AERIAL NETWORK ASSISTANCE SYSTEMS *for* POST-DISASTER SCENARIOS

Topology Monitoring and Communication Support in Infrastructure-Independent Networks

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ABSTRACT

Communication anytime and anywhere is necessary for our modern society to function. However, the critical network infrastructure quickly fails in the face of a disaster and leaves the affected population without means of communication. This lack can be overcome by smartphone-based emergency communication systems, based on infrastructure-independent networks like Delay-Tolerant Networks (DTNs). DTNs, however, suffer from short device-to-device link distances and, thus, require multi-hop routing or data ferries between disjunct parts of the network. In disaster scenarios, this fragmentation is particularly severe because of the highly clustered human mobility behavior. Nevertheless, aerial communication support systems can connect local network clusters by utilizing Unmanned Aerial Vehicles (UAVs) as data ferries. To facilitate situation-aware and adaptive communication support, knowledge of the network topology, the identification of missing communication links, and the constant reassessment of dynamic disasters are required. These requirements are usually neglected, despite existing approaches to aerial monitoring systems capable of detecting devices and networks.

In this dissertation, we, therefore, facilitate the coexistence of aerial topology monitoring and communications support mechanisms in an autonomous *Aerial Network Assistance System* for infrastructure-independent networks as our first contribution. To enable system adaptations to unknown and dynamic disaster situations, our second contribution addresses the collection, processing, and utilization of topology information. For one thing, we introduce cooperative monitoring approaches to include the DTN in the monitoring process. Furthermore, we apply novel approaches for data aggregation and network cluster estimation to facilitate the continuous assessment of topology information and an appropriate system adaptation. Based on this, we introduce an adaptive topology-aware routing approach to reroute UAVs and increase the coverage of disconnected nodes outside clusters.

We generalize our contributions by integrating them into a simulation framework, creating an evaluation platform for autonomous aerial systems as our third contribution. We further increase the expressiveness of our aerial system evaluation, by adding movement models for multicopter aircraft combined with power consumption models based on real-world measurements. Additionally, we improve the disaster simulation by generalizing civilian disaster mobility based on a real-world field test. With a prototypical system implementation, we extensively evaluate our contributions and show the significant benefits of cooperative monitoring and topology-aware routing, respectively. We highlight the importance of continuous and integrated topology monitoring for aerial communications support and demonstrate its necessity for an adaptive and long-term disaster deployment. In conclusion, the contributions of this dissertation enable the usage of autonomous *Aerial Network Assistance Systems* and their adaptability in dynamic disaster scenarios.

KURZFASSUNG

Kommunikation zu jeder Zeit und an jedem Ort ist für das Funktionieren unserer modernen Gesellschaft unerlässlich. Im Falle einer Katastrophe versagt die kritische Netzinfrastruktur jedoch schnell und lässt die betroffene Zivilbevölkerung ohne Kommunikationsmöglichkeiten zurück. Dieser Mangel kann durch Smartphone-basierte Notfallkommunikationssysteme überwunden werden, die basierend auf infrastrukturunabhängigen Netzwerken wie Delay-Tolerant Networks (DTN) der Bevölkerung ermöglichen, sich selbst zu organisieren und zu helfen. DTNs sind jedoch durch kurze Verbindungsdistanzen zwischen den Geräten eingeschränkt und erfordern daher Multi-Hop-Routing oder Datenfähren zwischen voneinander getrennten Netzwerkteilen. In Katastrophenszenarien ist die Fragmentierung der Netzwerke aufgrund des stark geclusterten Mobilitätsverhaltens der Menschen besonders schwerwiegend. In solchen Fällen können Luftfahrtsysteme zur Kommunikationsunterstützung genutzt werden, die unbemannte Luftfahrzeuge (Unmanned Aerial Vehicles, UAVs) als Datenfähren einsetzen, um lokale Netzwerkcluster verbinden. Um langfristige, situationsangepasste und adaptive Kommunikationsunterstützung zu ermöglichen, sind jedoch Kenntnisse der Netztopologie, die Identifizierung fehlender Kommunikationsverbindungen und die ständige Neubewertung der dynamischen Katastrophensituationen erforderlich. Diese Anforderungen werden aber in der Regel vernachlässigt, trotz vorhandener Ansätze für Luftüberwachungssysteme, die in der Lage sind Geräte oder Netzwerke mit Hilfe von UAVs zu erkennen.

Diese Dissertation erforscht daher die Kombination aus luftgestützter Topologieüberwachung und Kommunikationsunterstützung für infrastrukturunabhängige Netzwerke. Unser erster Beitrag, das Konzept für *Aerial Network Assistance Systems*, vereint beide Anwendungen als koexistente Mechanismen innerhalb eines gemeinsamen Systems. Um Anpassungen an unbekannte und dynamische Katastrophensituationen zu ermöglichen, liefern wir als weiteren Beitrag Ansätze zur Erfassung, Verarbeitung und Nutzung von Topologieinformationen. Dabei wenden wir kooperative Ansätze zur Informationsgewinnung an, um Netzwerkknoten im DTN in den Überwachungsprozess einzubinden. Außerdem konzipieren wir Ansätze zur Datenaggregation und zur Lageabschätzung von Netzwerkclustern, um die kontinuierliche Bewertung von Topologieinformationen und eine entsprechende Systemanpassung zu ermöglichen. Auf dieser Grundlage führen wir einen adaptiven, topologiebasierten Routing-Ansatz ein, um UAVs umzuleiten und so die Abdeckung von Knoten außerhalb von Clustern zu erhöhen.

Wir generalisieren unsere Beiträge durch die Integration in ein Simulationsframework, wodurch wir als dritten Beitrag eine Evaluationsplattform für autonome Luftfahrtsysteme schaffen. Dabei erhöhen wir die Aussagekraft der Simulationen durch die Modellierung der Bewegung und des Energieverbrauchs von Multikopter-UAVs basierend auf realen Messdaten. Zusätzlich verbessern wir die Simulation durch ein

Mobilitätsmodell für Zivilisten in Katastrophenszenarien auf Grundlage eines realen Feldtests. Anhand einer prototypischen Implementierung führen wir eine umfassende Evaluierung unserer Beiträge durch und zeigen die wesentlichen Vorteile von kooperativer Informationsgewinnung sowie von adaptivem topologiebasierten Routing. Zusammenfassend belegt unsere Evaluation die Bedeutung einer kontinuierlichen und integrierten Topologieüberwachung für die Kommunikationsunterstützung aus der Luft und zeigt deren Notwendigkeit für einen adaptiven und langfristigen Katastropheneinsatz. Die Beiträge dieser Dissertation ermöglichen dabei den Einsatz von autonomen *Aerial Network Assistance Systems* und deren Anpassungsfähigkeit in dynamischen Katastrophenszenarien.

PREVIOUS PUBLICATIONS

This thesis includes previous publications from scientific conferences. No text in this thesis is directly taken from these publications. Figures that showcase key concepts or individual results from these materials are clearly marked as such or adopted to the contents of this thesis. Tables with model parameters or evaluation settings are similarly adopted or have been restructured. The publications considered for the content of this thesis are summarized in Table 1.

Table 1: Previously published material.

Section	[171]	[312]	[310]	[313]	[315][311]	[316]
Chapter 4: Aerial Network Assistance System for Disaster DTNs						
Aerial Monitoring					✓	
Aerial Communication Support	✓	✓	✓			
Cooperative Aerial Monitoring					✓	
Cluster Detection			✓			
Transit Node Coverage			✓			
Chapter 5: Platform for Unmanned Aircraft Systems						
System Prototype	✓	✓		✓	✓	✓
Civilian Disaster Mobility				✓		
UAV Energy and Movement	✓	✓				
Chapter 6: Evaluation						
Cooperative Aerial-Ground Monitoring					✓	
Cluster Detection			✓			
Transit Coverage			✓			
Mechanism Coexistence	✓		✓		✓	
Appendix A						
CDM Model Evaluation				✓		
Dynamic Monitoring Areas						✓

The contributions in this thesis are the results of collaborative work and joint team efforts at the Multimedia Communications Lab (KOM) at the Technical University of Darmstadt (TU Darmstadt). If not stated otherwise, the mentioned persons were working at KOM at the time of their contribution. Throughout this thesis, I use "we" as a reference to each contribution's collaborative effort and use this section to provide an overview of the contributions of co-authors and contributors to the respective work. Furthermore, I detail the chapters that include verbatim and rephrased fragments from publications or collaborative work. The complete list of my publications, including those not included as part of this thesis, is given in Appendix C.

The genesis of this thesis and its contributions was supervised (in alphabetical order) by Dr.-Ing. Rhaban Hark, Dr.-Ing. Ralf Kundel, Dr.-Ing. Patrick Lieser, Dr.-Ing. Tobias Meuser, and Dr.-Ing. Björn Richerzhagen. Throughout their respective time at KOM, they provided valuable feedback on the considered approach, development, implementation, and used methodology. Apart from this input, I will mention them in the following for every contribution to which they added individually.

Chapter 4, Aerial Network Assistance System for Post-Disaster DTNs, presents the design of an aerial system as well as contributions to the collection, processing, and utilization of topology information, required for system adaptability in dynamic disaster scenarios. The presented concepts for Aerial Communication Support and the initial system designs were developed together with Patrick Lieser and Björn Richerzhagen. The design and results were published in [171] with Patrick Lieser and me as equal first authors. This design was the foundation for my later design of the Aerial Monitoring System and, consequently, the combined system design which is used in this thesis for the Aerial Network Assistance System. The system design was constantly improved with valuable feedback from Björn Richerzhagen. I developed the idea of cooperative aerial monitoring while working together with Simon Johannes Güthoff (student at TU Darmstadt), who assessed the feasibility in a first prototypical implementation. Later on, Tobias Meuser and me revised possible cooperative communication protocols and we published the first results of a working cooperative monitoring approach in [315]. The follow-up publication in [311] was extended with more protocols and a more extensive evaluation by myself, with Ralf Kundel contributing to the writing of the manuscript. The cluster detection and transit node coverage were joint efforts together with Benjamin Becker (KOM) and Ralf Kundel. Especially the routing approach was developed by Benjamin and me in close collaboration. The results were published in [310], with all co-authors contributing to the writing of the publication.

Naturally, the implemented system provided in Chapter 5, evaluation platform for unmanned aircraft systems, is based on the system designs presented in Chapter 4 and is, therefore, also developed on the foundation of the initial system design jointly created by Patrick Lieser, Björn Richerzhagen, and me. The system's implementation was constantly improved with assistance and valuable feedback from Tobias Meuser. Together with Niklas Stöhr (student at TU Darmstadt), I developed the concept of topology-aware monitoring area adaptations. Niklas developed a prototype based on my Aerial Monitoring System design, and the initial results were published in [316]. Although not within the main contributions of this thesis, we summarize the findings of this work in Section A.4. However, parts of the implemented prototype, like the monitoring area definition and the basic monitoring strategy, are used within the evaluation platform. The movement model for multicopter UAVs used in this thesis is based on initial designs and implementation work by Julian Kordisch (student at TU Darmstadt), Yashita Saxena (student at TU Darmstadt), and me. I extended the developed simplistic movement model with different flight states and, additionally, included acceleration and deceleration phases to the model. The thrust-based power consumption model of the Intel Aero RTF drone was a joint concept of Patrick Lieser and me. I finalized the model and its implementation; the results were published in [312]. The power consumption, initially measured under lab conditions, was later verified by real-world flight measurements with the Intel Aero RTF Drone by Tobias Faschingbauer (student at TU Darmstadt). The civilian disaster mobility model, presented and utilized in this work, is based on trace data from the Smarter field test [15, 166]. Patrick Lieser and Tobias Meuser contributed significantly to the analysis of the trace data as well as the design and implementation of the mobility model. Lars Baumgärtner from the Software Technology group at TU Darmstadt further contributed to the manuscript's writing, published in [313]. For the sake of completeness and to allow a comparison between the utilized civilian disaster mobility model in this thesis and other models, Section A.3 summarizes the assessment of the provided mobility model.

Chapter 6, EVALUATION, discusses the evaluation of the Aerial Network Assistance System and our respective contributions. The definition of the individual evaluation scenarios and the applied system parameters happened with Patrick Lieser for the estimation scenario and with Tobias Meuser and Ralf Kundel for the cooperative scenario, respectively. Furthermore, Patrick Lieser and Björn Richerzhagen assisted with the determination of the basic evaluation setup. The evaluation is founded on the insights of previous work, which was collaboratively investigated with the respective colleagues and students [171, 310–313, 315, 316]. The presented evaluation in this thesis was performed with valuable feedback from Dr.-Ing. Thomas Tregel (KOM) and Tobias Meuser.

CONTENTS

1 INTRODUCTION

COMMUNICATION anytime and anywhere is one of the key aspects of our modern society. We grew accustomed to receiving and accessing any publicly available information conveniently or communicating with basically anyone over messenger services and social media. Nevertheless, this also makes us and our society heavily dependent on critical infrastructure for Information and Communication Technology (ICT), which is the backbone of our utilized communication networks. At the same time, extreme weather conditions and other natural disasters have increased in frequency, scale, and devastation in recent years due to climate change and are expected to increase in the future [78, 279, 289]. Large-scale disasters, such as the devastation of Puerto Rico by Hurricane Maria in 2017 [101, 318] or the tremendous flooding of the Ahrtal in Germany in 2021 [52, 152], demonstrate the vulnerability of our infrastructure to disasters. Within a short time frame, parts of the ICT infrastructure are damaged or destroyed. The overload of the remaining ICT infrastructure and the additional disruption of the power supply infrastructure lead to further cascading failures [115, 285]. Eventually, this results in a complete infrastructure breakdown and the unavailability of any usable means of ICT in a post-disaster scenario. In this thesis, we use the term *post-disaster* to designate the phase directly after the disaster incident until the restoration and availability of ICT to the pre-disaster state. The recovery for at least basic communication takes days to weeks, while a complete recovery may take even months [52, 101, 152, 285, 318].

Society depends on communication

ICT infrastructure vulnerable to disasters

However, communication is crucial for efficient disaster relief to help affected civilians and limit fatalities. Emergency services require information about the location of civilians, incident sites, and more to coordinate and facilitate help. Civilians, on the other hand, try to call for help, coordinate rescue efforts in their local communities, or notify family and friends of their whereabouts [166, 196, 279]. After a disaster, the significantly greater demand for communication capability stands in stark contrast to its limited availability and capacity [124, 152, 206, 227, 285, 286, 295]. This large gap, nevertheless, can be overcome by using infrastructure-independent communication networks [167, 229]. Especially Delay-Tolerant Networks (DTNs) have shown their capability to provide essential services for disaster communication by utilizing the plethora of smart mobile end-user devices like smartphones available in the civilian population [15, 166, 167]. DTNs follow the *store-carry-forward* principle, where each device stores available data and uses spontaneous device-to-device communication — also known as *ad hoc* communication — to share data with other network nodes whenever possible. Thus, DTNs can be deployed on demand, are adaptable and relocatable, and do neither require fixed infrastructure nor end-to-end connectivity [15, 66, 136, 166, 251]. The drawback of DTNs, on the other hand, is their reliance on the mobility of DTN nodes to carry data over long distances without a steady

Disaster relief requires communication

Smartphone-based emergency services over DTNs connection. Since civilian mobility cannot be controlled, communication over long distances and between disconnected parts of the network is entirely opportunistic. This is, furthermore, increased by human mobility in a post-disaster scenario: People concentrate around and within Areas of Interest (AoIs) like shelters or hospitals and, when moving larger distances between different AoIs, tend to form and move around in groups. The resulting network topology is, therefore, highly clustered, intermittent, and subject to constant change [15, 166]. While communication within a local cluster works fine, communication between different clusters is scarce, highly delayed, or impossible at all.

Intermittent and clustered network

1.1 MOTIVATION FOR AERIAL NETWORK ASSISTANCE

Unmanned Aerial Vehicles (UAVs)[1] are used in a large variety of private, industrial, or commercial applications [17, 119, 161, 172, 201, 219, 254, 272, 278, 282, 296, 307] due to their mobility and versatility. While UAVs were initially remotely piloted, the advances in robotics in the last years facilitated UAVs with increasing autonomy and reduced size and costs [207]. Especially autonomy, ranging from remotely monitored autonomous flight to fully autonomous mission execution, is a key enabler in utilizing UAVs in large-scale applications such as parcel or goods delivery [17, 296]. Similarly, UAVs first resembled actual plane-like aircraft. The development of precisely maneuverable multi-rotor UAVs with the capability of hovering mid-air as well as vertical takeoff and landing with minimum space requirements, however, led to a replacement in many fields of application over the years. Especially smaller versions of these commonly called *multicopters* are particularly suited for deployment in urban city environments and nowadays constitute the most prevalent type of UAVs [207]. Their capability to perform missions autonomously and their independence from impassable terrain, like debris or broken road infrastructure, makes them particularly suitable for deployment in a post-disaster scenario [49, 79, 80, 283].

Autonomous multicopter UAVs

UAVs are typically part of a larger Unmanned Aircraft System (UAS), comprised of several autonomous UAVs and a central operation and coordination unit [80, 81, 119, 207]. In this thesis, we focus on *Aerial Communication Support*: a category of UAS applications with the particular intention to assist and support existing communication networks, for example, by relaying or transporting messages to facilitate communication when the communication network is not capable of itself. UAV-based communication support allows for compensating overloaded and broken ICT infrastructure, extending the coverage of a network, or providing a standalone Radio Access Network (RAN) [63, 82, 111, 180, 194, 203, 210, 249]. Furthermore, UAVs are used as quick and efficient data ferries between disconnected parts or single nodes of a network, providing delayed long-distance communication links [48, 110, 202, 301]. The latter approach is particularly well-suitable to connect network partitions of sparsely populated and highly clustered networks, such as disaster DTNs. The effi-

Aerial communication support systems...

...deploy data ferry UAVs to connect DTN clusters...

1 Typically, the term "drone" is used interchangeably in everyday language. However, UAVs specifically provide autonomous capabilities. Thus, generally speaking, every UAV is a drone but not every drone is a UAV. Confer Section 3.1 for more details.

cacy of aerial communication support is directly linked to the availability of topology information on the supported communication network. Without proper network information, the system cannot identify gaps in the network and deploy UAVs to close them. Furthermore, the situation in a disaster area is subject to constant, sometimes volatile change. Identifying changes and adapting the system to them is, therefore, a key requirement for long-term communication support in a disaster area.

... but topology information is needed.

While the aforementioned approaches rely heavily on up-to-date network information, they do not incorporate the collection and continuous update of this information, but focus on utilization and optimization based on information that is *assumed* to be available. Similarly, the adaptation of aerial communication support to a frequently changing scenario is rarely studied in the literature, despite being a paramount aspect of its applicability due to the uncontrollable, dynamic, and constantly changing disaster situation. Nevertheless, the identification and localization of people, objects, vehicles, or mobile devices via UAVs has already been studied extensively [3, 7, 59, 123, 172, 245, 250, 264, 293, 304]. Especially in a disaster environment, such *Aerial Monitoring Systems* can autonomously detect mobile devices even without line-of-sight, e.g., via 5G or Wireless Fidelity (WiFi) signals, and identify the present network topology [245, 304].

Negligence of information retrieval...

...but possible via aerial monitoring systems.

In this thesis, we study and analyze the characteristics of UAV-based communication support, UAV-based monitoring, and their respective systems. We propose the design of an *Aerial Network Assistance System* that combines aerial communication support and aerial monitoring in a single system to address the emerging challenges for deployment in disaster scenarios.

1.2 RESEARCH CHALLENGES

The post-disaster scenario imposes significant challenges for deploying aerial topology detection and communication support. The following research challenges, thus, influence the design and effective realization of our Aerial Network Assistance System presented in this thesis.

Challenge: *Scarcity, inaccuracy, and decay of information.*

Information in a post-disaster scenario, like the location of incidents or the affected civilian population, is critical and, therefore, highly valuable for any disaster relief effort. The availability and quality of such information, however, stand in stark contrast to the necessity and dependency on it because *(i)* a priori information in a post-disaster area is scarce or not available at all, *(ii)* this information can be inaccurate or incorrect, and also *(iii)* deteriorates in accuracy or correctness over time as a result of constant changes in the disaster area [110, 116, 213]. The constantly required collection, analysis, and processing of information, thus, constitutes a major challenge for any system and application in a post-disaster scenario.

Challenge: *Uniquity, dynamicity, and volatility of the disaster scenario.*

Every post-disaster scenario is unique and unforeseeable, making comprehensive preparation hard or even impossible to achieve. Furthermore, the scenario can be dynamic and under constant — sometimes even volatile — changes; in our case, we particularly focus on the network, which is directly related to the behavior of humans carrying their devices. Typical human mobility within the disaster area provides a dynamic network topology with constant but typically slow changes. However, emerging hazards like fires or floods, for example, could instigate rapid changes as routes or areas are getting impassable, and people need to relocate or change their way. The essential requirement for adjusting to the disaster scenario itself, but also the requirement for constant adaptations throughout the deployment, constitute further major challenges for our aerial system.

Challenge: *Constrained deployment and operational limitations of the UAS.*

Basically, an aerial system is limited by the number of available UAVs and their respective flight capabilities. The latter primarily depends on the used UAV hardware and encompasses important aspects such as battery size, flight speed, and the resulting flight range. Due to the limited battery, UAVs can only be deployed for a certain time and in a certain area around the starting location, given that they need to return. Furthermore, these constraints can change based on the system's objectives, for example, since an increased speed results in higher energy requirements and, thus, a shorter flight range. Additional restrictions like a time limitation for mission completion or insufficient UAVs for an optimal deployment further increase the complexity of operating the UAS and constitute additional challenges.

1.3 RESEARCH GOALS AND CONTRIBUTIONS

We show that the research challenges above can be addressed by an Aerial Network Assistance System, which combines topology monitoring and communication support of infrastructure-independent networks in the event of a disaster. The main goal of this work is, therefore, to develop an Aerial Network Assistance System to facilitate individual concepts to handle the different challenges emerging from the post-disaster scenario and, consequently, design, realize, and evaluate them. This objective is divided into the following three major research goals.

Research Goal 1: *Provision of coexistent topology monitoring and communication support for post-disaster ad hoc networks.*

Topology detection is a necessity to collect the required information that allows the deployment of communication support. Furthermore, information must be kept up-to-date to allow the adaptation and optimization of communication support to changes in the post-disaster ad hoc network, which requires the permanent monitoring of the system's operation area. Therefore, this research goal focuses on the necessary concepts and designs to allow the coexistent provision of topology monitoring and communication support in a single UAS. Both the system requirements and design decisions are based on an extensive literature survey of different aerial systems as well as the considered post-disaster scenario [171, 310, 314, 316]. The resulting combined system design of an Aerial Network Assistance System is able to autonomously perform aerial topology monitoring and communication support with a multitude of different strategies and existing approaches [171, 311, 315]. For aerial monitoring, we propose mechanisms for the cooperative collection of topology information to increase the initial detection performance and overall monitoring efficiency [311, 315], which can be combined with topology-aware monitoring area adaptation [316].

Research Goal 2: *Enabling topology-aware adaptivity of aerial communication support in dynamic disaster environments.*

Aerial communication support strategies are typically static and without detailed consideration for the encountered network topology in disaster scenarios. This can lead to an overall poor efficiency or reduce the system's efficiency over time when not adapting the system to dynamic changes in the network. To address this issue, we contribute methods to the long-term handling of topology information and the identification of network clusters for communication support [310, 316], which are requirements to facilitate the deployment of our system in dynamic post-disaster scenarios. Furthermore, we contribute an adaptive topology-aware routing approach for data ferry UAVs, utilizing topology data to increase coverage of disconnected network nodes [310].

Research Goal 3: *Evaluation of the Aerial Network Assistance System as well as aerial topology monitoring and communication support mechanisms.*

We need to demonstrate the applicability of our proposed Aerial Network Assistance System in dynamic disaster scenarios and evaluate the proposed concepts for aerial topology monitoring and communication support adaptations. For that, we contribute a comprehensive design for aerial systems that allows the evaluation of a wide variety of strategies for monitoring or communication support appliances [171]. Furthermore, we increase the expressiveness of our simulation-based evaluation by contributing a UAV movement model with realistic power consumption based on real-world measurements [312] as well as realistic mobility for civilians in a disaster environment based on an extensive analysis of real-world field test data [15, 313].

Thesis focus and non-goals

This thesis focuses on the combined application of UAV-based communication support and UAV-based topology detection. The optimization or design of new protocols for data ferry routing, UAV placement, or Coverage Path Planning (CPP) algorithms is not within the focus of this thesis, as many sophisticated protocols, protocol optimizations, algorithms, and heuristics have already been proposed [3, 26, 48, 80, 82, 111, 155, 180, 225, 248, 301, 303]. The design of our UAS allows the utilization of any suitable communication support strategy or topology detection strategy, respectively.

Since we focus on the UAS and its adaptability to changing disaster situations, security, safety, or privacy concerns are out of the scope of this thesis, especially of the supported communication network. Still, these factors need to be considered for a real-world deployment, which ponders their benefits against their drawbacks, such as increased overhead and reduced network longevity due to higher energy demand. Existing approaches for secured private communication [16, 150, 190, 205, 257, 273] in trustworthy DTNs [55, 102, 181] also include additional features like the detection of malicious nodes [47, 150, 273], which could be integrated into the communication network itself as well as the supporting UAS. Similarly, we specifically consider DTNs in this thesis as the only type of supported communication network. However, our UAS is not limited to interacting with and supporting a certain DTN or hybrid DTN-MANET protocol [140, 149, 166, 218, 256, 294]. Furthermore, we regard only the extreme cases where communication infrastructure is completely unavailable, and the DTN is the sole mean of communication available to civilian devices. Nevertheless, partially or temporally available infrastructure could benefit our system by providing additional communication resources between UAVs and the base station, or serve as a viable gateway to connect devices in the disaster scenario with the outside world over our system [188, 210, 242].

1.4 STRUCTURE OF THE THESIS

Following this brief introduction and motivation of our research challenges, goals, and contributions, Chapter 2 provides background information on communication services and communication networks for disasters. In Chapter 3, we discuss aerial systems with a focus on state-of-the-art mechanisms for UAV-based aerial communication support and aerial topology detection and monitoring.

Based on the identified research gap and a survey on the characteristics of disaster scenarios, we propose Aerial Network Assistance Systems for post-disaster DTNs in Chapter 4. These aerial systems combine communication support and topology monitoring as coexistent and jointly coordinated applications in a single system. We, furthermore, address several issues for its application in dynamic disaster scenarios for the collection, processing, and utilization of topology information.

Chapter 5 presents an evaluation platform for unmanned aircraft systems based on the simulation and evaluation framework Simonstrator.kom. Following an introduction to the core concepts of the platform, we detail our contributions by a prototypical implementation of the proposed system design. The platform is further extended by sophisticated models for UAV movement and civilian disaster mobility.

The prototypical implementation of our Aerial Network Assistance System and the contributions to aerial topology monitoring and communication support are extensively evaluated in Chapter 6. Additionally, we assess the possible impact of coexistent mechanisms on UAVs and highlight the necessity for application-specific UAV strategy designs.

Chapter 7 concludes this thesis with a summary of our contributions and an outlook on potential future work.

2 BACKGROUND

In this chapter, we provide relevant background information about communication in disasters and infrastructure-independent networks as a foundation for the discussion of the state-of-the-art in Chapter 3. We start by discussing existing services for post-disaster scenarios, focusing on communication and situation awareness in Section 2.1. Infrastructure-independent communication networks based on mobile devices are introduced in Section 2.2, followed by a presentation of the SMARTER field test, which applied such a network in a real-world scenario. The chapter is concluded with a brief introduction to the LoRa communication technology.

