138].

A.4 LIST OF ACRONYMS

AODV	Ad Hoc On-demand Distance Vector
AORVA	Ad Hoc On-demand Reservation Vector Auction
BSN	Beacon Sequence Number
C2C	Civilian-to-civilian
C2O	Civilian-to-organization
CI	Critical Infrastructure
D2CS.KOM	Decentralized Disaster Communication System
DRAS	Disaster Region Analyzing Service
DTN	Delay-Tolerant Network
DTN-MANET	Delay Tolerant And Mobile Ad Hoc Network
ECDF	Empirical Cumulative Distribution Function
EID	Endpoint IDentifier
GPS	Global Positioning System
GSM	Global System For Mobile Communications
ICT	Information And Communication Technology
IFRC	International Federation Of Red Cross And Red Crescent Societies
IoT	Internet Of Things
LCC	Location Consistency Check
LoRa	Long Range
LOS	Line Of Sight
MANET	Mobile Ad Hoc Network
NGO	Non-governmental Organization
NLOS	No Line Of Sight
O2C	Organization-to-civilian
O2O	Organization-to-organization
P2P	Peer-to-peer
POI	Point Of Interest
RDB	Resource Demand Beacon
RSN	Request Sequence Number
TTL	Time To Live
UAV	Unmanned Aerial Vehicle
VANET	Vehicular Ad Hoc Network
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor Network

A.5 SUPERVISED STUDENT THESES

[1] Marco Casili. “Methods for Disaster Boundary Detection Caused by Infrastructure Blackouts.” Bachelor Thesis. TU Darmstadt, 2016.

[2] Daniel Ehrhard. “Entwicklung und Evaluation von Funkbrücken zwischen Ad-hoc-Netzcluster bei Katastrophenereignissen.” Bachelor Thesis. TU Darmstadt, 2016.

[3] Tim Feuerbach. “Allocation Strategies for Physical Energy-Resources in Adhoc Networks.” Master Thesis (Best Thesis of the Year 2017). TU Darmstadt, 2016.

[4] Simon Luser. “Adaptive Prioritization Mechanisms for Post Disaster Communications.” Master Thesis. TU Darmstadt, 2017.

[5] Prasanna Mahadevaswamy. “Development of Efficient Recruitment Strategies for Participatory Sensing.” Master Thesis. TU Darmstadt, 2015.

[6] Till Schmitt. “Untersuchung und Entwicklung Minimal-invasiver Mechanismen zur Abschätzung des Energieverbrauchs von Elektrogeräten.” Master Thesis. TU Darmstadt, 2016.

[7] Sophie Schönherr. “Hybrid Communication in Vehicular Networks: Combining the Advantages of Cellular and V2V Communication.” Master Thesis. TU Darmstadt, 2017.

[8] Marcel Verst. “Design of a Disaster Mobility Model Based on Real-world Movement Traces.” Master Thesis. TU Darmstadt, 2018.

[9] Martin Wende. “Data Validity Model: Evaluation of Information Freshness in Mobile Ad-Hoc Networks.” Bachelor Thesis. TU Darmstadt, 2017.

[10] Julian Zobel. “UAV Support for Mobile Ad Hoc Networks.” Master Thesis. TU Darmstadt, 2018.

B

AUTHOR'S PUBLICATIONS

MAIN PUBLICATIONS

[1] Lars Almon, Flor Álvarez, Patrick Lieser, Tobias Meuser, and Fabian Schaller. "Ad-Hoc-Kommunikation: Gesellschaftlich Wünschenswert, Rechtlich Ungeregelt." In: *Die Fortentwicklung des Datenschutzes*. Springer, 2018, pp. 77–98.

[2] Flor Álvarez, Lars Almon, Patrick Lieser, Tobias Meuser, Yannick Dylla, Björn Richerzhagen, Matthias Hollick, and Ralf Steinmetz. "Conducting a Large-scale Field Test of a Smartphone-based Communication Network for Emergency Response." In: *Proceedings of the 13th Workshop on Challenged Networks*. ACM. 2018, pp. 3–10.

[3] Patrick Lieser, Alaa Alhamoud, Hosam Nima, Björn Richerzhagen, Sanja Huhle, Doreen Böhnstedt, and Ralf Steinmetz. "Situation Detection based on Activity Recognition in Disaster Scenarios." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2018, pp. 1–17.

[4] Patrick Lieser, Flor Alvarez, Paul Gardner-Stephen, Matthias Hollick, and Doreen Böhnstedt. "Architecture for Responsive Emergency Communications Networks." In: *Global Humanitarian Technology Conference (GHTC), 2017 IEEE*. IEEE. 2017, pp. 1–9.