2.1 COMMUNICATION SERVICES FOR DISASTER RELIEF

In today's society, smartphones and other smart devices are abundantly used and practically available everyday and everywhere. With a plethora of applications for various messaging services, social media, news, and information, we expect and often depend on reliable and instantaneous communication channels and services. Especially with the increasing occurrence and severity of natural disasters in the last decades [279, 289], these services play a similarly increasing role in the preparation, response, and recovery of crises and disasters [213, 232]. Information management is particularly critical during and after disasters [116, 213], in which it is often a problem of "getting the right information to the right person at the right time" [116].

Crisis Informatics

The large variety of the hundreds of available disaster-related applications for civilians [107, 108, 176] mainly focuses on *(i)* information on disaster preparation, *(ii)* information on potential and currently existing hazards, *(iii)* warning the affected population, and *(iv)* providing the possibility for self-help, self-organization, and citizen-to-citizen communication [167, 232–234]. Some applications are available from private providers, such as KATWARN from the Fraunhofer Institute for Open Communication Systems (FOKUS) in Germany and Austria [96]. Other applications come from the public domain and are, for example, offered by national civil defense departments, such as NINA in Germany [46, 51] or FEMA in the United States of America [92, 233]. Additionally, cellular broadcasts to push text messages to all cellular devices within the country or a specific geographic region in case of an emergency are either available or in development in some countries, [87, 90]. All these services are usually linked to national distribution systems like the *Emergency Alert System* (EAS) in the U.S. or the *Modular Warning System* (MoWaS) in Germany. These systems can also target, e.g., television, radio, and digital advertisement banners with text, graphics, audio, or video information on a current disaster situation [50, 91].

Civil warning applications

Distribution infrastructure

For both the affected population as well as involved emergency services, understanding the prevailing disaster is a crucial requirement for an effective disaster

Situational awareness

relief [101, 279, 318]. Accurate and up-to-date information is required to respond accordingly. However, which information is of interest and the requirements for information change, depending on who the receiver is [166]. On a personal level, the safety and well-being of family and friends have high value. Information is made available through services in social media like Facebook's Safety Check [134], applications like Google's Person Finder [133], or the Red Cross [277]. On a community level, applications allow organizing community help where and when it is needed [158]. On a governmental level, geospatial mapping provides a broader view of the overall disaster situation. Within the last years, the integration of various data sources like aerial imagery, digitalized infrastructure, or social media has shown to improve situational awareness significantly [186]. This includes the location or movement of affected civilians, cell tower connectivity, localized power outages, fires, or other emergencies [6, 148, 178].

Lack of ICT in disasters

All surveyed services depend on existing infrastructure for Information and Communication Technology (ICT), such as cellular networks. Nevertheless, recent events worldwide have shown that ICT infrastructure is often overloaded, damaged, or destroyed in a disaster scenario [52, 101, 152, 196, 227, 279, 295, 318]. ICT's dependability on other critical infrastructures like the power grid further increases its vulnerability in a disaster due to the possibility of cascading failures [105, 115, 184, 204, 214, 285]. The recovery to provide even basic infrastructure-dependent services after a breakdown can take weeks to months [69, 318]. Thus, research focuses on resilient infrastructures [33] to mitigate the effects of severe disasters in the future and improve the ability for a quick recovery [93, 124, 204, 269].

This thesis addresses an undeterrable breakdown of ICT infrastructure, with a complete loss of communication services. However, infrastructure-independent systems to provide basic emergency communication services are available [166]. In this thesis, we provide an Aerial Network Assistance System to support infrastructure-independent communication and gather valuable data for disaster relief efforts. It can be deployed swiftly and bridges the time until reliable infrastructure-based communication is available again.

2.2 INFRASTRUCTURE-INDEPENDENT COMMUNICATION NETWORKS

Communication networks connect multiple end systems over a shared communication medium [223, 275]. They are the fundamental technological requirement to provide communication services, such as the Internet as its most prominent example. Typically, communication within such a network relies on intermediate relay infrastructure to transport data between end systems [275], which is not possible anymore when ICT infrastructure breaks down in a disaster scenario. Therefore, we consider only infrastructure-independent communication networks via a shared, wireless medium. This thesis particularly focuses on device-to-device communication between smart mobile devices like smartphones of the affected civilian population. These devices — also called network nodes when contemplated from a network's point-of-view — can communicate with each other directly when in communication range. Due to the mobility of civilians and the limited communication range, however, communication paths are not static and can constantly change or get disrupted.

Ad hoc network

Generally, such an infrastructure-independent communication network is denoted as an *ad hoc* network [66]. The networking concept follows a decentralized approach without a central coordination unit, in which communication happens in a self-organized manner between all nodes, similar to a peer-to-peer system [76, 268]. The underlying communication technology used within this thesis is Wireless Fidelity (WiFi) due to the high throughput and communication range [15, 166]. Popular examples of WiFi-based ad hoc networks are Wireless Sensor Networks (WSNs) or Vehicular Ad Hoc Networks (VANETs) [39, 66, 191]. However, other technologies such as Bluetooth or LoRa are also capable of supporting ad hoc communication for low-range or low-throughput applications, respectively [42, 123, 124, 157, 235].

Multi-hop end-to-end connectivity...

End-to-end connectivity in ad hoc networks is achieved by multi-hop device-to-device data exchange. Since all nodes use the same shared medium, every peer overhears all messages within its reception range and may relay them towards the receiver [113, 156, 247]. However, classical wired routing protocols cannot be applied to ad hoc networks as communication paths can change, e.g., due to power conservation on a relay node or nodes running out of energy. In cases when nodes are mobile, connections also get disrupted due to increasing distance or obstacles between nodes, while new connections can emerge. For such scenarios, the term Mobile Ad Hoc Network (MANET) is used. MANET routing protocols are specifically designed to discover and maintain communication paths for end-to-end connectivity despite changing communication paths [12, 65, 141, 220, 244]. These protocols can be categorized based on their routing approach [2, 183, 193]. *(i)* Proactive protocols constantly maintain and update routing tables for each network node. The maintenance overhead is significant, but communication paths are available when needed [141, 221]. *(ii)* Reactive protocols discover and construct end-to-end connectivity only when needed. Overhead is lower than when maintaining all routes, but they require more time to establish a connection [143, 220]. *(iii)* Hybrid protocols combine traits of both categories, such as maintaining routes with on-demand discovery in case of a connection disruption while communicating [35, 211]. These design concepts for routing protocols in connected ad hoc networks build the foundation for the proposed set of cooperative monitoring protocols in disaster scenarios in Section 4.3.

...via MANET protocols.

Lack of lack end-to-end connectivity...

Nevertheless, highly dynamic behavior like mobility in a disaster poses significant challenges for typical MANET routing protocols. Parts of the network can get completely disconnected, nodes leave and join disjunct network partitions, or partitioned networks merge [15]. MANET routing protocols do not work under these conditions, as they require an available end-to-end route to provide communication. For these highly dynamic scenarios without end-to-end connectivity, we require Delay-Tolerant Networks (DTNs). The routing approach in DTNs differs from that of MANETs by employing the *store-carry-forward* principle, as shown in Figure 2.1. In general, messages are broadcasted from a source to all network neighbors that store copies, carry them around, and distribute further copies on contact to other nodes until, eventually, reaching the destination [12, 113, 149, 173, 174, 294]. This allows

...requires DTN protocols.

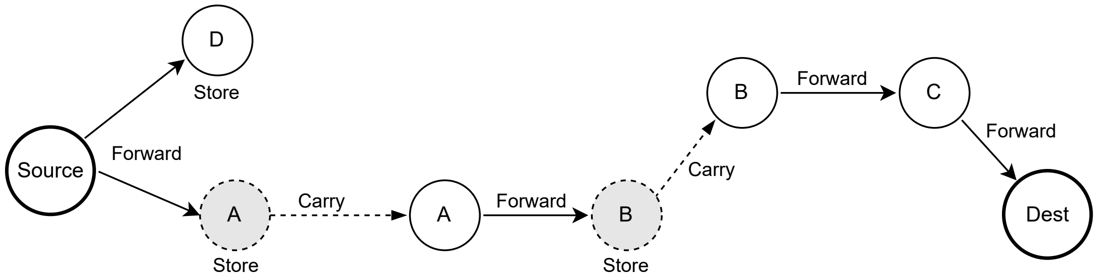


Figure 2.1: The *store-carry-forward* principle allows opportunistic message forwarding from a source to a destination without an end-to-end connection.

the decoupling of sender and receiver in space and time and does not require an existing end-to-end connection for communication. However, this highly opportunistic approach usually cannot guarantee that a message gets delivered [166].

Terminology and categorization

The categorization and terminology of DTNs and MANETs has changed over the years; both terms are often used ambiguously. As DTNs first emerged as a solution for issues in MANETs [53], terms like sparse, partially connected, intermittent, or disrupted MANETs are sometimes used to describe DTNs [58, 149, 173, 218, 224, 267, 308]. Some research combines end-to-end and store-carry-forward routing in hybrid DTN-MANET routing approaches [28, 140, 166, 218, 294]. In other cases, the separation of DTNs became more distinct [12, 147, 256] or resulted in new terms like *Opportunistic Networks* [127, 182]. This thesis uses the term Delay-Tolerant Network (DTN) to describe a disrupted, intermittent network without a generally available end-to-end connectivity. DTN routing protocols rely solely on the store-carry-forward principle, in distinction to MANET protocols with routed end-to-end connection or combined hybrid DTN-MANET protocols that could be applied in both scenarios [166].

Preventing broadcast storms

Similarly, the approaches to DTN routing have evolved from simple broadcasting to more sophisticated protocols over the years. Since the one-time flooding of the network partition with a message cannot deliver it to another network partition, messages have to be broadcasted repeatedly, which is known as *epidemic routing* [142, 247, 291]. As a result, however, DTNs suffer severely from broadcast storms — overloading the network and wireless medium with excessive message flooding. Within a network partition, broadcast storms can be prevented by limiting the re-transmissions by a certain probability (*gossiping*) [113, 149] or by waiting and re-transmit only when no other node re-transmits the same message (*controlled flooding*) [142]. Furthermore, the maximum number of copies in the network can be limited [267], or messages are only forwarded to previously unknown nodes [149]. More sophisticated protocols determine the probability of reaching the receiver based on node mobility or the history of node encounters (*probabilistic flooding*) [64, 100, 160, 173, 261], flood only within a specific direction from the origin (*directional flooding*) [131], or flood only a certain area (*geographic flooding*) [145]. Further restrictions can be applied, such as that only the node closest to the destinations forwards the message [64] or that the forwarding workload is shared equally among all nodes [145].

In general, DTN messages have a limited Time-to-Live (TTL), after which the message is not forwarded anymore and deleted on all nodes. On the one hand, using a TTL decreases the overall workload and resource utilization but, on the other hand, also inhibits the spread of messages over larger distances with slow carriers [15].

Time-to-Live (TTL)

Due to the lack of a central coordination unit, nodes make themselves visible to other nodes by sending small *beacon* messages. They are either sent periodically within a static interval or the beacon rate is adapted, for example, based on the number of nodes in their transmission range [30]. Thus, nodes know their neighbors within communication range, also referred to as *1-hop neighborhood*, and can detect changes therein. Simple beacons contain, for example, only the ID of the sending node. More sophisticated protocols, however, may share more information, such as the knowledge of their location, the neighborhood, or the whole network cluster [28, 75, 121, 130, 149, 173, 238, 241]. Such information can facilitate, e.g., location-aware MAC protocols for the beacon process to reduce collisions and utilize the wireless medium more efficiently [74, 75]. In this thesis, the specific information contained in beacons is a core principle for the cooperative distribution of monitoring information in a DTN cluster, as further discussed in Section 4.3.

Beacon messages

In large-scale disaster scenarios, the mobility of the affected civilian population is typically accumulated in specific Areas of Interest (AoIs). Usually, AoIs contain locations like shelters, marketplaces, city centers, or first-aid stations that attract the population. Mobility within such an area is typically high. However, movement is relatively infrequent between different areas, especially if the distances are considerable [15, 166]. In combination with the short communication distances between the smart mobile devices of civilians, the DTN's topology is highly intermittent as a result. On the one hand, the network is tightly interconnected within an AoI. Communication performs well with low delivery delays and high delivery rates. As depicted in Figure 2.2, we also speak of a *network cluster* due to the accumulation in the AoI [15] and refer to the communication inside it as *intra-cluster communication*. On the other hand, these network clusters are isolated from each other, only connected through the occasional movement of DTN nodes. Since these nodes carry data be-

Clustered DTN topology

Performant intra-cluster communication

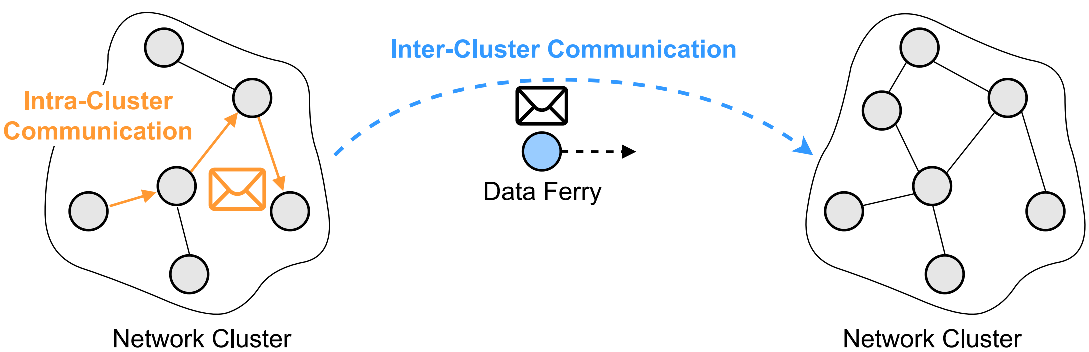


Figure 2.2: While intra-cluster communication typically performs well, inter-cluster communication depends on the mobility of data ferry nodes and, therefore, suffers from high transmission delays.

tween clusters, they are also referred to as *data ferries* [58, 224, 308]. The transmission delay is directly correlated to the distance and mobility between clusters. Therefore, *inter-cluster communication* suffers from significant transmission delays, especially if network devices are carried on foot [167]. Other means of data ferries, like cars, can decrease the delay [217, 283, 284, 308] but are similarly vulnerable to obstructed paths or destroyed roads as a result of the disaster [15, 167]. Thus, delivering a message may be impossible at all.

Sparse inter-cluster communication

Alternative solutions like using long-range communication equipment or satellite communication are generally possible. However, they depend on specific hardware that requires excessive training to use and significant time to deploy [29, 77, 104]. Furthermore, their static setup inhibits the ability to adapt to a changing network topology as we have to expect in a disaster scenario [15, 166]. Therefore, they are not suitable for the considered scenario, although being a viable solution to provide communication between static locations, especially for the disaster recovery phase [79].

In this thesis, our proposed Aerial Network Assistance System for post-disaster communication is designed to support and cooperate with a DTN based on the smartphones of the affected civilian population. The network consists of clusters, with well-performing intra-cluster communication but infrequent and delayed inter-cluster communication, due to the disaster-related mobility of nodes. The specific use of Unmanned Aerial Vehicles (UAVs) as data ferries is discussed in more detail in Section 4.2.2. A real-world example of such a network and its respective topology is presented in the following.

Regarded network topology

2.3 SMARTER: FIELD TEST OF SMARTPHONE-BASED COMMUNICATION SYSTEM

In 2017, a large-scale field test was conducted with 125 civilian participants, as part of the SMARTER project[1]. Its main objective was to assess the usability and performance of a smartphone-based DTN to provide disaster communication services for civilians under realistic conditions (cf. [15, 166]). The field test was executed in a military training area near Paderborn, Germany, 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 NGOs. The anticipated scenario was a long-lasting power outage caused by severe weather and a failure of ICT infrastructure. Coincidentally, there was no cellular coverage in this area. Communication could only be performed over DTN-capable smartphones and a disaster service application using the IBR-DTN implementation of the Bundle Protocol (RFC5050) [256].

Disaster scenario

The field test area consisted of three villages with various concrete buildings and stone walls, ensuring realistic communication characteristics for the DTN. The villages are connected through a main street, which mostly leads through forest, as shown in Figure 2.3. The distance between Villages A and B is approximately 5 km and around 1 km between Villages B and C; corresponding to a 1-hour and a 15-minutes walk, respectively. Several locations, like shelters, hospitals, and food distri-

1 https://smarter-projekt.de/ [Accessed 01.09.2022]

Figure 2.3: The SMARTER field test area, approximately 2x5 km^2. Villages are shown in yellow. The main road connecting all three villages is marked in blue. Figure source: [15]. Map Data: Google Maps ©2018.

bution points, were distributed within villages. Furthermore, special buildings like a gas station, a church, and an airport, in combination with several incidents staged by professional actors, added to an immersive experience for the participants. Detailed recordings of user behavior and device-to-device interactions were recorded; the resulting dataset provides real-world mobility traces, which build the foundation for the *civilian disaster mobility model* proposed in Section 5.4.

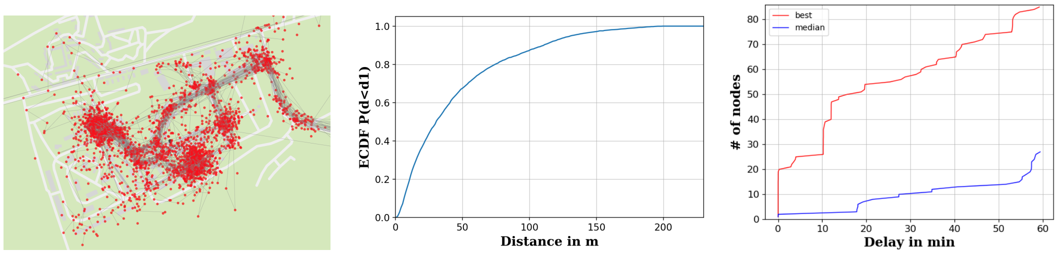
Participant mobility

As analyzed by Álvarez et al. [15], participants clustered around Points-of-Interest and stayed within the villages most of the time (cf. Figure 2.4a). When moving between villages, they formed smaller groups. Thus, each participant had an average of 6 to 8 neighbors. Furthermore, the median communication range was within 44 m, as shown in Figure 2.4b, although many communication links reached an unexpected distance of more than 100 m. Participants, however, moved rarely between the villages, which negatively influenced message distribution. As shown in Figure 2.4c, the median broadcast only reached around 22% of the participants, while the best-distributed broadcast reached around 70%. This clearly highlights that message spread was slow or impossible between the network clusters in different villages, resulting in only a small percentage of reached devices. With the provided text-based services, the practically available bandwidth of several Megabits per second of WiFi Direct connections [5, 57, 163] has not been exhausted. Thus, supporting multimedia content like SOS voice messages or pictures of emergencies within the disaster services could also be possible [15, 166].

DTN performance

Findings

Overall, the results of the field tests proved that communication services for civilians over infrastructure-independent networks are possible and that these networks are highly capable of supporting disaster services to a larger extent. Furthermore, the field test showed the anticipated clustering within AoIs with performant intra-cluster communication, but also the scarce mobility between network clusters and the resulting lack of inter-cluster communication. Our proposed aerial system, presented in Chapter 4, directly addresses this issue to increase inter-cluster communication performance.



(a) Participant GPS traces in Village A.

(b) Communication distance as ECDF.

(c) Best and median message propagation.

Figure 2.4: Communication characteristics and node distribution during the field test. Source of figures: [15].

2.4 LORA: LONG-RANGE LOW-POWER COMMUNICATION

Inexpensive

Long range

Low throughput

Long Range (LoRa) is a physical layer modulation technique for Low-Power Wide-Area Networks (LPWANs). Due to its relatively low costs for hardware and the operation within unlicensed frequency bands — e.g., the 433 MHz ISM band or the 868 MHz SRD band in the EU and the 915 MHz ISM band in North and South America —, LoRa is often used within Internet-of-Things (IoT) applications and WSNs. Communication ranges depend on the LoRa modulation settings such as Spreading Factor, Bandwidth, and Coding Rate. With the most robust settings, LoRa communication can reach several kilometers in non-line-of-sight environments [123] and more than 16 kilometers in line-of-sight environments [222] with reasonably low power consumption. However, these advantages come with the tradeoff for small data rates and long signal air times [61, 94, 157], resulting in low throughput. This drawback is further increased when strict duty cycle requirements apply, like a 1% duty cycle in the EU's 868 MHz SRD band [86]. Although the LoRaWAN protocol typically manages communication with commercial-off-the-shelf LPWAN gateways within a star topology, LoRa can be used independently to construct meshes and relay networks for the collection of sensor data [42, 157] or as an alternative communication technology for disaster DTNs [32, 123]. In this thesis, LoRa is used as a long-range control channel between UAVs and the base station in our aerial system.

3 RELATED WORK

This chapter discusses state of the art in relevant areas for our aerial network assistance system proposed in Chapter 4. We discuss Unmanned Aerial Vehicles (UAVs) and Unmanned Aircraft Systems (UAS) with a focus on applications, communication, and systems in Section 3.1. A more detailed overview of UAV-based Communication Support for both non-disaster and disaster-related scenarios is provided in Section 3.2. Aerial detection and monitoring of devices and networks on the ground is discussed in Section 3.3. Finally, the identified research gap addressed in this work is discussed in Section 3.4.

3.1 UNMANNED AERIAL VEHICLES AND UNMANNED AIRCRAFT SYSTEMS

Applications

Unmanned Aerial Vehicles (UAVs) are increasingly relevant and practically used for both private appliances [119, 278] and emergency services alike [49, 79, 80]. Especially in the delivery of goods or parcels [254, 272], UAV-based applications perceived a five-fold increase in worldwide usage in 2021 [17, 296]. They are also increasingly used for inspecting and monitoring powerlines, forests, coastlines, icebergs, or construction sites [81, 84, 161, 172, 219, 278, 282, 307, 309]. Other UAV-based services address Internet-of-Things (IoT) applications [200, 201], Wireless Sensor Networks (WSNs) [144], or Vehicular Ad Hoc Networks (VANETs) [309]. Another well-researched application is the provision of cellular coverage to support existing infrastructure [162, 188, 199, 242, 304]. In case of disasters or emergencies, UAVs are used for mapping and reconnaissance [9, 226], *Search-and-Rescue* (SAR) missions [118, 231, 255], or contamination measurement [10, 68, 84, 85]. The application of UAVs for communication support and situational awareness is discussed in more detail in Section 3.2 and Section 3.3, respectively.

Terminology

Due to the historical context and technological advances over the years, different terms like *Drone*, *Remotely Piloted Aerial Vehicle* (RPAV), and *Remotely Operated Aerial Vehicle* (ROAV) have emerged. Besides recreational purposes, however, modern applications are not interested in directly piloting or operating the aerial vehicle by a human but require a certain level of autonomy instead [207]. This autonomy is emphasized explicitly by Unmanned Aerial Vehicles (UAVs), denoting aircraft with autonomous capabilities that range from remotely monitored autonomous flight to the unsupervised, fully autonomous execution of missions. In everyday language, however, any unmanned aircraft is usually denoted a *Drone*, independent of its type, application, or other parameters, similar to a collective term or a hypernym. Therefore, the term UAV denotes a certain subset of drones, while not every drone is a UAV inherently. Furthermore, we generally speak of an *aerial system* whenever contemplating the aggregation of one or multiple aircraft in combination with ground-based assets like a controlling base station, communication equipment, or infrastructure for battery management. Following the specification of the *International Civil Aviation Organization*, the term Unmanned Aircraft System (UAS) is particularly used for a UAV-based aerial system [135, 207, 259].

Fixed-wing and rotary-wing UAVs

Most commercial off-the-shelf (COTS) UAVs can be categorized as either plane-like *fixed-wing UAVs* or helicopter-like *rotary-wing UAVs* and have highly application-specific usages [80]. While the former type allows for generally longer flights and to lift larger payloads, the latter can hover and enables *vertical takeoff and landing* (VTOL), making it significantly easier to control and more suitable for urban applications. As a result, most UAVs in civil, recreational, and emergency service applications are *rotary-wing UAVs*. For long-term use, *rotary-wing UAVs* have the additional advantage of allowing automatic battery replacement [81, 99, 290], providing better usability than time-consuming battery recharging [60, 114, 151, 212, 263]. In the case of multiple rotors controlling a rotary-wing vehicle, the term *multicopter* is commonly used. In this thesis, we rely on small, commonly available multicopter UAVs due to their primary application in urban disaster scenarios. In recent years, hybrid and convertible UAVs have emerged to combine the more energy-efficient flight of planes with the better controllability of VTOL-capable vehicles. As they are primarily used in large commercial applications and have a considerable size [296], they are out of the scope of this thesis. Nevertheless, the design of our aerial system is not explicitly restricted to a certain type of UAV and could be adapted accordingly.

Multicopter UAVs

Communication interfaces

Depending on the application, different communication interfaces must be available on UAVs and the base station. Especially for centralized mission control and coordination, a reliable control channel to the base station should be available [78, 259]. Depending on the size of the operation area and the available infrastructure, this can, for example, be realized by LTE or 5G cellular networks, satellite networks, or Low-Power Wide Area Networks, e.g., over LoRa [19, 72, 126, 208, 300]. In this thesis, we expect no cellular coverage to be available in our disaster scenario. Additionally, small COTS UAVs typically do not have satellite communication interfaces due to their size, weight, costs, and power consumption. Therefore, we rely on LoRa (cf. Section 2.4) for the control channel, which is well-suited for high-level mission control and coordination of UAVs using small-size data packets [19, 78, 126, 264].

Communication links

The technology used for Air-to-Air (A2A) communication links between multiple UAVs, and Air-to-Ground (A2G) communication between UAVs and ground nodes, is highly dependent on the application [209, 303]. With technical restrictions on the UAVs, using the same technology and interface for both A2A and A2G links is possible [31, 164, 196]. Most research, however, clearly separates A2A and A2G communication, constructing separate airborne overlay and A2G access networks [198]. This separation is achieved by either using different communication technologies for each network [164, 194, 195] or using different radio interfaces with the same communication technology to build different networks [14, 18, 82, 109, 128, 188, 198, 281, 302]. A separation has the clear advantage that the used technology can be specifically adapted to the A2A communication requirements on the one hand and the available communication technologies for A2G communication at the ground nodes on the other. The most widespread communication technology for A2A and A2G links is Wireless Fidelity (WiFi), providing stable, high-throughput, and multi-hop-capable broadband communication [19, 80, 109, 164, 298]. While ground-to-ground or A2G WiFi links can reach 100 meters in urban areas [15, 117, 299], A2A links have a higher probability of line of sight. The effective communication range between UAVs, thus, can reach or even exceed 300 meters [117, 119, 154, 298, 300].

Focus of the thesis

In this thesis, we particularly focus on A2G links due to the goal of supporting communication in a WiFi-based disaster DTN on the ground. Nevertheless, we also rely on WiFi A2A links for all communication purposes between UAVs. The following section discusses a wide range of different approaches and communication technologies for communication support over A2G links. Whenever we address the entire Unmanned Aircraft System (UAS) consisting of all UAVs, the base station, and the system's application we may refrain to the general terms *aerial system* to highlight the differently referenced viewpoint in contrast to individually regarded UAVs.

3.2 UAV-BASED COMMUNICATION SUPPORT

We define communication support in general as all actions that directly or indirectly *enable or improve communication in a network*. In which way communication support is required depends on various factors like the network and its topology, the scenario, and the type of communication. As an example, providing auxiliary infrastructure like cell towers in highly crowded scenarios such as festivals or fairs can greatly benefit communication, as it prevents overloading the existing infrastructure [4]. However, this requires time for planning and preparation, available infrastructure to connect to, appropriate power sources, and more. Whenever this is not possible, UAV-based systems can be used to either temporarily or permanently support communication for a wide range of applications.

Aerial Radio Access Networks

UAVs can compensate outages...

...and provide independent RANs.

Network-constructing approaches use one or multiple UAVs either as an addition to an existing Radio Access Network (RAN) or to construct a standalone network. In the case of an existing 3G, LTE, or 5G cellular network, UAVs with the respective cellular access point technology can transparently provide the same service to users as a regular cell tower. Overloaded cell towers can be relieved by sharing the workload, or outages can be compensated by a replacement UAV [188, 210, 242]. Similarly, UAVs can be used to extend the connectivity to a specific radio access network by relaying communication to and from it [56, 164, 196, 249]. Whenever ICT infrastructure is unavailable within a larger area, UAV swarms are able to construct and provide their own cellular networks, possibly connected to working infrastructure at the edges [63, 194, 203]. As depicted in Figure 3.1, A2A communication is used to build a mesh network between all UAVs to route and relay communication for nodes on the ground [82, 111, 128, 180, 248]. Similarly, these radio access networks can also be provided via WiFi [109, 195].

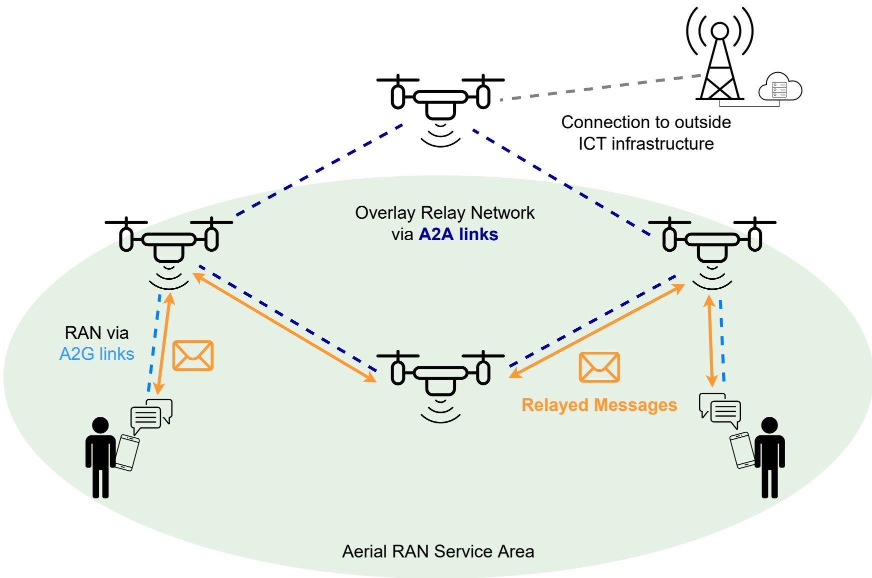


Figure 3.1: An aerial Radio Access Network (RAN) provides performant communication by relaying messages between sender and receiver via UAVs.

Many UAVs required...

...and finding an optimal placement is difficult.

Placement optimization

Constructing aerial RANs has the advantage to provide communication in large areas permanently. Using an overlay relay mesh network makes communication quick and performant [154]. A drawback, however, is the large number of required UAVs for permanent sustainability. Nevertheless, the most difficult problem for the construction of aerial RANs is calculating an appropriate placement for the UAVs, although manual placement may be a viable option in some cases [128]. Finding the optimal placement is subject to a large set of requirements, restrictions, and influences, such as the number of available UAVs, the size of the operation area, the number of network nodes to cover, or the communication range, and is an NP-hard problem [276]. However, several heuristics and metaheuristics approach this problem from different directions. As the covered ground area increases with a UAV's altitude, considering maximum communication ranges and communication properties [26] allows finding enclosing circles to cover a maximum of either the operation area [199] or the devices on the ground [129, 180] with a minimum number of UAVs. This also includes Quality-of-Service (QoS) requirements such as signal strength and throughput for A2G and A2A links [56, 248]. For the overlay network, connectivity between UAVs in the overlay network and connectivity to functioning ICT infrastructure at the edges of the operation area [56] need to be regarded. Using 3D models of the operation area, like a city with its buildings, allows calculating the line-of-sight (LoS) probability for A2G links and, thus, enhances the area coverage in complex urban scenarios [82]. Due to the complexity of optimizing UAV placement, most works consider only static placement without dedicated mobility of UAVs or ground nodes [111]. Nevertheless, in a real disaster scenario with moving civilians or rescue teams, it is necessary to continually assess the disaster situation, for example, to allow the re-positioning of UAVs for a persisting service.

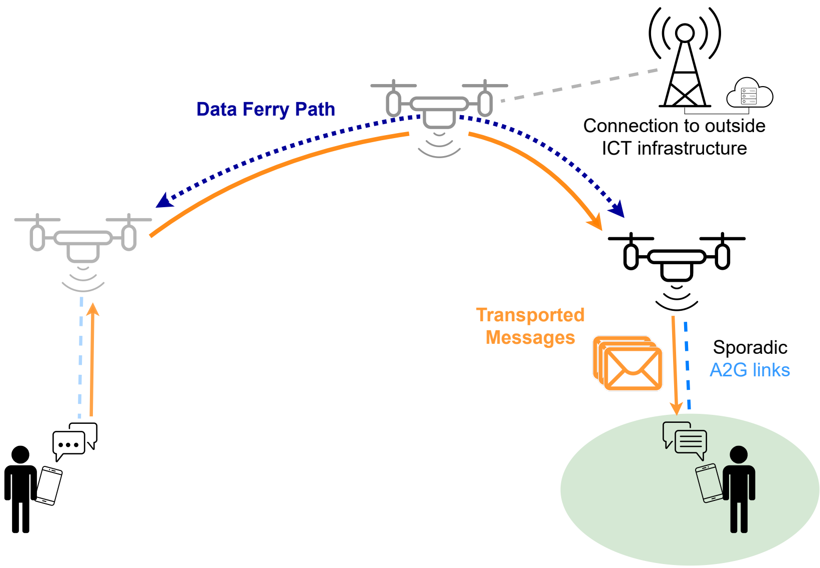


Figure 3.2: Aerial data ferries provide delayed communication by physical message transport between sender and receiver.

Aerial Data Ferries

Whenever an area is sparsely populated, distances between communication partners are large, or only a few UAVs are available, constructing a fully connected and comprehensive aerial RAN is infeasible or inefficient. In this case, the high mobility of UAVs can be utilized to send them as *data ferries* (cf. Section 2.2) between different parts of a network. The UAVs act as access points and exchange messages but have to physically move to the destination location instead of relaying it through an overlay network with many UAVs in between, as visualized in Figure 3.2. Thus, communication is delayed relative to the UAVs' speed and the traversed distance between sender and receiver. However, a data ferry approach is possible with only a single UAV due to the utilization of their high mobility. Aerial data ferries can generally cover a larger operation area than a static aerial RAN with significantly fewer UAVs [80, 303]. Data ferries are mostly used in Delay-Tolerant Networks (DTNs) or other networks, which are able to handle delayed communication.

Utilize UAV mobility...

...to transport data...

...with few data ferries.

Generally, we separate data ferry applications into area-centric, network-centric, and user-centric applications. Area-centric applications use UAVs to traverse a given area either randomly [189, 284, 292] or on a fixed trajectory [70, 146, 165, 308] with the goal of maximizing area coverage. Data is exchanged opportunistically during contact time, in the case that data ferry UAVs encounter devices on their trajectory. Due to the similarity to coverage path planning in area exploration, we discuss it in more detail in Section 3.3. Network-centric approaches apply UAVs in existing networks to increase performance by shortening routes or as an additional way of data transport [164, 196, 249]. This group is out of the scope of this thesis due to the lack of ICT infrastructure in our considered disaster scenario. The largest group, however, is constituted by user-centric data ferry approaches, which aim at maximizing device

Application types

coverage. UAV trajectories are planned to cover devices on the ground [201, 202, 217, 225, 297, 308]. Especially in highly clustered environments — as in our considered disaster scenario — the problem simplifies to planning a trajectory covering network clusters [3, 18, 155].

Traveling Salesman Problem

Finding the shortest trajectory covering a set of devices or clusters is known as the NP-hard *Traveling Salesman Problem* (TSP) [110]. Due to the importance of TSP in scheduling and routing optimization, heuristics are used to approximate the shortest trajectory [27, 41, 67, 112, 228]. However, additional restrictions like obstacles in the flight path [165], limited message Time-to-Live (TTL) [166], delivery deadlines [260], or message priorities [170, 261] further increase the complexity of planning a data ferry trajectory. Furthermore, planning can include different optimization criteria. Especially for fixed-wing UAVs, trajectory planning must consider required turning angles and the inability to hover [48]. This, however, allows finding longer but also more energy-efficient trajectories with smooth turns [301]. Trajectories can similarly be optimized for signal strength [217, 297] or throughput [302] to devices on the ground. Since A2G connection quality deteriorates when the UAV is moving [23], however, the usage of rotary-wing UAVs with hover capability has become prevalent [207]. Determining an optimal hover time over a network partition needs to consider both connectivity for the network and energy efficiency for the UAV [18, 202]. Furthermore, data ferry trajectories can be optimized by balancing connectivity and communication performance for all network clusters [18]. With multiple UAVs covering subsets of devices or clusters in parallel, trajectory planning must additionally plan contacts between UAVs for message exchange to allow communication between the subsets [95, 189, 224, 225].

Trajectory optimization

Topology knowledge is required

Within the plethora of approaches for both aerial RANs and aerial data ferries, knowledge of node positions, clusters, or the network topology is categorically required. Nevertheless, such information is usually not available a priori [201]. The acquisition of such knowledge is, therefore, a key requirement to enable aerial communication support and is discussed in the following section.

3.3 UAV-BASED DETECTION AND MONITORING

Highly mobile and equipped with different sensors, UAVs are usable in a multitude of different reconnaissance missions. They are especially suitable for mapping an area with onboard cameras due to the aerial perspective, e.g., providing an up-to-date aerial image of a disaster area [9, 54, 187, 226, 230, 231, 300]. Nevertheless, more detailed information is usually required for more sophisticated applications, such as the location of network nodes for aerial communication support, as discussed in the previous section. Similar to mapping, aerial detection can be performed by traversing a search area and localizing objects or persons with the onboard UAV cameras [21, 38, 71, 255]. This is usually referred to as a Search-and-Rescue (SAR) mission in the context of disasters. Once detected, it is also possible to track and monitor objects and persons to provide the latest information to SAR emergency response teams [118, 198, 255, 317].

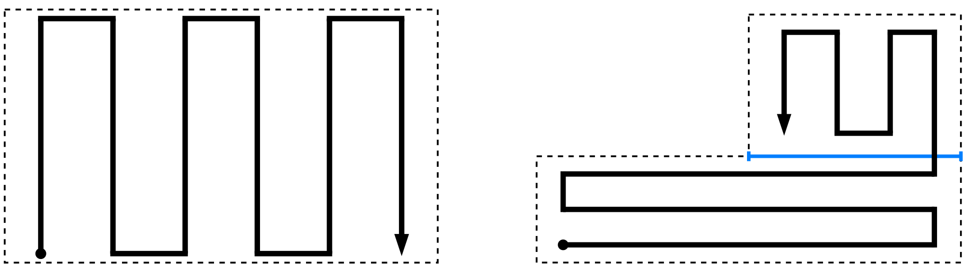
Visual detection for Search-and-Rescue

Nevertheless, camera-based visual detection has the significant drawback of requiring line-of-sight (LoS). Thus, it only works for detection and monitoring approaches outside buildings and is also blocked by buildings, trees, or other objects. Especially in urban environments, this will constrain the applicability of UAVs to identify affected civilians in a disaster. However, smartphones and other smart devices that civilians carry usually send out radio transmissions. Therefore, a UAV within reception range can detect such a device by listening, for example, for WiFi [3, 59, 245], 5G [304], or LoRa signals [7, 123, 172, 264] and approximate its location (cf. [238]). In the case that, e.g., a DTN is used, the received packet may further contain location information on the sender, increasing the accuracy of the detection [15, 239].

Radio signal detection for network monitoring

To detect and monitor nodes on the ground, a trajectory that covers the search area must be found. Finding a covering trajectory is known as the Coverage Path Planning (CPP) problem [70, 165]. The most common approach is calculating a Lawnmower or Boustrophedon path (cf. Figure 3.3a), which provides an exhaustive and deterministic coverage path of an area [11]. For complex environments, however, this requires a decomposition of the area and the optimization of the path calculation for the connections between each sub-region (cf. Figure 3.3b). Despite possible optimization of the decomposition and an adaption of the route calculations, the trajectory can be redundant and less efficient when guaranteeing full coverage [22, 165]. Other approaches, like the *Divide Areas Algorithm for Optimal Multi-Robot Coverage Path Planning* (DARP) algorithm, simplify the area to a grid and approximate the optimal solution by calculating a spanning tree over all cells [20]. In general, all CPP problems increase in complexity when an area is split up to be traversed by multiple UAVs in parallel (mCPP) [20, 118]. Alternatively, heuristics such as *Particle Swarm Optimization* (PSO) [262] for a single UAV or distributed PSO (d-PSO) [250, 293] for a cooperative UAV swarm can be used to traverse an area without a pre-calculated trajectory. However, heuristics like PSO or random flight can neither guarantee full area coverage nor complete node detection, despite the possibility of providing incomplete information faster than the complete lawnmower approach [250].

Coverage Path Planning



(a) Lawnmower path for a simple area.

(b) Complex areas may require decomposition for optimial route calculation.

Figure 3.3: Lawnmower routing is a common approach to Coverage Path Planning (CPP), providing an exhaustive and deterministic coverage path.

3.4 SUMMARY AND IDENTIFIED RESEARCH GAP

In this chapter, we discussed related work with respect to Unmanned Aircraft Systems (UAS) and focused on their application for aerial communication support and aerial detection and monitoring. Especially multicopter UAVs are often used in urban environments due to their versatility. Most research uses hardware prototypes or mathematical models to test and evaluate approaches and systems. While the former provides realistic results, it is time-consuming and lacks reproducibility and general applicability. On the other hand, the latter is reproducible and can be inexpensively tested for a vast set of parameters but usually neglects important issues like the mobility of nodes or UAVs, energy consumption, or communication networks. Therefore, other research uses simulations as a tradeoff to approximate realistic system behavior while maintaining testability and reproducibility. Existing approaches for UAV simulation, however, are either restricted to specific use-cases and scenarios [72] or over-simplify important aspects of UAV-based applications such as node mobility [180, 225, 250, 281], network topology [129, 249], as well as movement and energy consumption of the deployed UAVs [36, 180, 196]. Nevertheless, these factors are essential to evaluate our UAS design and the contributions to aerial network assistance systems in this thesis. Therefore, we extend an existing simulation platform by a sophisticated UAS representation, as presented in Chapter 5. This includes movement models and energy consumption for UAVs and a mobility model for civilians in a disaster scenario.

Within the discussed related work, we recognized a sharp distinction between approaches for aerial communication support on the one side and aerial detection or monitoring on the other. However, both fields of application are tightly interconnected. Specifically, the communication support requires information of the network and devices, which an aerial monitoring mission can provide. Most research assumes this information to be available but neglects its source and acquisition. Therefore, this thesis focuses on the combination and cooperation of both UAV-based communication support and UAV-based monitoring. Furthermore, applications for one-time detection are much more prevalent than for continuous monitoring. Although the former provides an initial foundation to allow, for example, an aerial communication support mission, the disaster situation changes over time, similar to the network topology due to the mobility of devices [15]. As a result, initially collected information gets deprecated and the efficiency of deployed UAS missions may deteriorate. Therefore, we regard both the continuous monitoring of the area and the network topology, as well as the adaptability of communication support to topology changes, as necessary requirements for our UAS design presented in the upcoming chapter.

4 AERIAL NETWORK ASSISTANCE SYSTEMS FOR POST-DISASTER DELAY-TOLERANT NETWORKS

The analysis of related work identified a wide range of applications for communication support and topology monitoring via Unmanned Aerial Vehicles (UAVs). As discussed in Chapter 3, however, their functionality is typically limited to either communication support *or* monitoring. Especially communication support approaches typically disregard a possible coexistence and their dependability on information about the supported communication network. Furthermore, deploying these applications to the highly dynamic scenario of post-disaster environments is problematic due to their limited adaptability, e.g., to changes in the scenario or the requirements on the aerial applications. In this chapter, we present a design for an *Aerial Network Assistance System*, combining topology monitoring and communication support mechanisms in a single Unmanned Aircraft System (UAS). Due to its generalized architecture, our system design allows the inclusion and evaluation of a wide range of existing approaches, including communication protocols, path planning algorithms, and more. Furthermore, it enables us to study the coexistence and combined application of UAV-based monitoring and communication support in the challenging post-disaster scenario. This combination is essential to address the scarcity and volatility of information in a disaster scenario. Thus, the proposed system design provides a necessary foundation for our contributions to situation-aware and adaptive communication support in coexistence with monitoring.

Initially, we specify the characteristics of the disaster scenario and the necessary requirements for our system in Section 4.1. The conceptual overview of our system design, including monitoring, communication support, and their coexistence, is presented in Section 4.2. After that, we present our contributions to aerial network assistance based on the proposed system design. In Section 4.3, we introduce *Cooperative Aerial-Ground Monitoring* (*CAMON*) for cooperative node detection in DTNs. The processing of monitoring data is discussed in Section 4.4, followed by their application for *adaptive topology-aware routing* in Section 4.5. The proposed system design is used as the foundation for our implementation as an extension to the SIMONSTRATOR.KOM framework in Chapter 5, which is used to evaluate the combined aerial network assistance and our contributions in Chapter 6.

4.1 SCENARIO CHARACTERISTICS

In general terms, disasters are "serious disruptions to the functioning of a community that exceed its capacity to cope using its own resources" [137]. Because all disasters have significant differences in their magnitude, their time span, or the threats they pose, no two disasters are the same. Disasters can generally be categorized into

Every disaster is unique

natural, man-made, or technological causes, although a clear separation into a single category may not be possible for each kind of disaster [137]. Some disasters can be predicted as a result of seasons, prevalent weather, or weather forecasts, such as snowstorms [305], wildfires [21, 106, 253, 295], extreme weather conditions like storms, hurricanes, or typhoons [101, 158, 318], as well as floods [6, 152, 214, 243] or landslides [138, 253]. In such cases, preparations can help to increase resilience against the disaster or allow a faster recovery afterwards. In other cases, however, like in the 2021 flooding of the Ahrtal in Germany, the disaster was predicted several days prior to the event but counter-measures and preparations were not made or started too late due to significant human errors and failures [52, 152]. Furthermore, man-made or technological disasters [115, 184] but also natural disasters like Earthquakes and resulting Tsunamis [214, 216, 227, 283–285, 305] are much harder to predict and leave only little or no time for preparation.

Prediction and preparation is complicated

Critical infrastructures are disrupted

The disruption or breakdown of critical infrastructures, such as water, energy, transport, or communication infrastructure, was revealed as a mutual disaster characteristic from the assessment of different past and recent disasters [52, 69, 166]. Especially in dense urban areas, infrastructure disruption affects a large number of the civilian population [227]. Furthermore, a recovery to provide basic infrastructure-dependent services after a breakdown can take several weeks to months [69, 318]. The most prevalent disruption is the loss of power supply and Information and Communication Technology (ICT) [52, 101, 105, 115, 152, 184, 196, 204, 214, 216, 227, 279, 285, 295, 318], which results in a lack of communication and information exchange despite being necessary for emergency services and the affected population for effective disaster relief [101, 106, 116, 213, 279, 285, 318]. Therefore, current research focuses on resilient infrastructures that can mitigate the effects of severe disasters in the future and improve the ability for a quick recovery [93, 124, 204, 269].

Lack of communication

Human mobility changes in a disaster

Another key characteristic that is revealed by assessing disasters is a general difference in the behavior of the affected population from that of everyday life [15, 97, 274]. Disaster-specific movement behavior shows that there are certain Areas of Interest (AoIs), such as emergency shelters, hospitals, or city centers, which are highly frequented and civilians accumulate at or within the closer vicinity around them [15, 175, 265, 274, 306]. On the other hand, as shown in Figure 4.1 at the example of the Ahrtal flooding, the mobility of the affected population is severely limited by the effects of a disaster, such as flooded streets, debris, or broken road infrastructure [15, 25, 101, 166, 265, 318].

Self-organized disaster relief by civilians

Furthermore, the affected population clearly shows social behavior, including collaboration and self-organization of disaster relief and help, but also the sharing of resources like food, water, and energy [103, 120, 139, 252, 280]. This can especially be observed in disaster scenarios with a functioning ICT infrastructure when social media is used for self-organization [8, 127, 148, 158, 176, 232, 252]. Anti-social behavior like looting, however, has shown to be a popular myth and is rather an exception [120, 280]. Nevertheless, this social behavior also increases the demand for communication, which stands in direct contrast to the usual nonavailability of ICT services in a disaster [69, 166, 196, 279]. The use of disaster communication appli-

Figure 4.1: Destroyed bridges and flooded streets after heavy flooding in the Ahrtal, Germany. July 17, 2021 (Photo by Landespolizei Thüringen).

cations over Delay-Tolerant Networks (DTNs), however, has shown to be a viable replacement for infrastructure-dependent communication systems, providing essential emergency communication services for the affected population [15, 32, 166].

Scenario characterization

In this thesis, we specifically focus on a disaster scenario with no available ICT infrastructure, where the affected population uses a DTN-based communication network. This may not only include private messaging or community organization for disaster relief but, more importantly, highly consequential communication with authorities, like requesting help in emergency situations or receiving warnings of possibly life-threatening situations. Due to the accumulation in AoIs, restricted movement capabilities, and the limited communication ranges between DTN nodes, the network is generally assumed to be highly clustered and intermittent. Thus, intra-cluster communication performs well [15], while inter-cluster communication is scarce and afflicted with significant delays, if possible at all. Although these gaps in the communication network can be overcome by UAV-based communication support, the aforementioned specific characteristics of a disaster scenario — especially the mobility and communication requirements of the affected population in combination with the general lack of information — must be considered in the design of an aerial network assistance system.

Detected requirements

Based on the analyzed scenario characteristics, an autonomous aerial system for communication support in a disaster scenario should regard the following requirements. *(i)* The system must be able to autonomously detect, identify, and monitor the network topology, i.e., identify where communication support is needed. *(ii)* Communication support must be provided with a focus on both a fast and extensive distribution of messages. *(iii)* Due to different objectives and applications of UAVs, monitoring and communication support should remain separate but collaborating elements in the UAS. *(iv)* Monitoring and communication support must be continuously performed and adjusted to the changing disaster scenario to allow a long-term situation-aware application of the UAS. These requirements build the foundation for the system design of a combined monitoring and communication support UAS for disaster scenarios, as presented in the following section.

4.2 Aerial Network Assistance System: Overview and Architecture

Combination of monitoring and communication

Based on the requirements identified from the related work and the analysis of disaster scenario characteristics, we propose the concept of *Aerial Network Assistance Systems*. It combines UAV-based topology monitoring and UAV-based communication support mechanisms in a single UAS architecture, to address the detected shortcomings in topology detection and topology monitoring in typical communication support systems and their lack of adaptivity to dynamic post-disaster DTNs. Since both applications have different objectives, topology monitoring and communication support are combined in the system as separate, concurrently executed strategies. In contrast to a system design that uses a single strategy for both appliances, this also allows for studying the coexistence of available approaches and strategies which only focus on one objective.

Central coordination

Similar to state-of-the-art UAS concepts [72, 81, 300], we rely on a central mission control that coordinates one or multiple autonomous UAVs in a known operation area. Mission control is located at a base station that also provides the infrastructure to recharge the UAVs' batteries for long-term deployment as well as communication capabilities. UAVs and mission control can communicate over a reliable long-range control channel with limited capacity, e.g., using LoRa communication, restricting the amount of data that can be sent. Short-range communication is available via a high-throughput technology like Wireless Fidelity (WiFi), enabling data exchange between UAVs on Air-to-Air (A2A) links in a limited range. A separate WiFi channel is used for the interaction between UAVs and DTN nodes, which matches the DTN communication protocol.

Execution layer: UAVs

Figure 4.2 illustrates the components and the structure of the system architecture. In the vertical, we separate into components of a *Coordination* and an *Execution* layer, respectively. The execution layer contains the UAVs for monitoring and communication that interact with the DTN. UAVs are capable of fully autonomous flight to execute a certain mission profile. This profile is defined by a strategy in the coordination layer. Strategies contain all components that plan, adapt, and coordinate the deployment of the monitoring and communication UAVs in the execution layer.

Coordination layer: base station

Typically, these coordination components are centralized in the controlling base station of the UAS. However, our system design can be adapted to allow for a distributed coordination as well, but this is out of the scope of this thesis. Horizontally, the system is separated into execution and coordination components that are split into two distinct application types: first, the *Monitoring* component for UAV-based detection, identification, and long-term monitoring of a disaster DTN and, second,

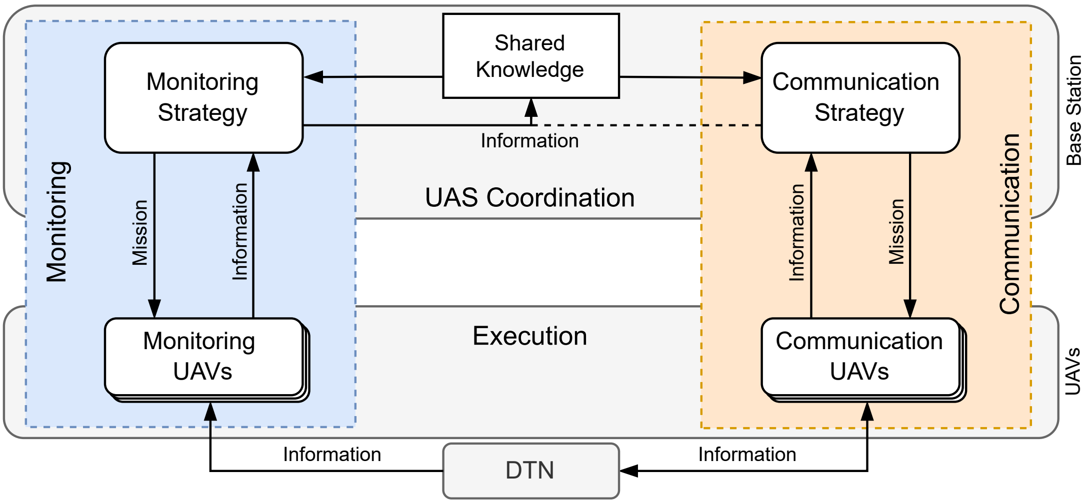


Figure 4.2: System architecture with separated entities for communication and monitoring on the base station and the UAVs, respectively.