[5] Patrick Lieser, Frank Englert, Alaa Alhamoud, Daniel Burgstahler, and Doreen Boehnstedt. "Towards Virtual Sensors for Estimating the Electricity Consumption of Networked Appliances." In: *Proceedings of the 2015 ACM Sixth International Conference on Future Energy Systems*. ACM. 2015, pp. 205–206.

[6] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, Tobias Meuser, Björn Richerzhagen, and Ralf Steinmetz. "Collaborative Decentralized Resource Reservation for Emergency Communication Networks." In: *Proceedings of the 43rd IEEE Conference on Local Computer Networks (LCN)*. IEEE, 2018, pp. 1–9.

[7] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, Leonhard Nobach, Doreen Böhnstedt, and Ralf Steinmetz. "Take it or Leave it: Decentralized Resource Allocation in Mobile Networks." In: *Proceedings of the 42st IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2017, pp. 1–8.

[8] Patrick Lieser, Nils Richerzhagen, Simon Luser, Björn Richerzhagen, and Ralf Steinmetz. "Understanding the Impact of Message Prioritization in Post-Disaster Ad Hoc Networks." In: *Proc. International Conference on Networked Systems (NetSys)*. ACM. 2019, pp. 1–8.

[9] Patrick Lieser, Julian Zobel, Björn Richerzhagen, and Ralf Steinmetz. "Simulation Platform for Unmanned Aerial Systems in Emergency Ad Hoc Networks." In: *Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM), awarded with the Best Student Paper Award*. 2019, pp. 1–15.

CO-AUTHORED PUBLICATIONS

[10] Frank Englert, Patrick Lieser, Alaa Alhamoud, Doreen Boehnstedt, and Ralf Steinmetz. "Electricity-metering in a Connected World: Virtual Sensors for Estimating the Electricity Consumption of IOT Appliances." In: *Future Internet of Things and Cloud (FiCloud), 2015 3rd International Conference on*. IEEE. 2015, pp. 317–324.

[11] Frank Englert, Patrick Lieser, Marius Rettberg-Paplow, Alaa Alhamoud, Doreen Böhnstedt, and Ralf Steinmetz. "LightMon: Apportioning the Effect of Light Switching Events on the Electricity Consumption of Buildings." In: *EWSN*. 2016, pp. 77–88.

[12] Paul Gardner-Stephen, Romana Challans, Jeremy Lakeman, Andrew Bettison, Patrick Lieser, Ralf Steinmetz, Flor Alvarez, and Matthew Lloyd. "Productizing Humanitarian Telecommunications Research: A Case Study of the Serval Mesh Extender." In: *Global Humanitarian Technology Conference (GHTC), 2017 IEEE*. IEEE. 2017, pp. 1–10.

[13] Tobias Meuser, Patrick Lieser, The An Binh Nguyen, Doreen Böhnstedt, and Ralf Steinmetz. "Adaptive Information Aggregation for Application-specific Demands." In: *Proceedings of the 1st BalkanCom* (2017), pp. 1–5.

[14] Tobias Meuser, Patrick Lieser, The An Binh Nguyen, Doreen Böhnstedt, and Ralf Steinmetz. "Lifetime-aware Information Aggregation under Uncertainty for Advanced Driver Assistance Systems." In: *Ad Hoc Networks*. Vol. 82. Elsevier, 2019, pp. 56–67.

[15] Tobias Meuser, Martin Wende, Patrick Lieser, Björn Richerzhagen, and Ralf Steinmetz. "Adaptive Decision Making Based on Temporal Information Dynamics." In: *Proceedings of Vehicle Technology and Intelligent Transport Systems (VEHITS) - Best Student Paper Award*. SCITEPRESS, 2018, pp. 91–102.

[16] Nils Richerzhagen, Roland Kluge, Björn Richerzhagen, Patrick Lieser, Boris Koldehofe, Ioannis Stavrakakis, and Ralf Steinmetz. "Better Together: Collaborative Monitoring for Location-based Services." In: *Proceedings of the 19th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, June 2018, pp. 1–9.

[17] Nils Richerzhagen, Patrick Lieser, Björn Richerzhagen, Boris Koldehofe, Ioannis Stavrakakis, and Ralf Steinmetz. "Change as Chance: Transition-enabled Monitoring for Dynamic Networks and Environments." In: *Proceedings of the 14th Wireless On-demand Network systems and Services Conference (WONS)*. IEEE/IFIP, Feb. 2018, pp. 1–8.

[18] Julian Zobel, Patrick Lieser, Bastian Drescher, Bernd Freisleben, and Ralf Steinmetz. "Optimizing Inter-Cluster Flights of Post-Disaster Communication Support UAVs." In: *Proceedings of the 44th IEEE Conference on Local Computer Networks (LCN)*. Oct. 2019.