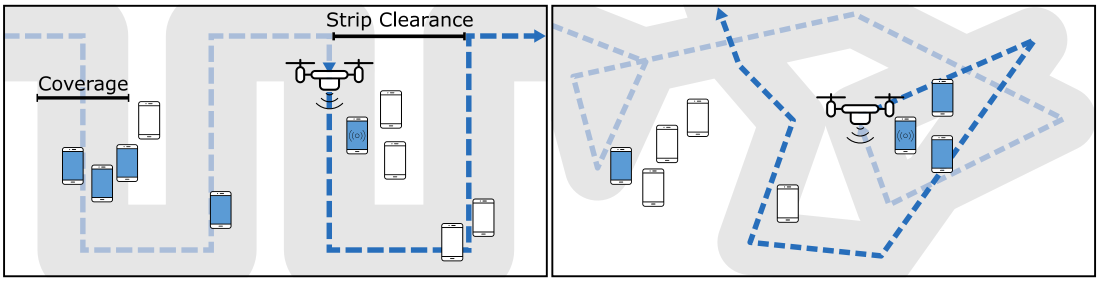
the *Communication* component for UAV-based communication support. This includes the UAVs in the execution layer, the respective strategies in the coordination layer, as well as all communication and information exchange between them.

Shared system knowledge

Providing separate applications for monitoring and communication in the same system is necessary to facilitate their coexistence. However, both use a shared knowledge base provided by a central *UAS Coordinator*. This coordinator also manages the executed strategies for monitoring and communication based on the system's knowledge as well as available UAVs and their capabilities. Furthermore, the coordinator can exchange or issue adaptations of the monitoring or communication strategies, if necessary. As strategies in our design have constant access to the system knowledge, it is also possible for strategies to constantly adapt themselves.

Strategies define UAV missions

Strategies define the behavior of their assigned UAVs by providing a specific mission profile to them, which is executed. Information, on the other hand, is collected from the DTN, flows from the UAVs to the strategies, and is inserted into the shared knowledge for further evaluation. As already discussed, information may also be generated from communication UAVs, depending on the mission profile, although not the primary task in comparison to monitoring UAVs. This issue is further discussed in Section 4.2.3, together with other arising issues from the coexistent execution of monitoring and communication support mechanisms. Our generalized system architecture is purposefully kept abstract to provide the inclusion of a wide range of existing strategies for topology detection and communication support. Strategies and applications for both components are discussed in the following.



(a) Lawnmower Routing. (b) Random Routing.

Figure 4.3: The used Coverage Path Planning (CPP) routing approach significantly influences the achievable area coverage.

4.2.1 *Aerial Monitoring*

The initial detection of nodes and the identification of the network topology, as well as the continuous monitoring of that network, is necessary to provide valuable information on a disaster DTN. Especially in our case, it is a prerequisite for an efficient and effective communication support. Furthermore, this information is similarly important for other disaster relief efforts like emergency services. As shown in the related work, detecting and localizing mobile devices such as smartphones is possible based on transmitted signals [123, 245, 304]. In this thesis, we specifically focus on detecting and monitoring WiFi-communicating DTN nodes, which we can identify and localize based on their regularly sent beacon messages [149, 166, 238].

Beacon detection...

...requires temporal...

Different factors influence the detection and monitoring of DTN nodes by UAVs. Basically, monitoring UAVs need to traverse specific areas and detect nodes on their flight by receiving transmitted beacons. This information is transmitted to the base station and, thus, to the shared knowledge in the strategy coordinator when the UAV returns. A detection naturally requires a spatio-temporal intersection, i.e., an overlap of a node's transmission range with a UAV's reception range at the time of the transmission. In the temporal domain, this intersection depends on the DTN's beacon interval. With a long interval, it is possible that no beacon is sent during a spatial intersection with the UAV, while a shorter interval can result in redundant detections on the UAV but, furthermore, can be problematic for DTN communication due to higher channel load, higher risk of collision, and higher energy consumption. The typical DTN beacon interval lies within a few seconds [15, 256] and, therefore, does not constitute a problem with a sufficiently large spatial intersection. Note that an adaptation of beacon intervals, for example, based on the number of nodes in the 1-hop neighborhood of nodes [30], is not within the scope of this work but could have some negative influences on the detection of larger groups.

...and spatial overlap.

Nevertheless, the spatial domain poses a much larger problem because UAVs need to traverse an area to detect and monitor nodes in it, which requires a definition of both the area and the path to cover it. A specific *Routing* approach must be applied to find a coverage path in a monitoring area, as discussed in Section 3.3. Area coverage may depend significantly on the applied approach, as sketched in Figure 4.3.

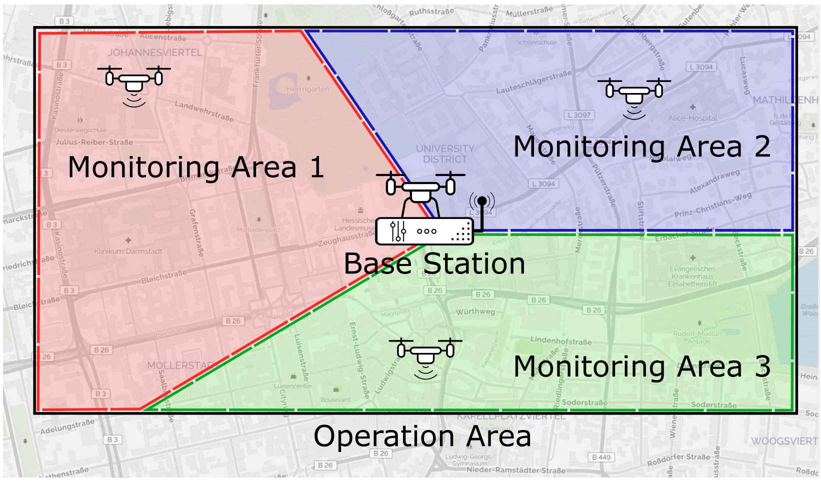


Figure 4.4: Segmentation of a rectangular operation area with the base station in the center. Each of the three smaller monitoring areas is monitored by one UAV.

Deterministic approaches such as lawnmower routing (cf. Figure 4.3a) provide a predictable area coverage depending on the clearance between lawnmower strips and the UAV's coverage, i.e., its detection range. Non-deterministic approaches like random flight, as shown in Figure 4.3b, are used for comparison in our system. Lawnmower routing is our routing technique of choice throughout this thesis due to its predictable but parameterizable nature. By adapting the strip clearance, we influence area coverage, route length, and traversal time, respectively. Since the traversal time is the paramount influence on the information age of the monitored area, because information generally needs to be brought back to the base station, a natural trade-off exists between area coverage and the information age. Full coverage provides a comprehensive but older view of the area, while partial coverage provides possible incomplete but newer information.

Lawnmower routing for CPP

On the other hand, we also need to define the area in which the coverage path is calculated. This is especially important as the larger *operation area* of the aerial system is typically segmented into smaller *monitoring areas*, as shown exemplarily in Figure 4.4. *Segmentation* is necessary for two reasons. First, UAVs have a limited flight range. Especially in a disaster scenario, due to the information dependence of disaster relief, full area coverage is desirable. Monitoring areas, therefore, need to be defined in an appropriate size to allow for full area coverage, which depends on the applied routing algorithm and UAV capabilities. Second, when aerial monitoring has several UAVs at its disposal, it allows for parallel monitoring missions in each monitoring area, which increases the system efficiency in terms of lower age of information and overall shorter time to monitor the complete operation area. Nevertheless, aiming for full coverage could also result in more monitoring areas than available UAVs, resulting in lower efficiency. Therefore, area coverage depends on *(i)* the operation area size, *(ii)* the number of available monitoring UAVs, and *(iii)* the flight range of available monitoring UAVs in combination with the applied Coverage Path Planning (CPP) routing algorithm.

Area segmentation...

...considers routing...

...and vice versa.

The calculation of coverage paths (*Routing*) and the definition of monitoring areas (*Segmentation*) are strongly associated aspects of aerial monitoring. We encapsulate routing and segmentation as individual and exchangeable modules in our system design that can interact with each other as parts of a larger *Monitoring Strategy*. This further provides a foundation for the individual as well as the combined assessment and evaluation of both routing and segmentation approaches (cf. Section 3.3). The monitoring strategy is further comprised of a *Monitoring Coordinator* that utilizes segmentation and routing to define the individual missions for available monitoring UAVs, coordinates mission execution, and accepts incoming information from returning monitoring UAVs before passing it on to the shared knowledge. Due to the disaster environment, we must consider the constantly changing situation, making a constant update process necessary. This requires the capability for a long-term monitoring operation and to constantly re-evaluate the monitoring areas, the prevailing network topology, and their respective coverage path. Therefore, all available knowledge is open to the monitoring coordinator. Depending on the concrete strategy, this allows the coordinator to adapt the mission execution, such as rearranging monitoring areas (cf. Section A.4).

Exchangeable routing and segmentation approaches

4.2.2 *Aerial Communication Support*

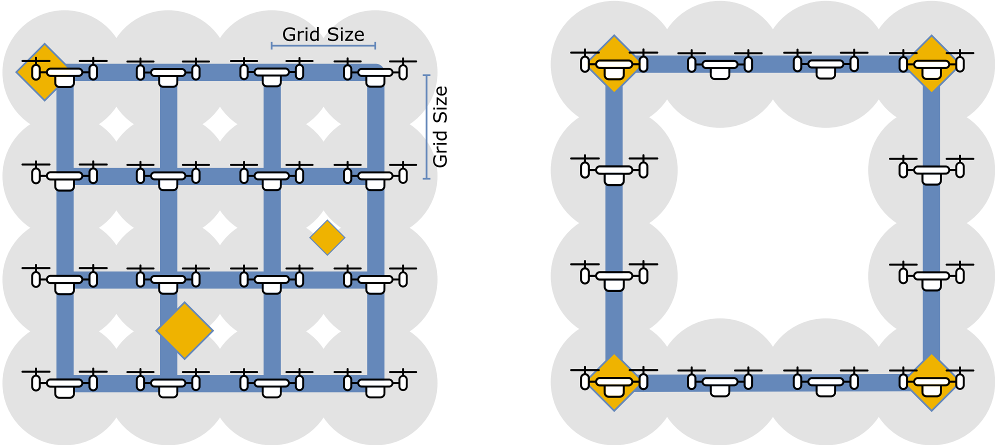
Within the envisioned disaster scenario, the lack of ICT infrastructure and the clustered topology of the available disaster DTN lead to insufficient means of inter-cluster communication. As the analysis of related work in Chapter 3 has shown, communication gaps can generally be overcome with UAVs-based support. For general applicability in a disaster scenario, communication support should be possible without requiring an adaptation of the prevailing DTN. By matching the used DTN communication protocol, UAVs can be easily integrated into the DTN — from a network point of view — by transparently behaving like any other DTN node to exchange messages.

The task of the aerial system is to execute a *Communication Strategy* that facilitates the effective and efficient distribution of messages in the disaster area by utilizing the mobility and controllability of UAVs. The communication strategy specifies a mission profile executed by a UAV. Similar to the monitoring component, a strategy contains a *Communication Coordinator*, which manages and coordinates the specific mission executions of *Communication UAVs*. In the following, we discuss four general concepts of aerial communication support strategies, which provide the basis for further investigations of the aerial system. Nevertheless, our system design allows for a plethora of different communication strategies and is not limited to these.

Different communication strategies possible

Relay Mesh

The *Relay Mesh* strategy is one of the simplest but also most extensive approaches to support communication in a disaster area. UAVs that can hover in the air are distributed over the area, for example, in a grid-like structure, as depicted in Figure 4.5a. Messages from the DTN are relayed and distributed through a dedicated overlay network between UAVs, which provides communication support with exhaustive message distribution and short delivery delays in the supported area. Adapting the



(a) Relay Mesh Strategy. Relay placement is agnostic of cluster locations.

(b) Relay Bridge Strategy. Bridges span between clusters.

Figure 4.5: Communication support with relay strategies.

Mesh adaptations

grid size, i.e., the distance between adjacent UAVs, influences the required number of UAVs and the size of the supported area. With a larger distance between UAVs, either fewer UAVs are necessary for the same area, or the same number of UAVs can cover a larger area. However, due to each UAV's limited Air-to-Ground (A2G) communication range d_{cr}, a larger grid size can also result in coverage gaps, as indicated by white spaces in Figure 4.5a. If a DTN cluster is located within such a coverage gap, the relay mesh will be unable to connect that cluster to the rest of the network. Thus, the theoretical optimal grid size — i.e., the largest possible distance between UAVs to circumvent coverage gaps in this square grid — equals $\sqrt{2} * d_{cr}$. On the other hand, the distances must not exceed the maximum transmission range of A2A links between UAVs. Empirical studies showed that A2A WiFi links between UAVs are able to support high throughput and stable connections of up to 300 meters [109, 117, 164, 298].

Excessive number of UAVs required

Due to these limitations, the *Relay Mesh* strategy requires a significant number of UAVs to provide full area coverage. As an example, full coverage without gaps of a 4 km^2 area requires at least 225 UAVs when considering the communication range as $d_{cr} \leqslant 100\,m$ [15, 166] and a relay altitude of 30 m. Nevertheless, the actual number is even higher due to the limited flight time and the necessity to have replacement UAVs available for a continuous support mission.

Topology-agnostic

The clear advantage of the *Relay Mesh* strategy is its independence of topology data and the possibility of providing communication support to an entire area. Furthermore, a full coverage mesh makes any monitoring approach unnecessary because information on the topology is not needed for the UAS and can be directly collected by the *Relay Mesh* for other disaster relief efforts. The significant hardware requirements, however, render the application of a *Relay Mesh* in a disaster scenario rather impractical. Additionally, the considered disaster scenario with a clustered topology results in large, scarcely populated areas, which minimizes the efficiency of a full-scale mesh approach.

The inclusion of topology knowledge, i.e., the location of network clusters, however, provides more efficient and more practical solutions for a disaster scenario by facilitating topology-aware communication strategies. The *Relay Bridge* strategy aims to provide similar communication properties as a emphRelay Mesh but specifically focuses on cluster interconnection. For that, UAVs with the ability to hover are placed, e.g., like a chain between clusters, as depicted in Figure 4.5b. DTN messages are distributed in the overlay network between UAVs, but only network clusters and the area below the relay bridges are covered by communication support. Adapting the distance between relays can optimize throughput and the number of required UAVs, since cluster coverage is more important than area coverage in this strategy. The specific placement of UAVs can be determined, for example, by calculating a Minimum Spanning Tree or a Minimum Steiner Tree [67, 98, 132]. Similar to our proposed routing adaptation in Section 4.5, relay bridges could also be directed over populated streets to provide additional coverage. Due to the focus on network clusters, the *Relay Bridge* strategy requires fewer UAVs than a full relay mesh while expectedly providing service to a majority of DTN nodes. Furthermore, relay UAVs can directly monitor their surroundings and, for example, adapt their placement over a moving network cluster. Without additional monitoring, however, the strategy cannot detect disconnected network clusters outside the provisioned area.

Relay Bridge

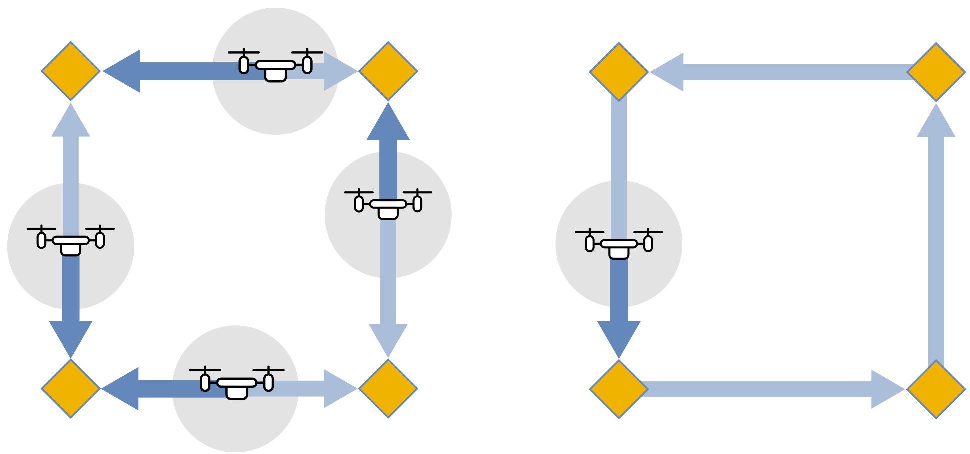
Drawbacks of relay strategies

The considerable drawback of both relay-based strategies is the dependence on an appropriate number of UAVs, both actively participating in the relay network and standing by as a replacement at the base station. Furthermore, static relay placement does not utilize the controllable, highly flexible movement capabilities of UAVs as an advantage other than an adaptive relay placement.

Data ferry strategies

In contrast, *Data Ferry* strategies deploy UAVs to physically transport data between network clusters. Multi-hop relaying over many statically deployed UAVs with constant area support is exchanged with temporary and recurring area support by only a few mobile UAVs. However, this results in increased dissemination delays and a higher probability of missing topology changes, compared to static area support. Thus, parallel area monitoring is mandatory without additional sources of information. Nevertheless, the utilization of UAV mobility also results in very low requirements for the number of communication UAVs. For example, cluster connections for an *Oscillating data ferry* strategy, like in Figure 4.6a, can be calculated similarly to that of the corresponding *Relay Bridges*. However, only a single UAV is required to oscillate between two supported network clusters for message dissemination. With even harsher restrictions on the number of available UAVs, multiple network clusters can be supported by a single UAV. In the extreme case, this results in the *Cyclic data ferry* strategy with only one UAV consecutively visiting each network cluster, as shown in Figure 4.6b. Clearly, the distances between network clusters connected by data ferries must be smaller than the UAVs' maximum flight range. Additionally, the increasing dissemination delay, as a result of the necessary flight time to traverse all clusters, must be regarded with respect to the network's Time-to-Live (TTL) setting for messages. Nevertheless, the *Data Ferry* strategies provide a viable solution for communication support with only a few UAVs.

Low number of UAVs required



(a) Oscillating Data Ferry Strategy. (b) Cyclic Data Ferry Strategy.

Figure 4.6: Communication support with data ferries between clusters.

Integration in DTN

Especially in the context of DTNs, the controllable, high mobility of communication UAVs is an excellent option to integrate them as data ferries, as it allows to efficiently and purposefully realize the *store-carry-forward* principle. Therefore, we primarily consider the group of *Data Ferry* strategies as a suitable solution for communication support of a disaster DTN.

4.2.3 *Coexistence of Monitoring and Communication Support*

Diametrical objectives

Despite some exemptions, such as the *Relay Mesh* strategy, topology information is a necessity for most communication support mechanisms. Nevertheless, as analyzed from related work, the objectives of aerial topology monitoring are typically diametrical to that of aerial communication support. While the former aims to provide a complete and up-to-date information state on the disaster situation for the UAS, the latter targets the exhaustive and quick dissemination of messages in the supported DTN. Thus, we deem the combination of both in a single strategy — although technically possible with our design — inadequate due to the contrary objectives. As a result, we separated monitoring and communication mechanisms based on their *primary* objective as distinct but coexisting parts of our system design (cf. Figure 4.2).

Local mechanism coexistence

Nevertheless, monitoring and communication mechanisms could be executed concurrently on the same UAV for local coexistence. On the one hand, monitoring UAVs could collect and disseminate DTN messages while traversing monitoring areas. This can result in increased service coverage if messages are exchanged with nodes currently not covered by communication UAVs. However, contacts with other UAVs during traversal are unlikely, especially with increasing distance from the base station and in sparsely populated areas. Message propagation between monitoring areas is, therefore, only happening sporadically, if at all. Furthermore, monitoring traversal is time-intensive; thus, the TTL of messages, known or collected at the beginning of the monitoring or exchanged with other UAVs, may expire before completing the area traversal or reaching other UAVs or DTN clusters. The overall contribution of coexisting communication mechanisms in the monitoring UAVs is, therefore, expected to be modest. On the other hand, communication UAVs could simultaneously collect topology information while disseminating messages. This is especially interesting as data ferry UAVs frequently approach densely populated areas. The information collected by coexisting monitoring on communication UAVs could, therefore, provide a coarse but recent information state on the supported areas to the UAS. Nevertheless, it is typically only possible to detect deviations from the available information state. Thus, parallel monitoring is still required to detect and identify the topology for areas that are not directly traversed by communication UAVs. We investigate possible implications and the impact of locally coexistent mechanisms in Section 6.5. However, communication strategies are aligned to the requirements of the communication mechanisms and monitoring strategies to that of monitoring mechanisms. We, therefore, expect a possible mismatch when combining several mechanisms without adapting the respective strategies. Nevertheless, the adaptation or creation of new strategies that blend several mechanisms and objectives together is not within the scope of this thesis.

System strategy coexistence

Generally, the coexistence of monitoring and communication support strategies in the aerial system does not necessarily denote a parallel execution at the same time. For example, an initial monitoring mission collects topology information, which is used to instantiate a data ferry approach for communication support. After that, the monitoring strategy is paused until a significant deviation in the network topology is registered by the aforementioned secondary monitoring mechanism on communication UAVs, which triggers another monitoring flight. Our system design facilitates such a solution with the centralized UAS Coordinator that can manage and coordinate the respective strategy's execution. Furthermore, the coordinator manages available UAVs and their assignment to the strategies, which enables the shared usage of UAVs for both monitoring and communication support. For the example above, this means that initially deployed monitoring UAVs can be used to increase communication support while the monitoring is paused. However, designing a sophisticated procedure involving the optimized coordination of communication and monitoring as well as the optimization of UAV allocation to strategies is not within the scope of this thesis. Nevertheless, we utilize the proposed architecture of the UAS Coordinator and strategies to enable the constant evaluation of topology data and actively trigger the re-calculation of communication support routes, presented in Section 4.5.

The provided system design combines monitoring and communication support as coexistent applications of a single UAS, both sharing a common information base. This allows the deployment of UAVs for each application, focusing on specialized tasks. We considered the interaction of different components like routing and area segmentation in monitoring and approaches for communication support. Furthermore, we discussed different aspects of coexistence for monitoring and communication applications. This combined system design facilitates our following contributions to an adaptive Aerial Network Assistance System.

4.3 INCREASING NODE DETECTION BY COOPERATIVE AERIAL MONITORING

Passive monitoring

Full workload on UAVs

The approaches for aerial monitoring mentioned above enable DTN node detection through eavesdropped beacon messages. As described in Section 4.2.1, detection requires a spatio-temporal intersection between monitoring UAVs and DTN nodes. While UAVs have to actively traverse the area to achieve coverage to allow eavesdropping, the detection itself is purely passive. Furthermore, full area coverage is required to allow the possible detection of all nodes; otherwise, nodes within uncovered areas can be missed (cf. Figure 4.3a). Clearly, node coverage and area coverage are directly correlated from the point of view of the UAS. The entire workload of node detection must be carried out by monitoring UAVs.

DTN nodes exchange information...

...but not used by UAS.

However, depending on the applied DTN protocol, the eavesdropped DTN beacons can include additional information from the sending node, as discussed in Section 2.2. This comprises, among others, their location, stored messages, or known neighbors of that node. DTN protocols use this information, for example, to identify a local cluster, which in turn allows nodes to disclose their affiliation to a certain cluster, e.g., with a cluster hash ID. The distinction of different clusters provides an efficient way to detect changes in the local network topology, like the formation or fragmentation of clusters and the merging of different nodes or clusters into a new cluster. Furthermore, exchanging information on already known messages allows to only exchange unknown messages, which is more efficient than pure flooding [15, 149, 166, 173, 238, 256]. More sophisticated protocols can even collect and distribute information in network clusters to enhance routing or balance workload [121, 130]. Despite the possible availability of topology information in a local cluster, this information is not used and integrated into available aerial monitoring approaches.

CAMON

Decoupling of area and node coverage

Therefore, we propose to enhance node detection with *Cooperative Aerial-Ground Monitoring* (CAMON) [311]: DTN nodes actively collect and share topology information with monitoring UAVs, increasing the overall monitoring performance. For itself, the detection of a single DTN node by a monitoring UAV still requires the reception of a beacon message. With CAMON, however, only a single DTN node must be encountered, which shares information about all DTN nodes in the local cluster. Ideally, this allows decoupling area coverage and node coverage from each other by providing node coverage without requiring the respective area coverage. Nevertheless, clusters are still missed entirely if not at least a single node is covered.

Active monitoring

Restrictions

For CAMON, we introduce active communication and information exchange between UAVs and DTN nodes. On beacon reception, a UAV can actively send a Cluster Information Request (REQ) message, declaring its interest in more information on the DTN. Furthermore, the UAV directly extracts important information from the received beacon, if possible. The beacon sender, in turn, can answer with a Cluster Information Reply (REP) message containing cluster information known by that node. Information is given as a set of triples *Triple(ID, Timestamp, Location)*. For each known node — indicated by the node ID — the latest location and the timestamp of that information are provided. To prevent broadcast storms, devices are addressed individually by UAVs. Furthermore, we employ a back-off interval to pre-

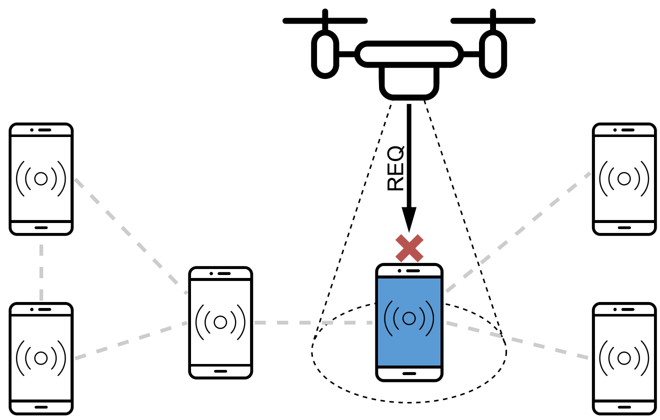


Figure 4.7: Beacon — Node detection is only possible via beacons within the UAV's detection range. REQ messages are dropped. Adapted from [311].

vent UAVs from requesting additional information when waiting for a reply message. This also prevents re-requesting information from the same cluster after receiving a reply within a certain time frame. However, topology changes within that back-off interval can still be detected, either based on eavesdropped information updates in the network or by the change of the cluster hash, which allows sending a new REQ message nonetheless.

CAMON as addition to DTN protocol

Generally, the mechanism for cooperative monitoring should be possible as a lightweight addition to any DTN protocol. Since there are different kinds of DTN protocols, as discussed in Section 2.2, the mechanism must fit the communication procedure of the respective protocol. Furthermore, CAMON should also be applicable as a standalone system in addition to simplistic, e.g., flooding-based DTN protocols (cf. [238]). Thus, we design different approaches for cooperative monitoring with CAMON: *(i)* a hierarchical proactive protocol (Hierarchy), *(ii)* a distributed proactive protocol (Proactive), and *(iii)* a reactive collection protocol (Reactive). These CAMON protocols follow typical communication concepts in DTNs, as discussed in Section 2.2, and primarily determine beacon content and message exchange in the DTN. For completeness and a baseline comparison, we also include a non-cooperative protocol (Beacon). In the Beacon protocol, as shown in Figure 4.7, REQ messages from UAVs are ignored and only simple DTN beacons are sent, constituting the standard case for DTNs without CAMON. In the following, we provide a detailed description of each protocol.

Beacon as non-cooperative baseline

Hierarchical Proactive Protocol (Hierarchy)

In case that topology information is similarly important for the DTN protocol as it is for aerial monitoring, the collection and distribution of information within the DTN is performed on a regular basis. We call this behavior *proactive* because it is performed without the external influence of a monitoring UAV. Whenever the DTN protocol constructs and maintains a layered *hierarchy*, for example, with a cluster

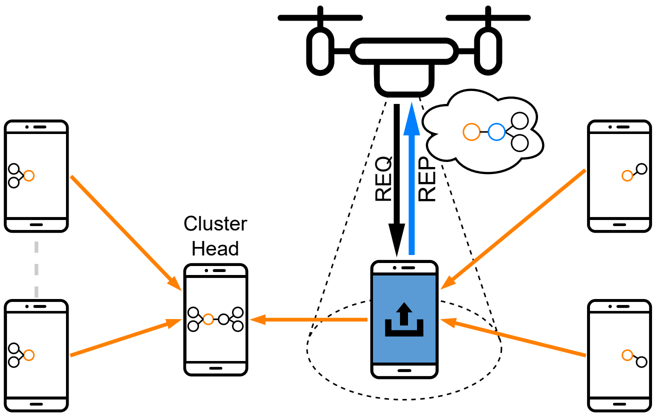


Figure 4.8: Hierarchy — Information flows in hierarchical layers towards a Cluster Head. REQ messages are immediately replied with current information available on the contact node. Adapted from [311].

head (CH) acting as a data sink, protocol-specific information is propagated "upwards" from the farthest nodes towards the designated CH [121, 238]. The *Hierarchical Proactive Protocol* (Hierarchy) utilizes this structure to specifically propagate topology information in addition. With that, each node holds the information of its local neighborhood as well as the hierarchy below itself, as shown in Figure 4.8.

Determining the hierarchy and the CH requires an exhaustive exchange of information initially and whenever significant changes in the topology occur. On the other hand, the overhead to maintain the hierarchy afterwards is relatively small, and information is only propagating towards the CH, both decreasing the overall bandwidth requirements on the wireless medium [238]. In particular, the workload to collect and push cluster information to the CH decreases with a lower hierarchy level. Nevertheless, these benefits reduce with increasingly frequent topology changes, as more maintenance messages must be sent. Hierarchical DTNs are, therefore, best used for less dynamic DTNs and constitute only a fraction of protocols. The CH is collectively determined by a metric, usually defined by the DTN protocol [241]. In our case, the metric selects the node closest to the geometric center of a cluster as CH.

Whenever a REQ message is received on a node using the Hierarchy protocol, recent information on the known part of the hierarchy is available and immediately transmitted in a REP message to the UAV. No further message exchange is performed in the DTN. Clearly, the most complete information is available on the cluster head, and thus, UAVs should specifically contact the CH if available. For that, the cluster head indicates its status with a specific flag in its beacon. This enables the UAV to distinguish the CH from a set of received beacon messages and actively target cluster heads as receivers for REQ messages. Additionally, we allow the monitoring UAV to send a REQ message to the CH, even when within the aforementioned back-off interval after receiving information from another node before, to gather the most complete information state.

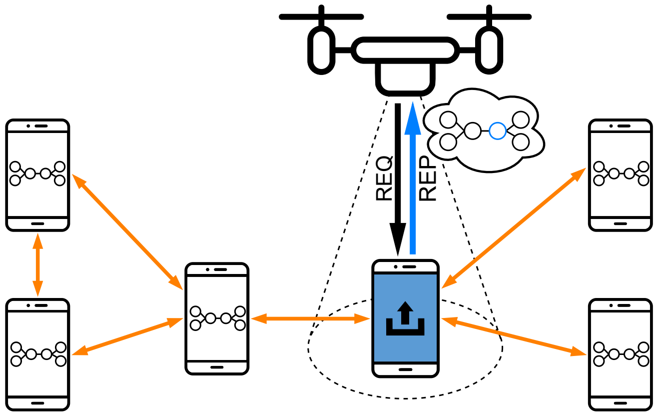


Figure 4.9: PROACTIVE — Information is constantly updated among all nodes in the cluster. REQ messages are immediately replied with current information available on the contact node. Adapted from [311].

Distributed Proactive Protocol (PROACTIVE)

The majority of DTN protocols follow a non-hierarchical and distributed approach: information is shared among all nodes to reach a common consensus. The *Distributed Proactive Protocol* (PROACTIVE) follows this idea by proactively spreading all topology information within each local cluster to be available on all nodes. With that, the contacted node can immediately respond with its current state of information when requested from a UAV, and no further communication in the DTN is required, as depicted in Figure 4.9.

On reception of a beacon, a node directly stores or updates the information triple of the sender, as well as its list of 1-hop neighbors. Furthermore, additional topology information as a set of aforementioned triples can be appended to the beacon, which represents the current state of information of the sender. Each datum, which is more recent than an already stored datum for a respective cluster node, is saved. The updated information is then appended to that node's next beacon, to update its neighborhood. By that, information propagates through the cluster and is constantly updated. This frequent synchronization, however, can impose significant stress on the communication network, especially for large clusters. Infrequent synchronization and slow information propagation, on the other hand, result in inaccurate or outdated data whenever the topology changes.

Therefore, we append cluster information to a beacon only when the node detects changes in the cluster topology. A direct change in the local topology is indicated by *(i)* a beacon of a node that is currently not in the list of known neighbors is received or *(ii)* no beacon of a node in the known neighbor list has been received within a certain time frame. A topology change inside the local cluster but outside the 1-hop neighborhood can be perceived when *(iii)* a neighbor has sent a beacon with a different cluster hash. Furthermore, devices only append topology information to their next beacon if the same information is not received with a beacon from another device. With that, redundant information exchange and overall stress on

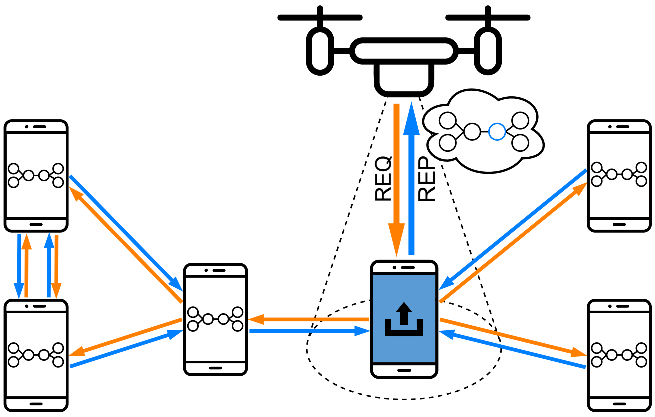


Figure 4.10: REACTIVE — Information collection is triggered by a REQ message. Up-to-date information is collected and propagated towards the UAV via the contact node. Adapted from [311].

the network are reduced, while allowing the propagation of changes as usual at the same time. But especially dynamic clusters will still require significant information exchange for an up-to-date state of information. However, recent changes can also be eavesdropped by a UAV after receiving a REP message or detected through the change of the cluster hash received in beacons. UAVs may, therefore, still perceive significant changes that occur shortly within the back-off interval.

Reactive Collection Protocol (REACTIVE)

The proactive topology information collection in HIERARCHY and PROACTIVE requires a large number of overhead messages and constant updates to synchronize and provide an always up-to-date information state. For simple DTN protocols that do not maintain hierarchies or distribute information by themselves — where topology information cannot be appended to messages that are already required by the protocol —, this enormous increase in overhead constitutes a severe issue. Furthermore, proactive collection and maintenance of topology information can be unnecessary when no UAV comes in contact with the cluster.

To overcome these issues, the *Reactive Collection Protocol* (REACTIVE) only activates in the presence of a UAV. Otherwise, the normal DTN protocol is executed without additional overhead, e.g., similar to the non-cooperative BEACON protocol. As shown in Figure 4.10, a UAV initially sends a REQ message to the contact node. This triggers the collection process of topology information in the local cluster. Information is flooded through the network by the same approach as the proactive protocol until a steady information state is reached that is transmitted in the REP message to the UAV. However, no new beacons are sent during the collection process once a node has broadcasted its most recent information state and not received any updated information from others, which reduces possible collisions and accelerates the collection process. Furthermore, no other REQ messages are addressed during the collection to prevent multiple collection processes running in the same cluster. The collection process is assumed to be terminated once the last updated beacon is received and a node has waited for the back-off interval to expire.

Reactive collection tends to overcome possibly redundant or unnecessary information collection in the DTN. However, it also requires exchanging a large number of messages within a short time frame. This could negatively influence other DTN applications, e.g., concurrently provided communication services, by exhausting the available communication bandwidth during the time of information collection. Furthermore, reliable information is only available directly after the collection process as no further updates are propagated, and other monitoring UAVs need to trigger the collection process again. Nevertheless, we expect that contacts between clusters and UAVs rarely occur since we utilize a static lawnmower coverage path and separate monitoring areas. The negative implications of this sudden information flooding could, therefore, outperform the constant requirement of information exchange by the proactive protocols.

In this section, we introduced *Cooperative Aerial-Ground Monitoring* (CAMON) as an enhancement to DTN protocols. By leveraging different protocol characteristics and providing the respective approach for CAMON, it can be added to a variety of existing DTN protocols while also being able to work as a standalone system. CAMON shares available topology information from within the DTN with the UAVs. This shifts the workload of node detection from the UAV to the DTN and allow the decoupling of area coverage and node coverage. A detailed evaluation of the different CAMON protocols, as well as their advantages and drawbacks, is described and discussed in Section 6.2.

4.4 IDENTIFICATION OF DTN CLUSTERS ON UNSTRUCTURED DETECTION DATA

Cluster identification must be possible...

...with simplistic,

...inaccurate,

The cooperative sharing of information in CAMON provides a simple method to identify and differentiate DTN clusters. After monitoring UAVs have returned to the base station and submitted their data to the strategy coordinator, cluster information can be used as input to communication support, such that each cluster is approached by data ferry UAVs. However, the identification of DTN clusters from the shared system knowledge must also be possible when cooperative systems like CAMON are not available and only DTN beacons can be collected. Furthermore, we must encompass alternatives to a network-based detection, such as aerial monitoring with camera-based identification or completely different sources of information like high-altitude and satellite imagery. In such cases, information must be assumed to be a simplistic, unstructured set of locations $P = \{p \mid p = (x_p, y_p)\}$, possibly with a timestamp of the detection, but without additional meta data. Within a certain time frame, updates of the disaster area or certain parts of it are received from the data source, e.g., after a monitoring UAV returned with new information. Inherent inaccuracies, such as the dilution of precision in satellite-based positioning systems like GPS, are an additional error source for correct cluster identification. Furthermore, information has already a certain age when reaching the coordinator and could already be outdated. The mobility of nodes is another issue when considering the disaster scenario. Mobility within AoIs should not negatively affect the identification, as a populated area typically also results in a well-connected cluster. Nodes in transit between AoIs, however, must be differentiated from static clusters, otherwise a data ferry would visit the identified location although the nodes have already progressed.

...and outdated data.

The application of well-known clustering algorithms like k-Means [13] or DBSCAN [83] is, therefore, problematic. In general, k-Means requires a-priori knowledge or at least an estimate of the number of clusters that should be found, which is unavailable information in our disaster scenario. Otherwise, k-Means can be repeated with different values for k, but requires a metric to define the best value for k and is — especially in large datasets — computationally expensive to calculate [83]. Furthermore, both approaches can result in the wrongful detection of two distinct but close clusters as a single cluster, or the inclusion of nodes in transit to a static cluster due to their properties of arbitrary shape detection and the clustering of all available data points. Generally, measurements of moving nodes can be seen as noise in the dataset. Since both approaches are susceptible to noise, a clear distinction of static nodes and moving nodes is not possible.

Classical clustering algorithms not applicable

Additionally, the determination of the network topology only based on the latest data can be problematic. If data is incomplete of erroneous, the topology can be miscalculated and the system could wrongly adapt to changes, that are not happening, or send a UAV to approach clusters, that are not existing or moved away. Therefore, we propose to include older data in the cluster detection process to make the system more robust against erroneous or incomplete data input. This could also allow to identify mobility by comparing data with different ages.

Inclusion of historic data

In conclusion, we specify the following requirements for the identification of DTN clusters: *(i)* It must be possible to detect or estimate clusters by interpreting simplistic, unstructured data. *(ii)* Updates in the topology data over time should be included to adapt and improve the cluster detection or estimation. *(iii)* Cluster detection or estimation must be robust against missing, incomplete, outdated, or erroneous data updates. In the following, we address these challenges by providing a scalable data structure for received detection data which allows to identify network clusters. Furthermore, our approach allows a distinction of node mobility which can be used for route adaptions of communication support UAVs as presented in Section 4.5.

Requirements

Gridmap for Aggregating Detection Information

Since we envision a long-term deployment of our UAS within a disaster area of several square kilometers in size, the system has to cope with a large number of data inputs over a long time, each including itself a large number of location measurements. Therefore, we require an efficient and scalable data structure that is able to process and store large amounts of input data. For that, we aggregate incoming measurement data into cells of a grid-based data structure, which resembles the UAS' operation area.

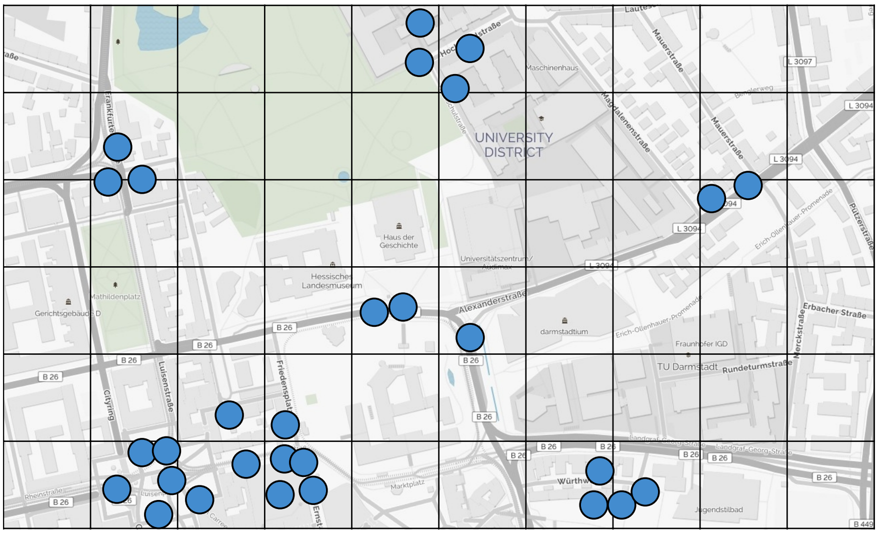


Figure 4.11: A single set of location measurements for an inner-city disaster environment showing clusters of different sizes. Apparently, the grid placement and the cell size influence to which cells measurements are assigned. Furthermore, clusters can spread over multiple cells. Mobility cannot be determined from a single snapshot. (Map and Data © www.osm.org/copyright)

Grid-based data structure

As sketched out in Figure 4.11, we divide the operation area into quadratic cells c of equal edge length d_{cell}. Location measurements are matched against the grid and, whenever a measurement falls within the coverage of a cell c_i, increase a measurement counter Ω_i for the respective cell. New data can be added easily to the gridmap, which resembles the node distribution within the observed area, without requiring to re-evaluate the entire dataset or re-assess the whole distribution. This allows to efficiently store a large number of data points and also absorb measurement errors in data points through the aggregation in larger grid cells. Nevertheless, this aggregation of measurements is highly dependent on the size of the grid as well as its placement. Large cells are less detailed and inaccurate, which can result in the loss of a detailed view and the inability to distinct different clusters, but they are also less complex. Smaller cells, on the other hand, provide a more detailed view of the area, but also lead to a significant increase of necessary grid cells. If cells get too small, no advantage over the raw data is gained due to the minimal data aggregation possible, which prevents the detection of clusters at all. As the main goal is to detect connected clusters of a DTN, the grid size should resemble the expected communication ranges in the network. By that, we have a high probability for existing communication links between nodes within a cell that form a cluster. Additionally, this allows to assume communication links between nodes in adjacent cells, which is especially important as clusters may spread over several cells, as indicated in Figure 4.11, either due to their size or a coincidental overlap with a cell border. Based on the findings of a real-world field test discussed in Section 2.3, the typical range for urban DTN communication links can be expected around 50 m to 100 m.

Aggregation of information

Adapt grid size to expected communication links

Before discussing the detection of clusters in the upcoming section, we must approach another issue arising from the continuous integration of new data in the gridmap. Clearly, information gets outdated over time due to the mobility of nodes and the changing network topology within disaster scenarios. Thus, simply inserting new data and working on the entire gridmap will result in an increasingly inaccurate static topology assessment. Nevertheless, historic data should still be included in the assessment to allow the detection of mobility and increase the robustness of the assessment against missing or erroneous data, as discussed before. Therefore, we introduce a half-life period $T_{1/2}$ which decreases the value for measurements over time. More recent data points should have a larger influence, while the influence of older data points gradually attenuates. As the gridmap only saves the aggregated measurements and no individual data points, we attenuate the measurement counter Ω_i for each cell with

Integrate but attenuate older data with half-life period

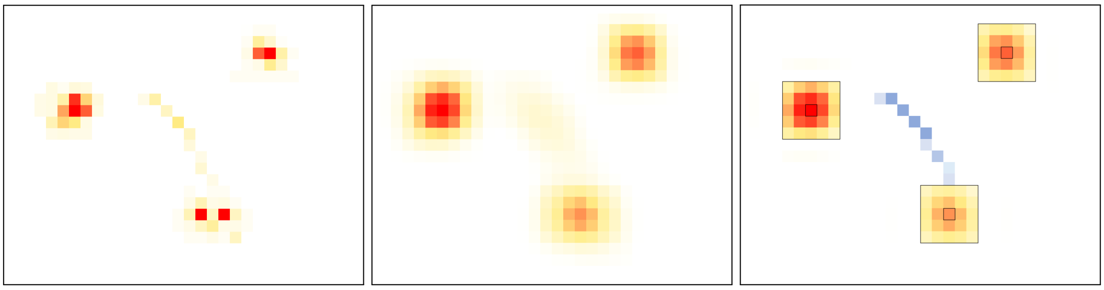
$$\Omega_i(t + \Delta t) = \Omega_i(t) * e^{-\Delta t * \frac{\ln(2)}{T_{1/2}}} \tag{1}$$

such that the value of Ω_i is halved after $T_{1/2}$. The attenuation time Δt denotes the interval since the last update of Ω_i. With that, the counter for cells without new measurements is reduced exponentially, which allows a quick detection of dissolving clusters in addition to a minimal influence of anomalous measurements and mobility between clusters, while cells with a steady number of input measurements over time also perceive a steady value for their counter. On the other hand, the system does not immediately discard existing cluster estimations if data is missing once-only. Nevertheless, both flexibility and stability of the cluster estimation depends on $T_{1/2}$. A large period incapacitates the system to perform quick reactions to changes, while a short period increases the vulnerability to anomalous measurements and leads to instability in the cluster estimation. Therefore, $T_{1/2}$ should be chosen depending on the aspired system performance and available data sources. More reliable data sources can allow the use of shorter periods that increase flexibility. Error-prone data sources or those that only provide data irregularly, however, need a larger interval for increased stability.

$T_{1/2}$ influences system performance

In our case, monitoring is part of our UAS deployment and we can anticipate a reliable update interval of location measurements, i.e., after monitoring UAVs traversed the area and returned to the base station. Furthermore, each monitoring UAV can be associated to a specific monitoring area, which allows to determine for which cells information is provided and, especially, for which cells no measurements are available. Therefore, $T_{1/2}$ can be adapted per cell based on the traversal interval Δt of their respective monitoring area, which is easily determined from the monitoring flight. With $T_{1/2} = \Delta t$, the counter attenuation is simplified and results in halving Ω_i directly for all cells that the incoming dataset covers, before new measurements are added afterwards. However, this approach can only be applied if our monitoring approach guarantees a complete view on the monitoring area and no other sources of information are used. Otherwise, incomplete data input can result in inconsistent attenuation and an erroneous assessment of the network topology.

$T_{1/2} = \Delta t$ for reliable data sources



(a) Aggregated raw data in a gridmap.

(b) Smoothed dataset.

(c) Detected clusters and mobility after filtering.

Figure 4.12: Exemplary sequence of cluster detection and the differentiation to node mobility in a populated gridmap. Clusters are detected within the extent of the applied filter kernel. Adapted from [310].

Processing Information for Cluster Detection

Problems of cluster detection

After integrating detection information in the gridmap, the next step is to estimate cluster locations and differentiate them from mobility. Figure 4.12a provides an example of a populated gridmap with aggregated measurements for three clusters and scarce mobility of nodes. The naïve approach of selecting the most populated cells is clearly not a viable option. First, it is unclear which n cells should be selected as the number of clusters is unknown from the point-of-view of the UAS. Second, multiple cells with large population can belong to the same cluster, while several less-populated cells can also belong to a more spread-out cluster, which should be detected individually. And third, as seen in the bottom cluster, non-uniform node distribution within a cluster can lead to non-adjacent highly populated cells — and thus, individual local maxima —, while still forming a single cluster from the network perspective. Furthermore, the spread of a cluster over multiple cells complicates its detection as a cluster from the gridmap, while a smaller high-density cluster is much easier to detect. Especially smaller cells lead to an increased severity of that problem, as clusters can spread over more cells. Overall, location measurements are unequally distributed and distorted, but need to be combined within a certain area to allow the estimation of clusters in the gridmap.

Smooth local maxima with Gaussian filter...

To combine adjacent cells and reduce the influence of very large localized maxima, we apply a Gaussian filter on the aggregated data. As shown in Figure 4.12b, the Gaussian filter smoothes and blurs adjacent cells together, like the two distinct maxima in the lower cluster. Furthermore, it also reduces the impact of noise in the data, i.e., measurements of moving nodes that do not belong to a cluster are blurred over a larger area and reduced in their general intensity. Similar to its typical application for digital image processing, applying Gaussian filter on the gridmap data requires a convolution with a discretized, two-dimensional kernel, that approximates a Gaussian distribution. Generally speaking, the center of the kernel is placed over a cell of

...using a 2D filter kernel.

the gridmap and the values for Ω_i of all cells that are covered by the kernel are aggregated to a new Ω for the center cell. Each cell, however, only has a certain impact on that calculation, with adjacent cells typically providing the largest impact after the center cell itself. That impact is defined by the width of the Gaussian distribution σ. Large σ provide a wide distribution, resulting in a larger impact of remote cells and a higher attenuation of the center cell. Smaller σ result in a narrow distribution, that puts more emphasis on the center cells and its direct neighbors. In general, a kernel should at least cover 2σ to allow a sufficient approximation of the Gaussian distribution. In combination with the cell size for the gridmap, σ should be chosen to resemble the expected communication range of DTN devices. By that, cells that are more likely to contain nodes with existing communication links and, therefore, a higher probability for a connected cluster, also provide the largest impact on the attenuated value for Ω. Each entry of the approximating kernel matrix is defined by two indices x and y, and calculated with

Kernel size based on communication range

$$\text{kernel}[x][y] = \frac{1}{2 * \pi\sigma^2} * e^{-0.5*((\frac{x-c_x}{\sigma})^2+(\frac{y-c_y}{\sigma})^2)} \tag{2}$$

where c_x and c_y denote the indices of the kernel center. The kernel size is typically symmetric and an odd number, for example, 5×5 or 7×7, and thus $c_x = c_y$ holds in such cases.

After attenuating and combining large local maxima with Gaussian filering, remaining fragments of detected node mobility must be removed to prevent false cluster detection. Therefore, we subsequently apply a high-pass filter which removes all cells below a specified threshold, which is the minimal number of nodes that is considered a network cluster the UAS should serve. Nevertheless, this threshold is highly scenario-specific. Lower thresholds could negatively influence the detection of small valid clusters, while a higher threshold can lead to false cluster detection. A dynamic adaptation is required to allow its application to a broader range of different scenarios, but is out of the scope of this thesis.

Scenario-specific high-pass filtering

Following the high-pass filtering, noise and small fragments are removed from the gridmap. As shown by Figure 4.12c, clusters can then be detected by searching for the local maxima in the filtered gridmap. Specifically, we utilize the extents of the applied kernel as stencil for clusters, adding all non-zero cells within the kernel range around the local maxima to the cluster estimation. The obtained information is crucial, as it now allows to deploy communication UAVs to accurately connect the found DTN clusters. In addition, however, cells with node mobility can be differentiated from clusters by dissecting the estimated cluster extents with the original gridmap. Figure 4.12c visualizes these cells in blue, indicating some node mobility between the left and the lower cluster. This information is especially useful to adapt routes of communication UAVs when coverage of nodes outside of clusters is desirable, as shown in the following section.

Estimate clusters on filtered data

Differentiate mobility

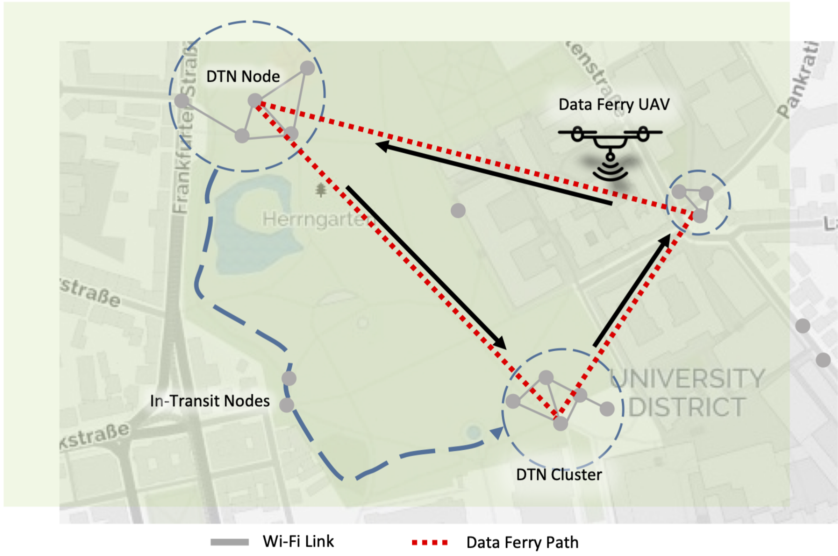


Figure 4.13: Nodes in transit between clusters are disconnected from the rest of the DTN. They are not covered by aerial communication support if their path does not match or cross a data ferry's path [310].

4.5 INCREASING TRANSIT NODE COVERAGE WITH ADAPTIVE TOPOLOGY-AWARE ROUTING

The application of *data ferry* communication UAVs is a highly efficient ways to provide delayed communication support between identified network clusters, as discussed in Section 4.2.2. To minimize the dissemination delay of messages and to minimize the risk of exceeding the lifetime of messages before reaching its destination, data ferry UAVs typically fly the shortest path — usually a straight line for multicopter UAVs — between clusters.

Disconnected transit nodes

However, a large number of nodes can also be outside of clusters, usually to move to another location [15]. As showcased in Figure 4.13, these *transit nodes* are typically disconnected from the rest of the DTN for the entire transition time. Only when meeting other transitioning nodes or clusters by coincidence on their way, message reception or forwarding is possible. Similarly, communication support is only possible if these nodes cross the path of a UAV coincidentally, most probably when they use a similar direct way towards another cluster. Typical data ferry applications neglect these transit nodes and focus on the majority of nodes within the clusters. Especially in larger disasters with considerable transit times for DTN nodes, such long disconnection times can pose a significant problem due to the incapability of sending or receiving important messages. It can even by life-threatening, if highly relevant messages such as evacuation notices or threat warnings are missed at transit nodes.