DEMO PAPERS

[19] Patrick Lieser, Nils Richerzhagen, Tim Feuerbach, The An Binh Nguyen, Björn Richerzhagen, Doreen Böhnstedt, and Ralf Steinmetz. "Decentralized Resource Allocation in Mobile Networks." In: *Demonstrations of the 42nd IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2017, pp. 1–3.

[20] Patrick Lieser, Nils Richerzhagen, Michal Lipinski, Clemens Krug, Tobias Meuser, Björn Richerzhagen, and Ralf Steinmetz. "Decentralized Disaster Area Detection in Mobile Networks." In: *Demonstrations of the 43rd IEEE Conference on Local Computer Networks (LCN)*. IEEE, Oct. 2018, pp. 1–3.

[21] Julian Zobel, Patrick Lieser, and Ralf Steinmetz. "Multi-Strategy Simulation of Aerial Post-Disaster Ad Hoc Communication Support Systems." In: *Demonstrations of the 44th IEEE Conference on Local Computer Networks (LCN Demonstrations)*. Oct. 2019.

C

CURRICULUM VITÆ

Personal

Name	Patrick Lieser
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Place of Birth	Wiesbaden-Dotzheim, Germany
Nationality	German

Education

09/2017-12/2017	University of Massachusetts Amherst, USA Visiting researcher at the department of Electrical and Computer Engineering
Since 02/2015	Technische Universität Darmstadt, Germany Doctoral candidate at the Department of Electrical Engineering and Information Technology
10/2012-11/2014	Technische Universität Darmstadt, Germany Master studies in Electrical Engineering and Information Technology (Informationssystemtechnik) Degree: Master of Science
10/2007-09/2012	Technische Universität Darmstadt, Germany Bachelor studies in Electrical Engineering and Information Technology (Informationssystemtechnik) Degree: Bachelor of Science
08/2005-07/2007	DBV-Winterthur/AXA Versicherung, Wiesbaden, Germany Vocational training as a Computer Science Expert Subject Area: System Integration
08/2002–07/2005	Friedrich-List-Schule, Wiesbaden, Germany, Degree: Allgemeine Hochschulreife

Academic Experience

Since 04/2019	Technische Universität Darmstadt, Head of the research group “Distributed Sensing Systems” at the Multimedia Communications Lab

Since 01/2019	Researcher funded by the LOEWE initiative project – Nature 4.0 “Sensing Biodiversity”
03/2015-02/2018	Researcher funded by the BMBF (German Federal Ministry of Education and Research) project – SMARTER “Smartphone-based Communication Networks for Emergency Response”
02/2015-12/2018	Researcher associated by the LOEWE initiative project – NICER “Networked Infrastructureless Cooperation for Emergency Response”

WORK EXPERIENCE

Since 02/2015	Technische Universität Darmstadt & the httc e.V., Germany Research assistant at the research group “Distributed Sensing Systems” at the Multimedia Communications Lab
08/2005-09/2007	IT Specialist, Decentralized Systems, DBV-Winterthur/AXA Versicherung, Wiesbaden, Germany

TEACHING ACTIVITY

Since 02/2015	Lab and Project “Multimedia Communications Lab/Project”, Supervisor.
Since 02/2015	Seminar “Advanced Topics in Future Internet Research”, Supervisor.

HONORS

05/2019	Best Student Paper Award for “Simulation Platform for Unmanned Aerial Systems in Emergency Ad Hoc Networks” at ISCRAM 2019.
03/2016-11/2017	Selected candidate in BMBF funded SOFTWARE CAMPUS program.
03/2016	Best Master Thesis, Energy Award 2016 for the Multi Disciplinary Topic Energy, Technische Universität Darmstadt

Darmstadt, July 1st, 2019

Patrick Lieser

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ERKLÄRUNG LAUT PROMOTIONSORDNUNG

§8 Abs. 1 lit. c PromO

Ich versichere hiermit, dass die elektronische Version meiner Dissertation mit der schriftlichen Version übereinstimmt.

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Ich versichere hiermit, dass zu einem vorherigen Zeitpunkt noch keine Promotion versucht wurde. In diesem Fall sind nähere Angaben über Zeitpunkt, Hochschule, Dissertationsthema und Ergebnis dieses Versuchs mitzuteilen.

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Ich versichere hiermit, dass die vorliegende Dissertation selbstständig und nur unter Verwendung der angegebenen Quellen verfasst wurde.

§9 Abs. 2 PromO

Die Arbeit hat bisher noch nicht zu Prüfungszwecken gedient.

Darmstadt, 1. Juli 2019

Patrick Lieser