No UAV coverage

Therefore, we aim at increasing the transit node coverage for data ferry strategies. In general, this requires to adapt the routes of communication UAVs to the paths of transit nodes. One apparent approach is to map UAV routes on the street layout to increase the probability for transit encounters. However, this requires some definition which streets to traverse. Shortest distances or largest streets could be viable approaches, but might not correlate with the path taken by nodes; some streets may be obstructed due to the disaster, or nodes could move offside official streets or footpaths. Thus, using the street layout without any further information cannot provide a viable solution for increased transit node coverage.

Adapt routes for transit node coverage

Instead, we propose to utilize available topology data, such as the identified node mobility from the gridmap in the previous section, to reroute UAVs over possibly populated areas. As discussed in Section 4.2.2, calculating an optimal route over a set of clusters is no trivial task and commonly known as the Traveling Salesman Problem (TSP) [27, 41, 67, 112, 228]. Its optimization is not within the scope of this thesis; instead, we focus on adapting the path between one starting cluster towards one destination cluster. Clearly, this topology-aware adaptation increases the overall route length for the UAV and, thus, also the dissemination delay of relayed messages. Furthermore, note that taking a detour can render a previously optimal TSP solution suboptimal, if not integrated in the shortest route calculation.

Utilize mobility information

Specifically, we model our rerouting problem as a shortest path problem within the given gridmap from a start to a target cell, as visualized in Figure 4.14. Each cell c_i provides a certain benefit for visiting that cell, which is defined by the number of location measurements Ω_i. The benefit itself represent the normalized value of location measurements

Shortest path problem

$$b(c_i) = \frac{\Omega_i}{\Omega_{max}} \tag{3}$$

to allow a direct comparison between cells, indicated by the shade intensity in the figure. Ω_{max} is the maximum value in the gridmap. The general idea is that more frequented cells are favored over less frequented or empty cells, despite resulting in a longer path. As a longer traversal time will also result in larger message delivery delays or possibly a lifetime expiration of messages, we introduce a scaling factor f which balances the tradeoff between transit node coverage with longer paths and faster message delivery with shorter paths. In the gridmap, we define directed edges from each cell to its vertically, horizontally, and diagonally adjacent cells. Each edge from one cell c_i to another cell c_j is assigned a weight

$$\omega(c_i, c_j) = d(c_i, c_j) - b(c_j) * f \tag{4}$$

based on the benefit $b(c_j)$ to visit that neighbor scaled by f, and the distance d between the cell centers — in case of the given example, d is 1 for directly adjacent and $\sqrt{2}$ for diagonal cells. As a result, we can define the complete costs for a certain route over a set of cells as the sum of all traversed edges, such that

$$\begin{aligned} \omega(c_0..c_n) &= \sum_{i=0}^{n-1} \omega(c_i, c_{i+1}) \\ &= \sum_{i=0}^{n-1} d(c_i, c_{i+1}) - f * \sum_{j=1}^{n} b(j). \end{aligned} \tag{5}$$

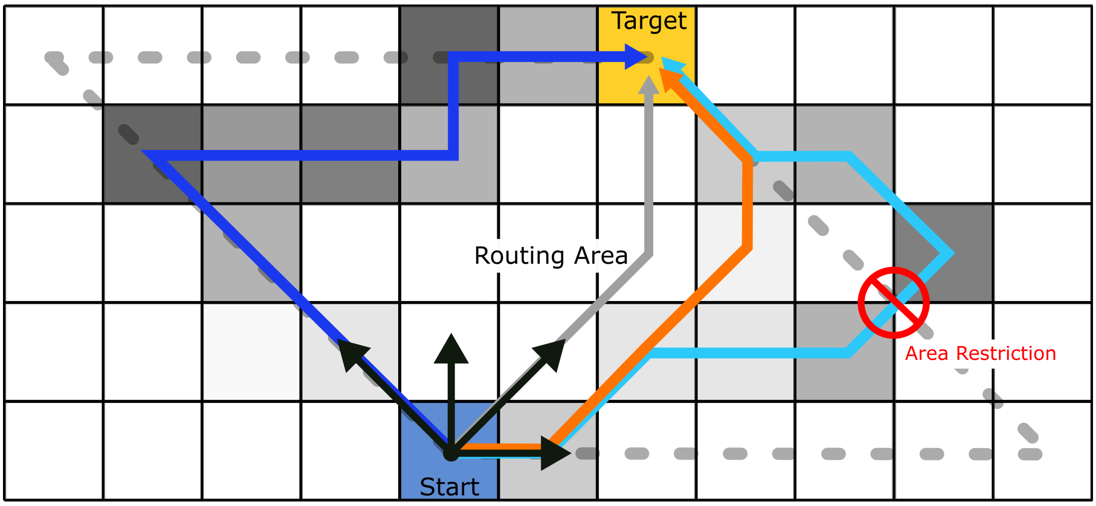


Figure 4.14: Routing on the gridmap for increased transit node coverage between start and target. Paths calculation is restricted to the dotted routing area, thus, the right path is invalid. The resulting path depends on the choice of f for the allowed detour. Adapted from [310].

Problem simplification

Based on the definition for our weighted directed edges between adjacent cells in the gridmap, the emerging graph on which we need to calculate the best path can contain negative edge weights and negative cycles, depending on f. Thus, common shortest path algorithms like Dijkstra's algorithm or the Bellman-Ford algorithm cannot be applied for a solution. The possibility of cycles in the graph are a result of — apart from the edges of the map — the eight movement directions at each cell. Therefore, we restrict movement in the gridmap to only four directions in the direction towards the target cell, as indicated by the black arrows at the starting cell in Figure 4.14. This removes the cycles and reduces the problem to a shortest path problem with negative edge weights, but without negative cycles [197]. Furthermore, the restriction to generally move in the direction of the target cell also prevents exceedingly long detours. We can now determine the path with the lowest costs using dynamic programming [67].

f affects length increase

Figure 4.14 visualizes different possibilities for our path planning approach as well as the restricted routing area. The result depends on the weight of each cell and the scaling factor f. The shortest path (grey) is chosen for $f = 0$. With increasing f, however, longer paths with a higher transit node coverage are chosen instead, if they outweigh the costs of shorter paths. In this case, the size of f determines whether the orange path to the right with a small detour, or the blue path to the left with a long detour but also a higher coverage is chosen. Due to the area restriction, the longer path on the right (cyan) is not a valid result despite providing a larger coverage than the orange path. Nevertheless, even with this area restriction the resulting maximum path length is $1 + \sqrt{2} \approx 2.41$ times the length of the shortest distance path on the grid. Therefore, determining a reasonable value for f must take the maximum UAV flight range into consideration.

5 EVALUATION PLATFORM FOR UNMANNED AIRCRAFT SYSTEMS

Our presented contribution of a combined aerial monitoring and communication support system and the proposed mechanisms for improvements in their respective fields need to be tested and extensively evaluated. The Simonstrator.kom platform [235, 236] provides a comprehensive environment for rapid prototyping and extensible simulation-based evaluation, on which we base our evaluation platform for Unmanned Aircraft Systems (UAS). Specifically, the extension of the Simonstrator.kom platform comprises *(i)* the integration of the proposed combined UAS design with strategies for aerial monitoring and aerial communication support, *(ii)* the facilitation of a base station, Unmanned Aerial Vehicles (UAVs), and their interoperability, as well as *(iii)* the consolidation of Delay-Tolerant Network (DTN) nodes and UAVs by mutual means of communication and communication protocols.

Initially, we provide an overview of the Simonstrator.kom platform in Section 5.1 before discussing the prototypical realization of our UAS design within the framework. Furthermore, we improve the expressiveness of the simulations by contributing to the utilized PeerfactSim.kom runtime environment. In Section 5.3, we present an energy and mobility model based on measurements with a real-world aircraft. Afterwards, in Section 5.4, we discuss a mobility model for civilians in a disaster scenario based on a real-world field trial.

5.1 OVERVIEW OF THE SIMONSTRATOR.KOM PLATFORM

Simonstrator.kom is a Java-based prototyping and evaluation platform aiming at providing researchers a framework to rapidly design and evaluate prototypes, focusing on distributed communication systems. As visualized in Figure 5.1, the core of Simonstrator.kom consists of a framework, providing an abstract view of *hosts* and *components*, and a global functionality for *scheduling* and *instrumentation*.

Hosts and Components

Hosts represent individual entities within a simulation, such as devices like smartphones, UAVs, or the UAS base station. The interaction with hosts is possible either directly by user input or by a pre-defined workload, which defines specific actions that the host performs by interacting with its components. Components are defined individually per host; thus, different types of hosts are defined by their composition of components. These components represent host-specific functionalities, including hardware components (e.g., actuators, batteries, GNSS modules), communication interfaces (e.g., WiFi, LoRa), or network layers (cf. [235, 238]). Each component is designed and implemented following the APIs defined by the core framework of Simonstrator.kom. This layer of abstraction allows realizing a plethora of additional mechanisms as components within the platform, such as the DTN protocols dis-

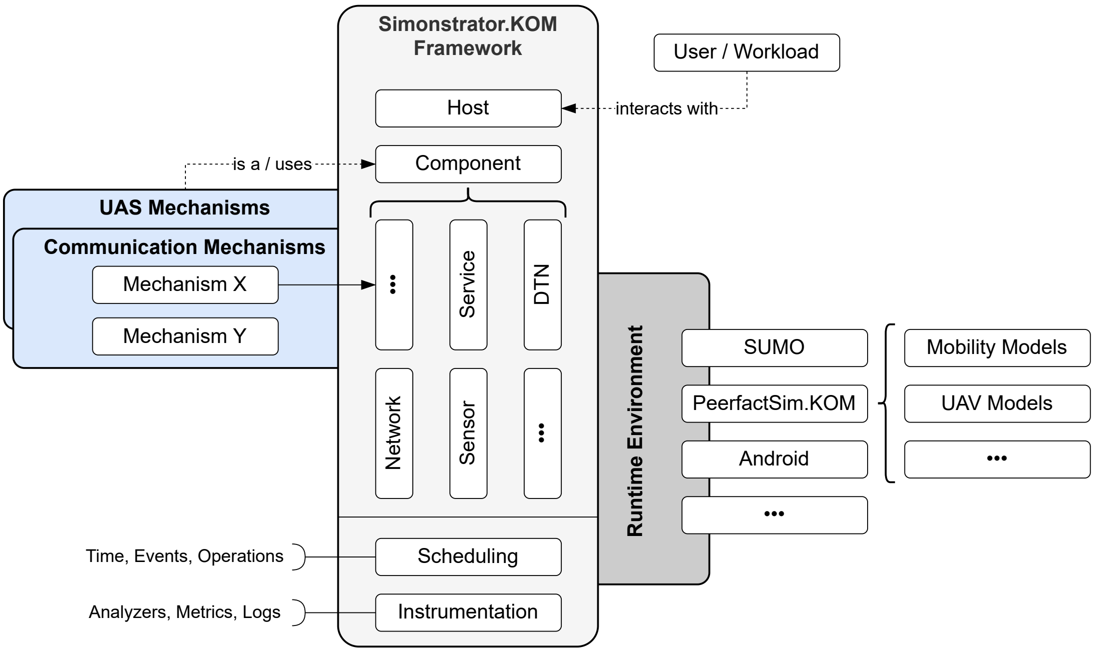


Figure 5.1: Overview of the Simonstrator.kom platform architecture. Adapted from [235, 236].

cussed in Section 4.3 or individual strategies for aerial communication support or monitoring (cf. Section 5.3).

Determinism and reproducibility

The global scheduling mechanisms provide a continuous abstraction of the time within the simulation and the precise planning and respective timely execution of operations as events. At the intended time, the event is triggered, and the operation is passed to the framework for execution. This functionality allows, e.g., the modeling of device sleep cycles or the regular broadcast of DTN beacons (cf. Section 2.2). Furthermore, Simonstrator.kom provides a seeded random number generator for the entire framework. Combined with the global time representation, this enables a deterministic simulation execution and reproducible simulation results for a certain seed. However, simulations are repeated with different random seeds to evaluate the effects of randomness.

Metrics and analyzers

Testing and evaluating implemented features requires measuring a large variety of different system parameters or complex system behaviors, which is facilitated by the global instrumentation mechanisms. Besides writing simple logs, Simonstrator.kom provides *analyzers* and *metrics* for that purpose. Metrics rely on standardized interfaces, which are implemented by components and provide read-only access to internal system states. With that, metrics can observe states, for example, at a specific time or regularly with periodic sampling. Analyzers, on the other hand, require the definition of mechanism-specific interfaces but allow event-based reporting of operations or specific system conditions. Hence, if required, they enable a more complex assessment of mechanisms and systems. It is noteworthy that all instrumentation interfaces provide read-only access and cannot alter the states of the evaluated components. At the same time, different implementations of analyzers can transparently bind to the same interface and, thus, can be used in parallel.

Runtime environments

The SIMONSTRATOR.KOM platform on its own is neither a simulator nor an emulator. Instead, it provides a framework with the given interfaces that allows the exchangeable usage of different *runtime environments*. These runtime environments implement the respective core components and, with that, allow performing simulations, emulations, or prototyping on real-world devices. At the point of writing this thesis, SIMONSTRATOR.KOM provides runtime environments for Android devices [237], the vehicular traffic mobility simulator SUMO [34], and other simulation or testbed environments (e.g., cf. [37]). However, the most important runtime environment is the peer-to-peer network simulator PEERFACTSIM.KOM [270] which is the most feature-complete environment due to the closely related concurrent development over the years. PEERFACTSIM.KOM already provides a large variety of functionality for DTN and post-disaster scenario simulation, including realistic models for WiFi propagation and node mobility made available by different mobility generators [24, 192, 240] or trace files [313]. Therefore, PEERFACTSIM.KOM constitutes a perfect choice as our utilized runtime environment since it provides a solid foundation for further enhancements. For the simulation of aerial systems, we initially extend PEERFACTSIM.KOM to facilitate the simulation of UAVs, base stations, and their respective components (Section 5.2), following the Aerial Network Assistance System design provided in Section 4.2. Furthermore, we add models for a realistic thrust-based UAV movement simulation (Section 5.3) as well as a more realistic simulation of civilian mobility in disaster scenarios (Section 5.4).

5.2 SYSTEM PROTOTYPE

The implementation of our prototypical aerial system follows the conceptualization we discussed in Section 4.2, consisting of a base station and several UAVs. Besides the conceptual properties for strategy coordination and execution, however, we also consider additional features required for a realistic simulation (cf. [72]), such as the available hardware and their limitations, energy consumption on UAVs, and a battery maintenance process. Already available components, e.g., for WiFi communication, were integrated into our system, while others, like a simplistic battery model, were extended and adapted to suit our needs. In the following, we detail our implementation for the base station and the UAVs as SIMONSTRATOR.KOM clients, respectively, and discuss their system design with a focus on modularity and extensibility.

5.2.1 *Base Station Client*

The central entity of our UAS is the base station, coordinating the strategies together with their executing UAVs and maintaining the shared system knowledge. The client implementation is split into two parts, as depicted in Figure 5.2. The *Base Station* represents the actual base station, including hardware and necessary infrastructure to

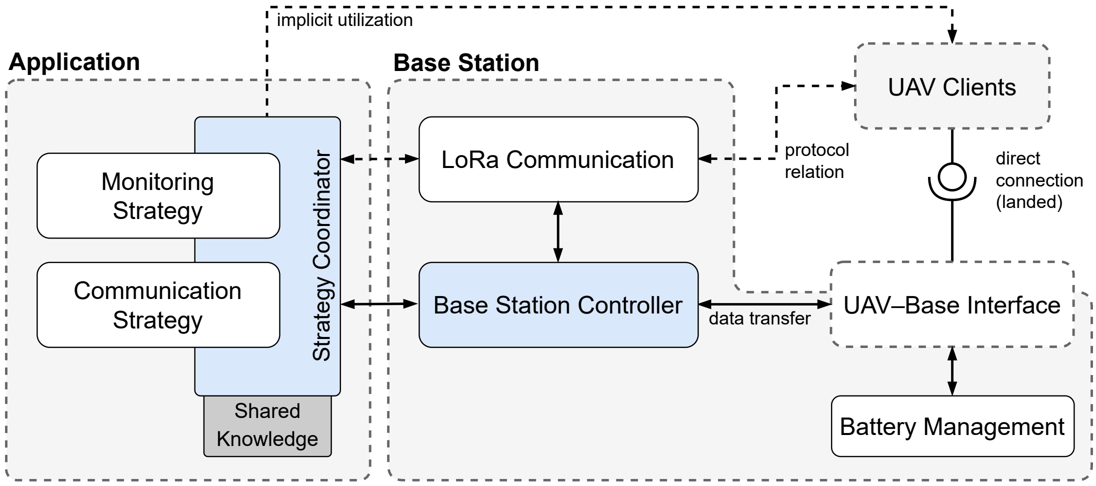


Figure 5.2: Overview of the prototype's base station client design.

maintain the UAS functionality. The base's *Application*, on the other hand, incorporates the designs we discussed in Chapter 4.

Application The *Application* part encompasses all components directly related to the coordination and execution of strategies. This could include various approaches from the related work or available software that could be executed directly at the base station. For our purposes, the application is represented by the *strategy coordinator*, which also holds and maintains the shared knowledge as a collection of all known and valid DTN data messages and all known locations of DTN nodes. Nevertheless, multiple coordinators or independently running strategies are also possible within this design. Furthermore, the coordinator manages the execution of strategies. According to our system design, specifically, these are a *Monitoring Strategy* and a *Communication Strategy* executed in parallel. However, the strategy coordinator can hold any number and type of strategies, provided that the given interfaces for the interaction between strategy and coordinator are applied. Strategies are encapsulated to allow flexibility and exchangeability, and data exchange is possible over the shared knowledge provided by the strategy coordinator.

Base Station The *Base Station* abstracts the actual ground-based hardware that is part of a real-world Unmanned Aircraft System (UAS). Simulations usually focus on UAVs and their applications; base stations are often neglected. However, they are an essential part of every UAS: they usually serve as the central control instance for multi-UAV deployments and provide maintenance, recharging, or battery-swapping appliances for long-term deployments [81]. Therefore, base stations must definitively be incorporated into aerial system simulations. Our prototype mainly consists of the *Base Station Controller*, an interface for *LoRa Communication*, the *UAV–Base Interface*, and the *Battery Management* component. The controller serves as the core component of the base station, managing all other components and providing inter-component accessibility by different layers of abstraction. For example, it manages the communication interfaces, like the LoRa communication component in our specific case, and allows its indirect utilization for the strategy coordinator and, by that, the executing strategies. Furthermore, the base station controller manages the interaction with *UAV Clients* through the *UAV–Base Interface*. In combination with the *Battery Management*, the UAV–Base interface abstractly simulates ground-based assets like landing pads, where a physical connection to UAVs is possible and batteries can be recharged or exchanged. The current implementation supports either recharging the UAV battery over time or a battery exchange within a fixed time interval. Albeit, we use the latter option by default, as it constitutes the more efficient alternative considering UAV utilization and service lifetime [81, 99, 290].

UAV–Base Interface

Additionally, the base station controller handles landed UAVs and monitors their flight readiness, e.g., by guaranteeing a sufficiently charged battery before allowing their take-off. Information on ready UAVs, such as their flight properties, like maximum range or speed, is made available to the strategy coordinator, that in turn manages the assignment of UAVs to the strategies. When a strategy requires a UAV, it can review the available information and request the allocation of a specific UAV to it. To prevent some strategies from receiving all available UAVs and others none, it is the primary responsibility of the coordinator to allocate the UAVs fairly. The specific definition of how UAVs are allocated highly depends on the concrete scenario and the utilized strategies. After the coordinator receives the request, it may block and assign the UAV to the requesting strategy, which then gains access to the UAV through the base station controller and the UAV–Base interface to configure the UAV for its mission. After the mission concludes and the UAV returns, the same connection is available to transfer data to the strategy, such as gathered monitoring information. Other strategies cannot use blocked UAVs until their release, which happens either after returning from the mission and landing at the base or only when the strategy actively releases the UAV. The base station controller conclusively regulates the interaction of strategies and UAVs. If necessary, strategy execution can be terminated and UAV control can be taken over, for example, when a technical failure is determined at a UAV. Furthermore, it allows the controller to instruct all UAVs to return immediately, facilitating a quick shutdown of the UAS, e.g., in case of changing weather that would prohibit a safe UAV application. Similarly, the coordinator can temporarily take over the operation of UAVs, which allows exchanging strategies or performing transitions between them, providing a way to actively migrate UAVs on-the-fly [288].

Allocation of UAVs...

...requested by a strategy...

...and managed by the base station controller.

Overall, the base station is kept minimal with all necessary components for a realistic UAS simulation but can easily be extended with other components, such as different communication interfaces. Furthermore, our base station implementation considers the recharge and exchange process of UAV batteries as a critical component for a realistic long-term deployment [81]. Nevertheless, we generally neglect any energy sources and the energy consumption of the base station in total. Although we deem this generally unneeded for the expressive simulation of aerial systems and presume a capable and sufficient power source, this additional regard for the challenging disaster scenario could be considered for future work. The current implementation of the application running at the base station is tailored to our system design presented in Chapter 4. Nevertheless, it already provides the possibility to

Extendable base station implementation

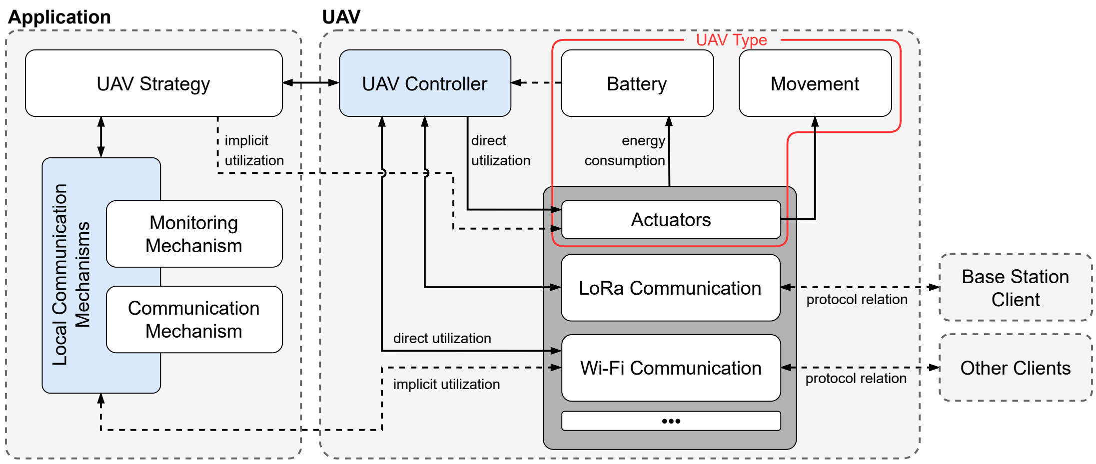


Figure 5.3: Overview of the prototype's UAV client design.

either add or adapt strategies within the strategy coordinator or replace the strategy coordinator entirely through encapsulating the UAV management within the base station controller and its accessibility via interfaces.

5.2.2 *Unmanned Aerial Vehicle (UAV) Client*

In accordance with the base station, the UAV client design is similarly split into one *Application* part for the strategies, as discussed in the previous chapter, and the *UAV* part, which resembles the deployed hardware. The components and their interaction with the UAV clients are depicted in Figure 5.3.

The core component of the UAV is the *UAV Controller*, managing and supervising all components and their correct functionality. Most importantly, the UAV controller incorporates the autonomous piloting functionality of the UAV, and thus, has direct control over its *Actuators*. Furthermore, the controller supervises the *Battery* state in combination with its current location and the location of the base station, ensuring that the UAV can always return to the base safely and enforcing its return whenever needed. Available communication interfaces, in our case the components for *LoRa Communication* and *WiFi Communication*, are also managed by the UAV controller. It provides access to these interfaces and multiplexes messages between strategy and communication devices. Direct commands can also be send from the base station to the controller, which then processes the message and executes the command. Except for the direct connection between the base station and a landed UAV, the interaction with other clients, like the base station, other UAVs, or DTN devices, is only possible using the provided communication interfaces.

Communication

Energy Consumption

Actuators, communication interfaces, and possibly other components, like GNSS sensors, implement *energy-consuming components*, marked in dark grey in Figure 5.3. These components consume energy from the battery depending on the component state. For example, the WiFi component available from PeerfactSim.KOM can either be in a turned off, listening, receiving, or sending state. The energy consumption is configured per state and calculated for the time the component was in a certain state.

Battery and actuators are, however, two components highly specific to the applied UAV. To address the theoretically endless variations of different UAV types and configurations, and allow their implementation in the simulator, we encapsulate the most important hardware components into a specific *UAV Type*. This model can be defined per UAV client and, thus, allows applying various types and configurations of UAVs in parallel in our evaluation platform. Note that each model can be extended with additional components, albeit we focus on the battery and the actuators as the most important aspects for the simulation of UAVs. Generally, actuators contribute most to energy consumption [110, 185] and should, therefore, also receive the most attention. Within our evaluation platform, we require both the LoRa and WiFi communication components to fulfill our design specifications; thus, they are a mandatory part of the UAV and not a component of the exchangeable UAV models. Another aspect we need to address within the simulator is the *Movement* of the UAVs, which is similarly an integral part of the UAV model itself but also highly important for a realistic and expressive UAV simulation. The utilization of the actuators by the controller is forwarded to the movement model, which in turn calculates changes in location, orientation, and other parameters for each simulated UAV client. The modeling of realistic UAVs with a focus on energy consumption and movement is further detailed in Section 5.3, where we discuss how such a model is derived from measurements with a real-world UAV.

UAV Type

UAV Movement

The *UAV Strategy* component, as part of the application, defines the exact mission profile a UAV executes. As discussed in the previous section, the concrete strategy is configured and uploaded to the UAV by the respective strategy coordinator when landed at the base station. The UAV strategy implicitly controls the UAV's movement by providing flight instructions like flight routes to the controller. We also discussed the possible coexistence of monitoring and communication mechanisms within a single strategy in Section 4.2.3, with one being the main and the other the secondary mechanism. In contrast, other strategies may only serve a single purpose. To address possible coexistence, we specify different mechanisms for monitoring or communication, respectively, as separated *Local Communication Mechanisms*. These components implement the required functionality, like interaction with the DTN nodes for message exchange or cooperative monitoring information collection (cf. Section 4.3). Interactions with the UAV strategy follow a common interface, e.g., defining the implicit usage of the WiFi communication component. This encapsulation of strategy and mechanisms facilitates the modular exchange of different mechanisms using the same UAV strategy and vice versa. Different UAV applications typically define the required mechanisms as part of the configuring strategy. Nevertheless, our approach provides not only increased flexibility in the use of different mechanisms and strategies but, for example, also enables the representation of communication mechanisms that are fixed, non-configurable parts of the UAV, such as proprietary communication equipment.

Application

Monitoring & Communication Mechanisms

Our prototypical implementation combines the design specifications discussed in Chapter 4 with the necessary components for the simulation of UAVs and the base station in an aerial system. Overall, the system is designed with a focus on flexibility, modularity, and extensibility. It provides the capability to evaluate different strategies and mechanisms as part of the simulation but also facilitates the further utilization of the system with other applications or scenarios in mind. In the following, we provide insights into how we enhanced the expressiveness and realism of the PeerfactSim.KOM simulator with a UAV movement model and a civilian disaster mobility model, respectively.

5.3 MODELING UAV FLIGHT IN SIMULATIONS

The application of UAVs clearly is the emphasized feature within our evaluation platform. Depending on the actual hardware, UAVs are highly constrained by their limited battery size and flight properties, which limits their applicability, for example, over large distances. Therefore, the simulation of UAV flight also plays a key role in the performance evaluation of the entire aerial system. In the following, we present our implemented design for a generalized multicopter movement model, extended modularly with a specific *UAV type* model, according to the concepts discussed in the previous section (cf. Figure 5.3).

5.3.1 *Multicopter Movement Model*

UAV movement is typically simplified

Similar to human behavior, which is discussed specifically in Section 5.4, recreating realistically accurate UAV movement in simulators is problematic due to the extreme complexity of aerodynamics and flight mechanics [48]. Therefore, UAV mobility is typically simplified depending on the intended application. As pointed out by Bujari et al., this surprisingly often involves oversimplified approaches like random walk, random waypoint, or random direction models, which are clearly unsuitable for the representation of UAV mobility [48]. More sophisticated approaches, however, address the specific characteristics of UAV mobility, e.g., constraint turn capabilities for fixed-wing UAVs, while still providing a considerate level of abstraction, such as the restriction to level flight only [44, 292]. For simulations running in real-time, software-in-the-loop simulators, as available for ArduPilot[1], allow the direct utilization of the actual UAV autopilot software for more realism. However, this cannot be easily integrated into other simulators and lacks scalability, especially in the time domain [88].

Split movement in flight phases

The most common approach to model UAV movement is its breakdown into specific parts: hover, ascend, descend, level flight, curved flight, and appropriate acceleration and deceleration phases. The combination of these simple maneuvers allows depicting most capabilities [48, 217]. Additionally, the set can be limited, for example, to decrease complexity [73] or depict fixed-wing UAVs without hover capabili-

1 https://ardupilot.org/dev/docs/sitl-simulator-software-in-the-loop.html [Accessed 1.9.2022]

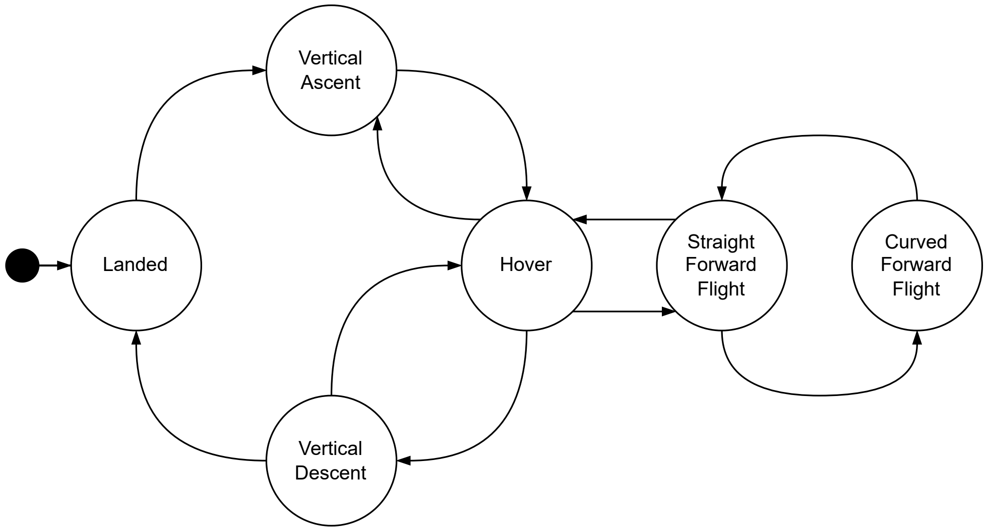


Figure 5.4: Abstract state machine for simplified UAV movement.

ties [70, 71]. Therefore, we followed the same approach and implemented the movement model for UAVs as a state machine with these simplified movement phases, as shown in Figure 5.4. *Stateful UAV model*

The abstract model, however, does not define specific parameters like flight speeds or similar. Instead, it is designed to interface with the later-described *UAV Type Model*, from which it requests, for example, a forward acceleration. The movement model then gets the specifically provided acceleration by the UAV Type, on which the changes for current location, velocity, and acceleration are then calculated. The UAV Type, on the other hand, must provide the request methods for the implemented movement phases. By that, the abstract movement model can be used with a variety of different UAV configurations, implementing the given interface. In its current form, the model specifically depicts the utilized multicopter UAVs with typical capabilities like *vertical take-off and landing* (VTOL) and hovering. For simplification, altitude is changed via vertical ascent or descent, while forward flight is always performed at the same altitude. Nevertheless, more sophisticated models for multicopter movement or similar models for fixed-wing or hybrid UAVs could be implemented based on our model, for example, by adding additional states for horizontal landing and take-off functionality.

Interfaces with UAV type

Modularity and extendibility

5.3.2 *UAV Type Model*

Within our implementation, different multicopter specifications are represented by the UAV Type Model. Basically, it defines flight properties like acceleration or speed for different flight phases and the respective energy consumption. Despite some generalized mathematical approaches [73], the most common modeling is based on real-world measurements due to the large variety of different UAVs and external impact factors on the flight [54, 71, 215]. In our case, we utilized the *Intel Aero Ready-*

Intel Aero RTF Drone

to-Fly Drone as a real-world counterpart for our UAV type. Unfortunately, the Intel Aero has already been discontinued for more than a year at the time of writing this thesis, and thus, the official documentation and specifications we used for the modeling are not publicly available anymore.

Since our movement model includes acceleration and deceleration in the phases to provide movement as realistic as possible, we adapted the approach of Paredes et al., which models the thrust of individual rotors in detail, to simulate the thrust that acts upon the entire UAV [215]. Using the thrust generated by the rotors in dependency on the blade revolutions has several benefits. First, acceleration and deceleration can directly be calculated from the thrust, based on the UAV mass and the drag induced by velocity. Second, this allows the estimation of speed and power consumption for various flight maneuvers without requiring a direct measurement of each of them. And third, a thrust-based model allows the alteration of the UAV's mass, e.g., when adding extra payload, without requiring additional measurements. Furthermore, thrust-based modeling can also include wind as an extra force acting on the UAV [89]. In this thesis, however, we did not include wind or other external weather-related factors like humidity or temperature in our model, despite their possibly non-neglectable influence in real-world deployments [1].

Simulation of rotor thrust

Omitting wind and weather

Multicopter UAVs generate thrust by spinning their rotors and, as discussed in Section 3.1, count to the *rotary-wing* UAVs, in contrast to plane-like *fixed-wing UAVs*. In general, the provided thrust depends on the shape of the rotating propellers and their revolutions per minute (RPM). It is calculated as

$$T(n) = c_{T,n}\ \rho\ n^2\ D^4 \tag{6}$$

with n as RPM, $c_{T,n}$ as the propeller's thrust coefficient at a specific n, the air density ρ, and the propeller diameter D [215]. Furthermore, the required power to spin the propeller at a given RPM n is calculated as

$$P(n) = c_{P,n}\ \rho\ n^3\ D^5 \tag{7}$$

with $c_{P,n}$ as the propeller's power coefficient [266].

Propeller performance

The Intel Aero uses four 9 by 6 inches two-bladed propellers, but they are not further specified by the manufacturer. However, researchers at the University of Illinois at Urbana-Champaign, USA, measured a substantial number of different propellers and their performance properties [45]. The datasets are publicly available and can be used to reconstruct the performance of our UAV. Thus, we use the performance data of a comparable standard 9 by 6 inches APC propeller, which provides the thrust coefficient $c_{T,n}$ and the power coefficient $c_{P,n}$ for different RPM n of the propellers.

Rotor characteristics

Based on these properties, we calculated a total of seven rotor characteristics that describe thrust and current draw at different RPM, which correspond to different states. An overview is given in Table 5.1. Other rotor characteristics are approximated by a linear interpolation on the thrust to calculate intermediate *(RPM, thrust, current)* triples. The minimum and maximum rotor speeds of 2500 RPM and 8200 RPM are taken from the manufacturer's specification. The intermediate characteristics are approximations based on the UAV's mass and drag. For example, the Intel Aero has a

Table 5.1: Rotor characteristics for the Intel Aero RTF Drone. Adapted from [312].

n [RPM]	$c_{T,n}$	$c_{P,n}$	Thrust [N]	Current [A]	Note
2500	0.1291	0.0610	0.74	0.23	minimum throttle
4000	0.1245	0.0652	1.76	1.00	
5150	0.1263	0.0648	3.06	2.08	$5\,\frac{m}{s}$ descent
5550	0.1293	0.0630	3.59	2.53	hover
6000	0.1273	0.0640	4.20	3.25	$5\,\frac{m}{s}$ ascent
7000	0.1232	0.0649	5.52	5.24	
8200	0.1210	0.0647	7.43	8.43	full throttle

safe ascent and descent velocity limitation of $5\,\frac{m}{s}$ enforced by the UAV's autopilot. The up or down movement induces a parasitic drag [215, 301] on the UAV's top or bottom surface, respectively, which is generally expressed as

$$D(v) = \frac{1}{2}\,\rho\,v^2\,A\,c_D \tag{8}$$

for the exposed area A and a drag coefficient c_D. Furthermore, the Intel Aero's dry mass — without any battery and payloads — is around 865 g. Typically, a multicopter should not exceed a thrust-weight ratio of 2.0 to maintain high maneuverability; therefore, 1.465 kg constitutes the upper weight limit for the Intel Aero, with a maximum thrust of 7.43 N per rotor available. To allow for the maximal possible battery size — circa 97 Wh in this weight range — this mass is used for the model. Similarly, we can calculate the necessary hover thrust T_h, which is simply the thrust required to hold the altitude, when neglecting influences like wind that would require adjustment. In a nutshell, the combination of drag, gravitational pull, and intended velocity allows calculating the required thrust, which allows calculating the required RPM with Equation 6, and eventually, the current draw with Equation 7, which is shown in Table 5.1.

Payload determines characteristics

The specific thrust required for up- and downwards movement is calculated similarly to the given example. Typically, the directional thrust T_v to hold a velocity v is equal to the parasitic drag D_v in the direction of movement (cf. Equation 8). For up- or downwards movement, the exposed area which determines the drag is, simplified, either the upside or underside of the UAV. For all other movement types, however, the multicopter must be pitched in the direction of movement to induce a force. By that, the exposed area A changes with the forward pitch angle α such that

Air drag determined by exposed area

$$A_\alpha = \sin(\alpha)A_{top/bottom} + \cos(\alpha)A_{front/rear} \tag{9}$$

with the respective areas of the aircraft. As shown in the equation, lateral areas are not included since we omit sideward movement in our model. Furthermore, we

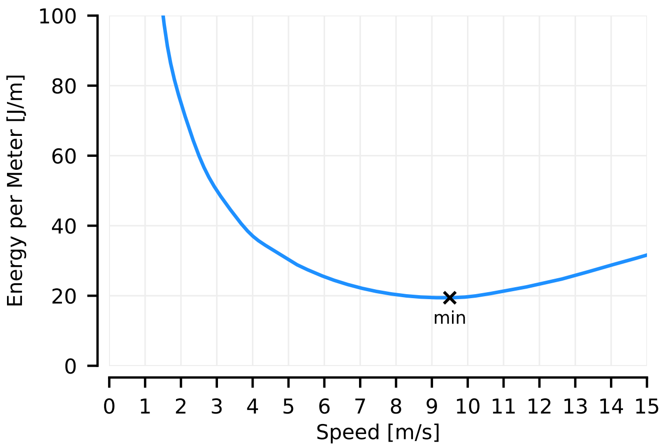


Figure 5.5: Modeled energy efficiency curve for the Intel Aero RTF. Adapted from [312].

simplify the calculation by approximating top and bottom areas as well as front and rear areas, respectively, as planar areas equal in size.

Thrust increases with pitch angle

In the example of straight forward movement, it becomes clear that pitching the UAV requires an increase in the total thrust T_t to keep its altitude, with

$$T_t = \frac{T_v}{\sin(\alpha)} \tag{10}$$

depending on the pitch angle. While the hover thrust remains constant, T_v increases and accelerates the UAV in the given direction. In the case of the Intel Aero Drone, α is capped at a maximum of 60°. Nevertheless, Equation 10 highlights the necessary increase for T_t with increasing α. Since the available maximum thrust depends on the payload, rather than a static value for α, our model calculates the maximum possible pitch angle based on the available thrust instead.

Equilibrium of thrust and drag defines velocity

The maximum possible horizontal velocity v is reached in the equilibrium of forward thrust and parasitic drag induced by the velocity. Thus, v at a given pitch angle α and a given forward thrust T_v calculates as

$$v(\alpha) = \sqrt{\frac{2T_v}{\rho A_\alpha c_D}} = \sqrt{\frac{2\tan(\alpha)T_h}{\rho A_\alpha c_D}} \tag{11}$$

with the constant hover thrust T_h and the exposed area A_α. The resulting energy consumption with increasing pitch angle asymptotically approaches that of the maximum thrust and pitch angle [89, 215]. Relatively small pitch angles provide low acceleration but result in relatively large end speeds due to low drag. For large speeds, however, a larger pitch angle and more thrust are necessary to overcome the increasing drag. Therefore, as shown in Figure 5.5, the energy consumption for moving the UAV has a minimum on which the best energy efficiency is reached. In the case of the modeled Intel Aero Drone, this is at approximately 9.5 $\frac{m}{s}$. Outdoor measurements with the Intel Aero yield comparable results with roughly 9 $\frac{m}{s}$ as the most energy-efficient speed with slight wind [89], which endorse us that our approach models

Energy-efficient velocity

Intel Aero Model

the Intel Aero Drone close to reality. The theoretical flight range of our modeled UAV with a 97 Wh battery and the maxed out weight of 1.465 kg is approximately 12.6 km at 9.5 $\frac{m}{s}$ straight forward flight. This already includes a 15% security margin for the battery capacity, which is necessary to maintain battery lifetime, guarantee the required minimum voltage, and, most notably, account for external influences [1, 215] to prevent a crash. Nevertheless, the flight range is shortened by other flight maneuvers like hovering or turning the aircraft, for which energy consumption is calculated accordingly by our model.

In conclusion, the proposed approach for multicopter movement with models for concrete UAV types allows simulating different flight phases and maneuvers of various multicopter UAVs. Additionally, the approach could be similarly adapted for fixed-wing UAVs, but this is not within the scope of this thesis due to the sole use of multicopters. The UAV type we specifically modeled and use throughout this thesis is based on the Intel Aero RTF Drone. The resulting energy consumption model for the UAV was validated in real-world flights and, therefore, provides reliable results for our simulation environment. However, external factors like temperature and humidity — which can greatly influence the available battery capacity — or especially wind are not included in our model. Nevertheless, our approach already provides the possible adaptability to allow the integration of complex and realistic wind and battery models if required. Within the scope of this thesis, this simulation model for multicopter UAVs provides the necessary means for an expressive application of UAVs as the aerial system's most crucial components. The following section provides further approaches to increase the expressiveness for simulating the civilian population and the DTN that our aerial system should support.

5.4 MODELING CIVILIAN DISASTER MOBILITY IN SIMULATIONS

One of the major issues that need to be dealt with by any wireless network simulator is the movement and mobility behavior of senders and receivers, i.e., network nodes. This is especially important in the case of DTNs, where not only the network is strongly characterized by its topology, but mobility is also the key factor for data transport and the functionality of network protocols. Therefore, an expressive simulation must include these factors under realistic viewpoints to increase the validity of its results, albeit the near impossibility of recreating a real disaster with all its complexity and detail.

Related mobility models

The most extensively used mobility models, however, are variants of a Random Walk or a Random Waypoint models, in which mobility is constructed using, e.g., randomized direction vectors or target locations. Despite some efforts to include real-world map data to restrict mobility realistically [62, 271] or using multiple nodes as moving groups to result in a more clustered network topology [125], such models still cannot depict the non-deterministic, non-random, and non-uniformly distributed characteristics of human mobility — especially within a disaster scenario [15]. Therefore, approaches focusing on human behavior, such as the SLAW mobility model [159], were developed and later enhanced to include map data [258]. Other mobility models are specifically designed to resemble mobility in one specific disaster scenario, facilitating different types of vehicles, different roles for nodes, and more, based on profound expert knowledge and assumptions of human mobility [274, 287]. Nevertheless, these models typically lack comparability to reality due to the lack of mobility data from within disaster scenarios [274].

Real-world traces

The most realistic mobility within a simulation would be achieved by real-world traces, i.e., datasets describing the recorded movement of people or nodes within a specific scenario. Nevertheless, traces from real disasters are extremely scarce, either due to missing records as a result of inhibited or destroyed ICT infrastructure, a lack of applications or hardware for specifically tracking a device's mobility in that exact incident, or due to security of privacy concerns of users and network operators [15, 218, 274]. Creating traces in a simulated disaster event is, therefore, the most prominent data source, despite being expensive with respect to preparation, execution, and the vulnerability to software and hardware failures or human errors [15, 25, 153, 182]. The most significant drawback of traces, however, is their static provision of node mobility for a simulator but without consideration of any events happening at the simulation level, which is only possible with mobility calculated at the simulation runtime [238, 240].

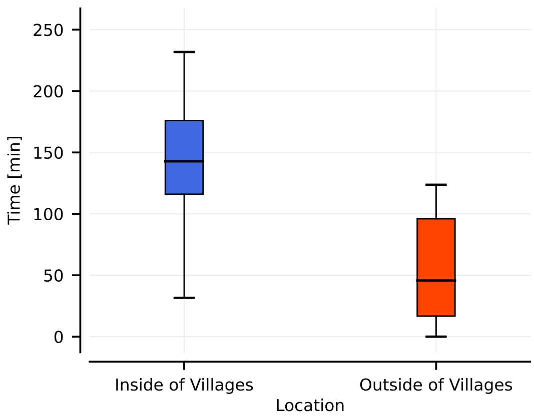
To understand human mobility characteristics within a disaster scenario, we analyze real-world trace files from the large-scale disaster field test presented in Section 2.3 [15, 166]. Based on this, we generalize our findings and use the provided information to develop a model for *Civilian Disaster Mobility* (CDM) in such a scenario. The CDM model is integrated into the PeerfactSim.KOM simulator and directly applied for the mobility of DTN nodes throughout the entire evaluation provided in Chapter 6.

5.4.1 *Analyzing Real-World Trace Files*

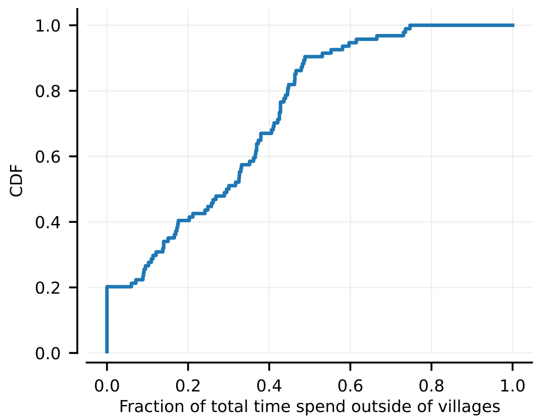
The overview of the SMARTER field test in Section 2.3 highlighted that participants typically formed groups, especially when walking larger distances between villages. Therefore, the utilized DTN was highly disconnected and clustered, resulting in a fast and comprehensive message spread within villages on the one hand, but slow or even compromised spread over larger distances — especially between distant villages — on the other hand [15, 166]. To gain a more profound understanding of the mobility within the performed field test, we analyze the trace files, which the authors thankfully provided to us with the help of Simonstrator.KOM. The dataset consists of 125 traces individually measured for each DTN device. However, 60% of the traces are fragmentary as a result of hardware and software issues, empty batteries, or wrong user interaction [15], highlighting the difficulties to be expected for the execution of real-world measurements. 30% of the traces cover 3 hours or less of the 4.5-hour-long field test. In addition, measured GPS locations are inaccurate, jittered, and partially fragmentary, possibly due to the dense vegetation and the concrete buildings in the field test area, and the rainy weather. To accommodate these issues,

Dataset issues

GPS issues



(a) Time spent in and outside villages.



(b) CDF for time spent outside villages.

Figure 5.6: The participant location highlights that most of the time is spent in villages, with only a few participants moving between villages most of the available trace time. Adapted from [313].

measurements were smoothed and gaps of up to 30 seconds were interpolated. Otherwise, nodes are not analyzed for the time frame when no information is available. The resulting set of refitted traces allows the simultaneous simulation of up to 94 nodes.

The most distinct behavioral difference discerned by Álvarez et al. was the relatively static behavior within villages in contrast to the group-wise mobility outside of them [15]. Thus, we first analyze the traces concerning participant location for inside and outside of villages, respectively. Figure 5.6a depicts the time of participants in the respective environment, which suggests that participants resided longer inside villages than they moved between them. Furthermore, the upper half of time spent outside villages is between 50 to 120 minutes, thus, roughly the time required to move one or two times between the remotest villages. 25% of the time spent outside villages was less than 20 minutes. Nevertheless, these measurements must be taken with care: some traces are incomplete and may distort the result since they do not depict the same time frame as others. Figure 5.6b considers this issue by providing a distribution of the fraction of the entire time — in relation to the total trace time — that is spent outside villages. Interestingly, we see that only 9% of traces were outside for more than 50% of their time, while nearly 30% of traces were inside of villages for more than 90% of their respective trace time, and 20% never left their starting village at all. Conclusively, we see a stark contrast between the dominant location of participants inside villages and a scarcer and shorter stay outside.

Location inside and outside villages

In a second assessment, we separated the measurements for the participants' speed depending on the environment. The results, visualized in Figure 5.7, highlight the apparent influence of the participant location on other measurements. Only considering the overall speed distribution would give a wrong picture as most measurements are taken inside villages and, therefore, resemble it predominantly. Here, more than 50% of measurements show static or near-static behavior, with the majority of data points below 1 $\frac{m}{s}$. The average speed is measured as 0.4 $\frac{m}{s}$. The speed distribution

Participant speed

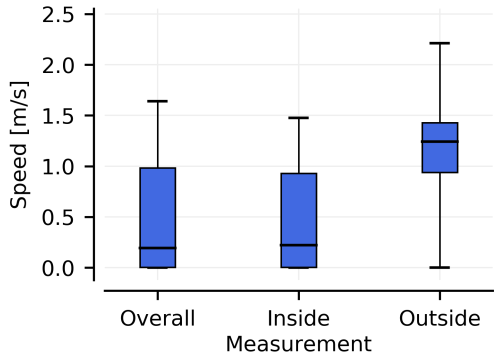
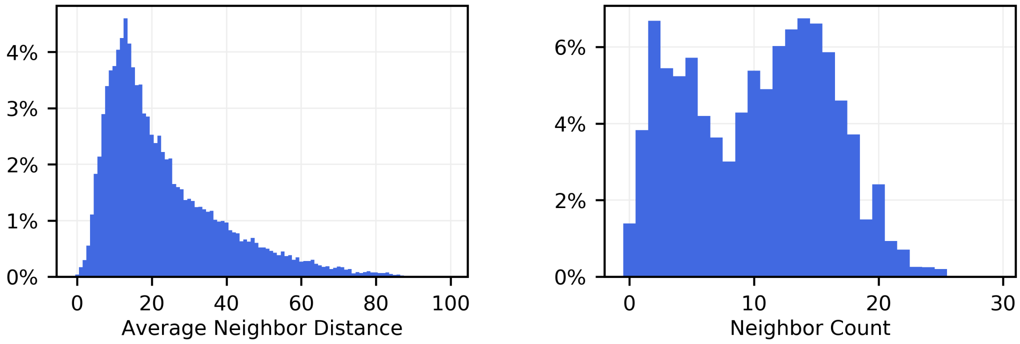


Figure 5.7: Speed distribution itemized for outside and inside of villages [313].



(a) Average distance to direct network neighbors.

(b) Number of direct network neighbors.

Figure 5.8: Number of neighbors and their distances as distribution for all measurements [313].

for outside of villages, however, shows an entirely different behavior. Approximately 50% of measurements are within 0.9 $\frac{m}{s}$ and 1.5 $\frac{m}{s}$, providing a similar walking speed assessed by related work [274]. Nevertheless, we also see faster speeds of more than 2 $\frac{m}{s}$ as well as significantly slower speeds. The latter case is especially important to mention because participant groups met on their way between villages and stopped for a while for social interaction before resuming their way [166], which results in around 13% of static behavior in the measurements. It becomes clear that there are differences in the participants' mobility behavior, whether inside villages or moving between them.

Network neighborhood

We already discussed the natural human behavior to cluster around points-of-interests like shelters or hospitals, the formation and movement of groups, as well as social interaction. Such behavior was predominantly perceived throughout the field test and was a major factor influencing the DTN performance [15, 166]. This is similarly resembled by the trace file analysis when comparing the average distance between network neighbors (Figure 5.8a) with the number of neighbors in the direct

1-hop neighborhood (Figure 5.8b). Clearly, the connected parts of the network — i.e., the villages and moving groups — are highly interconnected with up to 20 neighbors within 90 meters, although most neighbors are significantly closer, with the peak around 17 meters. Furthermore, the number of neighbors shows two aggregations, one between two and six neighbors, which is also the typically encountered group size between villages, and another around 10 to 18 neighbors. Similar properties can also be found when analyzing the message spread, which can generally reach between two and 20 nodes instantly, i.e., in the 1-hop neighborhood [15].

5.4.2 *Civilian Disaster Mobility (CDM) Model*

As shown in the field test, mobility — or rather the lack of it — is the most significant negative influence on communication performance within the DTN. The analysis of the field test traces revealed a significant deviation in the participants' mobility when separating for their mobility inside or outside of villages, respectively. Hence, a mobility model for such disaster scenarios must differentiate between individual mobility within areas of interests like villages and the mobility of groups when moving between them. In this work, we focus on the design of a mobility model for civilians in a disaster scenario that addresses the characteristics perceived in the field test. Nevertheless, such a model must also be generalized to allow the utilization and adaption in a wide variety of disaster scenarios and environments.

Modular and configurable

In accordance with our present contributions in this chapter, we, therefore, put particular emphasis on modularity and configurability when designing the model and implementing it as part of the PeerfactSim.KOM simulator. The resulting *Civilian Disaster Mobility* (CDM) model is comprised of several components, modeling different features that emerged from the trace analysis. The specific components *individual mobility*, *group selection*, *group formation*, *group mobility*, and *group encounter* are visualized with their interaction in Figure 5.9. Within our implementation, individual and group mobility are actually two independent mobility models that can be parameterized separately or fully exchanged. The group selection and group formation components define the transition of nodes between the mobility models, while the group encounter component defines special states for nodes within group mobility. All node movement is strictly bound to paths and walkways accessible for pedestrians, based on map data available through PeerfactSim.KOM.

Areas of Interest

The field test shows that civilian mobility is highly clustered within or around important locations, such as shelters, hospitals, or entire villages. More precisely, the villages in the field test were comprised of several close locations which defined a common area with similar mobility behavior. We approximate these close but virtually individual locations by an abstract definition of an *Area of Interest* (AoI). Within PeerfactSim.KOM, these are already available as a circular area definition based on a center point and a radius. Although more complex area definitions could be integrated into the simulator, they are sufficient to represent generic areas like the villages from the field test. The functionality of CDM is based on the availability of AoIs, and thus, requires the existence of at least one.

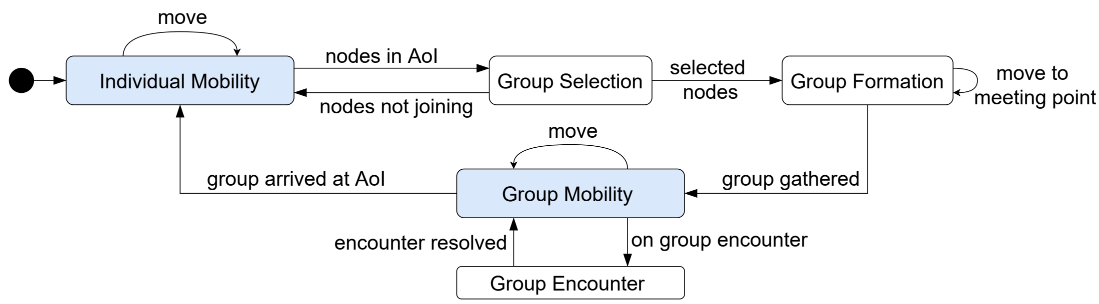


Figure 5.9: Components and interactions in the *Civilian Disaster Mobility* (CDM) model. Adapted from [313].

Node placement At the start of the simulation and the initialization of CDM, all nodes are placed within the available areas of interest and assigned to *individual mobility*. Note that the placement of nodes is a separate part of PeerfactSim.KOM and not a part of the mobility model itself. Initial node placement could, therefore, be configured differently. However, we determine the initial placement within the areas of interest as a requirement for a correctly functioning CDM.

Individual Mobility Movement in the individual mobility component is configured by a target selection, a movement speed distribution, and a pause time distribution. Each node in an AoI either moves to a target within the area or, once arrived, waits for a certain time before moving to the next target location. The target selection provides specific targets to nodes; in our case, this target is randomly chosen within the area. Note that due to the restriction of map-based movement, targets off accessible paths cannot be reached directly. Therefore, nodes approach the closest location on a path instead and use that as their target. The movement speed distribution defines the possible range of movement speed for nodes. Whenever a node starts towards a new target, its movement speed is specified and used for the entire path. For our configuration based on the trace file analysis, *node speed* is defined as a normal distribution with $\mu = 1.05\,\frac{m}{s}$ and $\sigma = 0.3\,\frac{m}{s}$. On arrival at the target, the pause time distribution defines how long the node waits until moving to the next target, e.g., modeling social interactions. We employ a uniform distribution between 5 and 10 minutes for all areas of interest to approximate the field test.

Node speed

Group Selection Over the entire field test, the number of groups that moved between the villages was usually between four and seven, with an average of five. New groups formed roughly every 10 minutes, although no clear preference for group formations within a specific village was discernible. The group selection component models this feature by randomly selecting an AoI every 10 minutes in which it tries to form a group. All nodes within the AoI are considered possible candidates for the group. However, participants stayed at least 30 minutes within an area after arriving; thus, nodes that were already a part of a group within this time frame are automatically not joining in our model. From the set of remaining nodes, between 2 and 6 are randomly chosen as group members, which resembles the approximate size of groups in the analyzed traces. While the selection could also follow different criteria, like the oldest nodes first, and the adaption is technically possible within CDM, there was no indication for a certain preference to form groups from the traces. If there are not enough nodes in the area to reach the minimum group size, the group selection is aborted and repeated at another AoI. All nodes not chosen to join the group are returning to individual mobility.

Group Formation

Selected nodes are proceeding to group formation. One of the nodes is chosen as the group leader, and its location is used as a joint meeting point for all nodes. After the group has gathered at the meeting point, another target selector is used to define a target location for the group. This selector typically picks a different area of interest than the group's origin as the new target and directly calculates the route for the group. Counterintuitively, more groups moved the longer distance between Village A and C than between Village B and C in the field test. To address this issue, we include the definition of weights for each area of interest [240]. Weights influence the selector's choice for the next target area, with a higher weight resulting in a higher probability of being selected. Besides the already published material in [313], we included two additional features to CDM for human behavior that is expected in urban disaster environments and was also observed in the field test [166, 274]. First, we adapted the routing of PeerfactSim.KOM to allow the use of a longer alternative route from the set of possible routes with a certain probability. This is included because we must expect detours since not every civilian will take the optimal route to move between locations [15]. Due to the presumably extreme size of possible alternatives, we restrict the calculations of alternatives to be within twice the length of the optimal route. Second, we can assume that civilians sometimes venture to locations other than the well-known disaster locations, e.g., in search of resources [166]. Thus, we included an optional exploration probability in the group target selector, where a location outside of areas of interest is chosen as a target instead.

Route variations

Group Mobility

The gathered group now proceeds to group mobility, which, similar to individual mobility, defines a speed distribution used to determine the group's speed. For our depiction of the field test results, we use a normal distribution with $\mu = 1.3\,\frac{m}{s}$ and $\sigma = 0.3\,\frac{m}{s}$. Specifically, not each node in the group moves individually, but only the group leader moves on its pre-defined route towards the target location. All other group members are placed with the leader accordingly, which reduces the number of routing operations needed for the group considerably.

Group Encounters

In case groups meet on their way, i.e., come within 5 m of each other outside of any area of interest, the group encounter is triggered. This module can specify different behavior, for example, that the groups pause their movement for a certain time, that some group members switch groups, or that nothing happens and all groups immediately resume their way. Based on the field test, we define the standard behavior as waiting for some time, after which all groups resume without changing group members. The wait time is chosen from a uniform distribution between one and five minutes to approximate social interaction. Whenever another group encounters already waiting groups, the initial wait time is unsolicited, and the arrived group just waits with the others until the time expires. Groups that have already encountered each other are not triggering the encounter again, preventing continuous encounters when moving in the same direction. When the encounter behavior is resolved, all groups resume their way and return to group mobility.

Return to Individual Mobility

On arrival at their target, it is checked if the target is an area of interest. In case it is not, i.e., when the group explores another location, an area of interest is chosen as the new target, and the group commences again towards the new target after a short pause time of five minutes. If the group arrives at its target AoI, the group dissipates, and all nodes are transferred back to individual mobility, roaming within the area.

Potential adaptations

The presented design for the *Civilian Disaster Mobility* model allows a wide range of potential adaptations and changes. Since our goal was the imitation of the participants' behavior within the field test, all modules were designed accordingly. In general, however, each component is fully parameterizable and exchangeable, e.g., as seen with the group encounter modules, to depict various scenarios and behaviors. The mobility model was evaluated in previously published material [313] and is summarized as part of this thesis in Section A.3. The presented implementation of the evaluation platform for Unmanned Aircraft Systems and its components and adaptations in this chapter is utilized in the following chapter to evaluate the contributions proposed in this thesis.

6 EVALUATION

Based on our prototype implementation of the Unmanned Aircraft System (UAS) within the Simonstrator.kom platform, we conduct an extensive evaluation of our proposed contributions for aerial network assistance in the event of a disaster. To characterize the combined aerial monitoring and communication support approach and assess the properties of the individual components, we need to compare various mechanisms and parameter settings against each other in a realistic and reproducible setup. The most realistic results would emerge from real-world measurements. As shown by the large-scale field test for disaster DTNs presented in Section 2.3, however, the inordinate effort to plan, arrange, and execute such real-world measurements make them infeasible to asses different mechanisms or parameters [166]. Furthermore, the required reproducibility of such measurements cannot be guaranteed as influence factors like human behavior are never replicable in the exact same way. Consequently, we rely on the simulation-based evaluation within the proposed evaluation platform for unmanned aircraft systems based on the Simonstrator.kom framework [235] and the PeerfactSim.kom simulator [270], as described in Chapter 5.

This evaluation addresses our contributions to aerial network assistance integrated into our UAS design, as presented in Chapter 4. The evaluation of individual monitoring or communication support strategies has already been performed in earlier work [171, 312, 314, 316] and is, therefore, not part of this evaluation. Starting with Section 6.1, we detail the setup of the evaluation environment and the basic post-disaster scenario. In addition to the environmental and system parameters used in the evaluation, this includes applied mobility and communication models, metrics, and the methodology used. However, it is necessary to specify individual evaluation scenarios and appropriate metrics to demonstrate the advantages and disadvantages of the different components. These specifications are provided separately in the respective sections. *Cooperative Aerial-Ground Monitoring* (CAMON) is evaluated in Section 6.2. We assess the cluster estimation performance based on unstructured data in Section 6.3, followed by the evaluation of *adaptive topology-aware routing* for increased transit node coverage in Section 6.4. Section 6.5 combines network monitoring and communication support strategies to evaluate the influence of coexisting mechanisms for aerial network assistance.

6.1 EVALUATION SETUP

We evaluate our UAS design and the proposed contributions based on the prototypical implementation of the combined aerial monitoring and communication support system within Simonstrator.kom, as described in Section 5.2. The event-based sim-

Table 6.1: SIMONSTRATOR.KOM Evaluation Settings.

	PARAMETER	VALUE
Environment	Simulation area	2000 m x 2000 m
	Scenario	Inner City, Post-Disaster
	Map Data	Darmstadt, OpenStreetMap
	Duration	10 h, 10 random seeds each
	Node Density	75 $\frac{nodes}{km^2}$
Mobility	Movement Model	Civilian Disaster Mobility [a]
	Areas of Interest (AoIs)	RND — 5 randomly placed AoIs OSM — 6 to 14 disaster locations
	Exploration Probability	0.1
Communication	WiFi Model	ns-3 IEEE 802.11g [122]
	Max. Transmission Range	88 m
	Max. Interference Range	205 m
	Data Rate	5 Mbit/s
UAS	Base Station Placement	Centered
	UAV Type	Quadrotor Multicopter [b]
	Flight Range	max. 12 km at 10 $\frac{m}{s}$
	Recharge Procedure	Battery swap, 60 seconds

[a] cf. Section 5.4 [b] cf. Section 5.3

ulator PEERFACTSIM.KOM [270] is used in an updated and enhanced version [312, 313] as runtime environment. This version includes the additional UAV flight model described in Section 5.3 to allow the simulation of UAV movement and energy consumption based on real-world counterparts. Furthermore, it includes the civilian disaster mobility model described in Section 5.4 to simulate node mobility based on real-world data. These enhancements allow the evaluation of both the UAS and the Delay-Tolerant Network (DTN) under realistic conditions. Section 6.1.2 describes the environmental setup used for the standard post-disaster scenario evaluation within this chapter, including the specific application of the discussed mobility model to depict disaster scenarios. The utilized network model for WiFi-based communication on DTN nodes and UAVs is presented in Section 6.1.3. Afterwards, used metrics and boxplots are described. Table 6.1 summarizes the most important settings utilized in this evaluation.

6.1.1 *Metrics*

We evaluate our proposed contributions with various metrics, implemented as time- and event-based analyzers in the SIMONSTRATOR.KOM platform. Due to different aspects of their assessment, contribution-specific evaluation metrics are described at the appropriate part of the evaluation. However, the utilized communication network is evaluated throughout this chapter with the same metrics. Thus, we describe this set of metrics in the following:

RECALL Recall is defined as the ratio of successful message receptions out of the set of all intended message receivers. In case of a message broadcast, i.e., all network nodes are intended receivers for that message, the recall resembles the message spread within the network. In general, a recall value close to 1.0 can be seen as optimal. Within a clustered disaster DTN, recall is strongly influenced by node mobility and the Time-to-Live (TTL) of messages.

DELIVERY DELAY Message delivery is typically delayed in DTNs as a result of the store-carry-forward approach being necessary to allow communication between distinct parts of the network. This metric measures a message's time to successfully reach its recipients before its TTL expiration. We measure the average delivery delay and the maximum delivery delay, respectively. Especially for highly intermittent DTNs, the maximum delay allows quantifying the required time for message propagation. The delivery delay metric alone is not expressive enough to assess the DTN communication, as it provides measurements only for received messages. Thus, it must always be considered together with the recall metric.

TRAFFIC METRICS. The shared wireless communication medium used by the DTN must be utilized efficiently due to its limited capacity. To assess the overhead introduced in the network by our approaches, we measure traffic characteristics like the number, size, and type of messages, as well as the required bandwidths for sending and receiving, respectively.

Most of our results using these metrics are visualized using box plots, as exemplarily shown in Figure 6.1. Box plots visualize statistical data distribution, in our case, for the aggregated simulation results. The y-axis denotes the metric values, while different environments — such as varying parameter sets — are denoted on the x-axis. Each environment comprises several systems, for example, different communication protocols applied within the same environment, that is represented by a single box plot. The solid, bold line denotes the median of the metric data, also called the 50th percentile or the second quartile (Q2). The box, colored in the system's color, shows the range of the data from the median down to the 25th percentile (Q1) and upwards to the 75th percentile (Q3), respectively. Thus, the colored box comprises 50% of all results. The two whiskers extend this range down to the 2.5th percentile (Q0) and up to the 97.5th percentile (Q4), which encompasses 95% of measurements. Additionally, an error marker left of the box plot indicates the mean of means and the

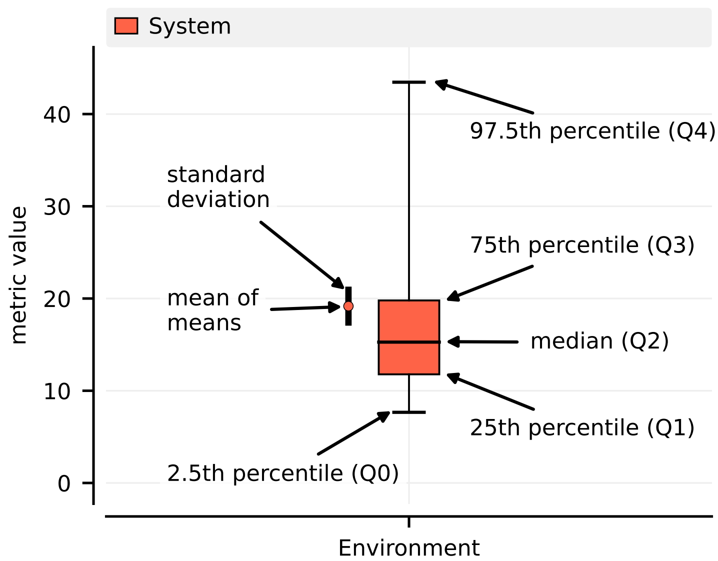


Figure 6.1: Box plot example with annotations.

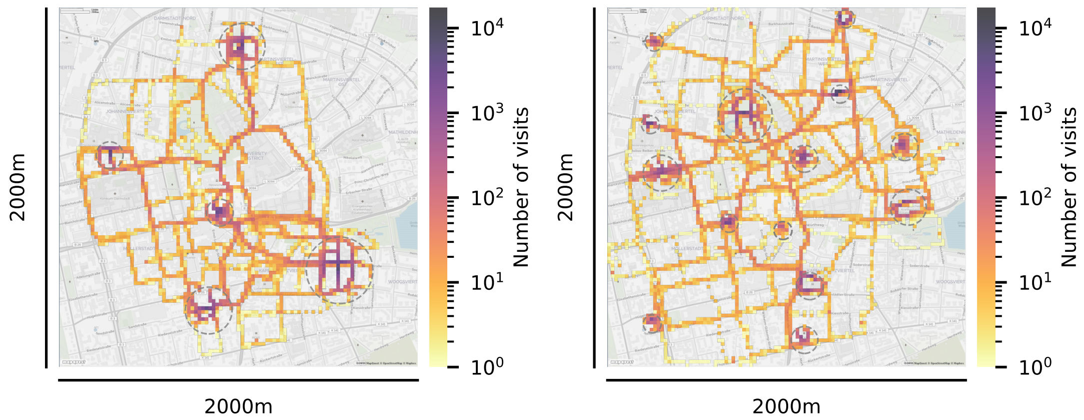
standard deviation of all simulation runs with different random seeds. A missing marker indicates that the box plot provides the aggregated results of all simulation runs combined.

6.1.2 *Post-Disaster Scenario and Node Mobility*

For the evaluation of our contributions, we consider a post-disaster scenario where Information and Communication Technology (ICT) infrastructure is unavailable as a result of the disaster event. However, a smartphone-based communication network relying on delay-tolerant networking is already in place and provides basic means of communication to the affected population [166]. Certain areas of interest (AoIs) are distributed throughout the disaster area and represent locations that are important in a disaster scenario, like shelters, resource depots, or supermarkets. In coherence with the field test findings (cf. Section 2.3), the affected population is spread mainly within these AoIs but may generally also move between them in smaller groups. Hence, the DTN must be assumed to be highly clustered and fragmented, with considerably low performance for inter-cluster communication (cf. Section 2.2). Within this general post-disaster scenario, our proposed UAV-based aerial network assistance system is deployed to increase and provide the required communication performance for successful disaster relief.

Simulation runs

Simulations are performed for 10 hours, whereby the first hour is used as an initialization and stabilization phase for the simulation [235]. Thus, all measurements start after one hour and capture a total time frame of 9 hours. Each simulation run is repeated with ten different random seeds to alternate node movement and workload generation. We use the inner city of Darmstadt with a size of 4 km^2 as simulation area. This area includes public parks and plazas like the city center, hospitals, and



(a) RND_T: Random area placement with transit mobility.

(b) OSM: Disaster-related areas with transit mobility.

Figure 6.2: Node mobility for the inner city scenario in Darmstadt. (Map © www.mapquest.com, Data © www.osm.org/copyright)

Map data, routing, mobility

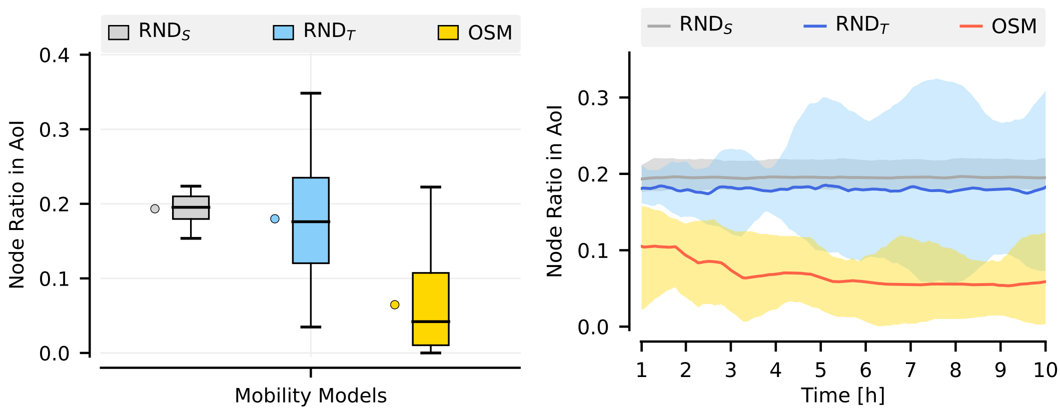
several residential areas. The used map data is provided by OpenStreetMap[1]. For the navigation of nodes on the map — i.e., to actually reach a target location given by the used movement model — we rely on the open-source routing library GraphHopper[2]. Node movement is bound to paths and walkways accessible for pedestrians, as given by the map data, and uses the civilian disaster mobility (CDM) model described in Section 5.4. CDM provides node mobility based on real-world measurements from a field test and, therefore, allows realistically representing the network topology and communication properties in a disaster scenario. This is extremely important since DTN communication performance, most notably message spread and distribution delay, is predominantly characterized by node mobility due to the store-carry-forward approach. The exploration probability of CDM is set to 0.1; thus, one in ten groups takes a larger detour and pauses at a random location outside of any AoI on their way. As a result of the aggregation of nodes around areas of interest, the specific communication characteristics are also highly dependent on the actual distribution of AoIs and mobility between them.

Scenario representation

To represent different scenarios and allow the assessment in a wider variety of DTN topologies, we use two options to specify the AoI distribution. At the start of the simulations, all nodes are randomly placed within the AoIs. The first option, RND, provides a randomized distribution of AoIs in the simulation area, including variations in their covered area. Within this evaluation, RND places five circular AoIs with a diameter between 50 and 300 m, which remain throughout the entire simulation time. To adapt the mobility between AoIs, however, we provide one version without transit mobility and a static allocation of nodes to each AoI (RND_S) and another with the typical transit mobility (RND_T), as provided in Section 5.4. Node mobility for RND_T is visualized in Figure 6.2a. The second option of the AoI

RND

1 https://www.openstreetmap.org/ [Accessed 01.09.2022]
2 https://www.graphhopper.com/open-source/ [Accessed 01.09.2022]



(a) Aggregated node distribution in areas. (b) Node distribution in areas over a single run.

Figure 6.3: Distribution of nodes over areas of interests, measured by the ratio of simulated nodes per area.

OSM distribution, OSM, is based on 14 disaster-related locations in Darmstadt, including public plazas, schools, hospitals, supermarkets, and others. However, only six areas are used at the simulation' beginning and remain permanently active. All other areas are added over time and have a limited lifetime before being removed. Nodes can designate any active AoI as a transit target but will directly go to another AoI once it is removed. Thus, the OSM mobility results in a more distributed, highly dynamic scenario with increased changes in the network topology, as shown in Figure 6.2b. More details on the used areas are provided in Section A.1.

Differences in node distribution To highlight node movement and distribution for the different mobility settings, Figure 6.3 visualizes the ratio of nodes inside areas of interest, measured for the entire simulation time. As shown in Figure 6.3a, the node ratio with RND$_S$ is relatively constant, only affected by the random placement in AoI at the simulation start. Despite the same areas and initial placement, RND$_T$ results in a considerably larger spread and lower median, which clearly demonstrates the nodes' transit mobility and significant changes in the number of nodes within the areas. OSM mobility, in contrast, results in an entirely different node distribution due to the more numerous and dynamic area placement. Therefore, areas are generally less populated and can even be empty. A detailed view of this behavior is given in Figure 6.3b, visualizing the node ratio over the simulation time for a single exemplary run. Clearly, RND$_T$ perceives large fluctuations in the number of nodes within areas due to transit mobility, albeit a relatively stable median node distribution over all AoIs. The node ratio for OSM, however, declines with the emergence of more areas of interest despite remaining fluctuations and temporarily empty areas. Thus, RND$_S$ represents a static mobility scenario with similar node distributions in all AoIs. RND$_T$ and OSM, however, represent more dynamic scenarios, which is expected to pose a more significant challenge for our autonomously deployed Aerial Network Assistance system.

6.1.3 *Communication*

Each civilian is represented by a smartphone, modeled by a Simonstrator.kom host entity. Smartphones are capable of WiFi communication and collectively take part in constructing a disaster DTN [166]. Therefore, we refer to all hosts representing smartphones as *DTN nodes* in the following. If not stated otherwise, DTN communication utilizes an adaptive gossip protocol based on the work of Khelil et al. [149]. Within our simulation, we neglect energy consumption on smartphones and the provision of energy resources in the disaster area, which has already been assessed extensively [166, 168, 169]. The base stations and UAVs are similarly represented by hosts, as described in Section 5.2.

WiFi-based communication between DTN nodes as well as DTN nodes and the UAVs is modeled using the 802.11g model from the network simulator ns-3 [122], which is already part of PeerfactSim.kom [236]. The employed logarithmic path loss model is used to determine an effective maximum communication range on the one hand but also calculates a noise floor for interference with other signals beyond the communication range. This allows the realistic simulation of collisions and signal interferences typical for a shared communication medium. Collisions and interferences are especially important for DTN evaluation, as node density and concurrent transmissions highly impact the DTN communication performance [30, 149]. The log-distance model in the simulations is used with a loss exponent of 3.8 based on related work [43, 179, 235, 238]. This results in an effective maximum communication range of 88 m, approximating the communication range observed with real-world DTNs [15, 166], and a probable interference range of up to 205 m.

The UAV-to-UAV communication over WiFi is modeled as a separate channel. This not only encapsulates the networks from each other, as commonly endorsed by related work [14, 18, 82, 109, 128, 188, 198, 281, 302], but also allows the adoption of the different communication properties of Air-to-Air (A2A) links. Therefore, we use the same WiFi model as for the DTN communication but adapt its properties to allow for stable communication ranges between UAVs for up to 250 m in approximation to real-world measurements [117, 119, 154, 298, 300]. In addition to WiFi, UAVs and the base station are further capable of using LoRa communication.

6.2 cooperative aerial-ground monitoring

In this section, we evaluate the prototype of *Cooperative Aerial-Ground Monitoring* (CAMON) and assess its impact on the node detection performance of our UAS. In addition to the common evaluation settings discussed in Section 6.1, we describe the evaluation parameters, metrics, and setup specific to the utilized monitoring scenario in Section 6.2.1. The evaluation is separated into three parts. We start by analyzing the communication overhead introduced by CAMON and the impact of the beacon interval in Section 6.2.2. Afterwards, we evaluate the impact of CAMON on the direct communication between UAVs and DTN nodes in Section 6.2.3, followed by the overall node detection performance of the UAS in Section 6.2.4.

Table 6.2: Parameter set for the evaluation of CAMON.

Parameter	Value
Monitoring Areas	4 (1000 m x 1000 m each)
Coverage Path Planning	Lawnmower Pattern
Mobility	RND_T
CAMON Protocol	Hierarchy, Proactive, Reactive
Baseline	Beacon
Beacon Interval	1 s, 2 s, 5 s
Information Validity Interval	10 s, 20 s, 50 s

6.2.1 *Monitoring Scenario*

The evaluation setup described in Section 6.1 provides the basis for communication and movement behavior in the simulation scenario. Nevertheless, the evaluation of CAMON and its protocols requires additional parameters and simulation features. The evaluation parameters used for this monitoring scenario are outlined in Table 6.2.

Protocol comparison

In this part of the evaluation, we compare the proposed CAMON protocols from Section 4.3 against the non-cooperative Beacon protocol as the baseline: Hierarchy constructs and maintains a network hierarchy with lower layers having less topology information of their cluster, Proactive constantly maintains a distributed full information state on all cluster nodes, and Reactive only collects topology information when triggered by a UAV.

Monitoring areas

In general, the simulation area is divided into four square-shaped monitoring areas of 1 km^2 size. Each area is monitored by one UAV using the lawnmower pattern for Coverage Path Planning (CPP) in the monitoring areas. Each monitoring UAV starts from the base station to approach the first waypoint on its path, traverses the planned trajectory, and returns to the base station after completing it. Information monitored during the traversal is transferred to the base station after landing. Then, the UAV is readied by replacing its battery and continues with another traversal, repeating the procedure. The first monitoring flight starts after 30 seconds.

UAV monitor metrics

Specifically to this monitoring scenario, we use additional metrics to assess the performance of the DTN and the UAS, as well as the impact of CAMON on both. On the part of the monitoring UAVs, the contacts with DTN nodes are essential for their detection. A contact is counted as a reception of a DTN beacon, whereas a detection is defined as the reception of specific node information included in that beacon. Note that Cluster Information Reply (REP) messages extend DTN beacons and, thus, are similarly counted as one beacon. However, they may carry information on multiple nodes and could, therefore, result in multiple detections. The following UAV metrics are measured per UAV and per traversal, providing insights into the contact characteristics during a single monitoring flight.

NUMBER OF DIRECT CONTACTS The total number of received DTN beacons on a UAV. Multiple beacons from the same node are counted.

NUMBER OF DIRECT DETECTIONS The total number of directly detected DTN nodes, i.e., nodes that were only detected based on their own beacons. Multiple detections of the same node are neglected.

NUMBER OF DETECTIONS The total number of detected DTN nodes, i.e., direct detections combined with indirect detections via cluster information in REP messages. Multiple detections of the same node are neglected.

COOPERATIVE DETECTION METRICS Based on the contact and detection metrics, we further measure the number of detections acquired solely by cooperation with CAMON, as well as the share of cooperative detections on all detections.

System metrics

Nevertheless, the overall system performance mainly depends on the quality and accuracy of information when it arrives at the base, as well as the time it takes to assess the DTN topology. Thus, we further investigate the following metrics from a system point-of-view.

NODE DETECTION RATIO The share of nodes that the whole system is able to detect from all DTN nodes. Multiple node detections at a single or multiple UAVs are not counted.

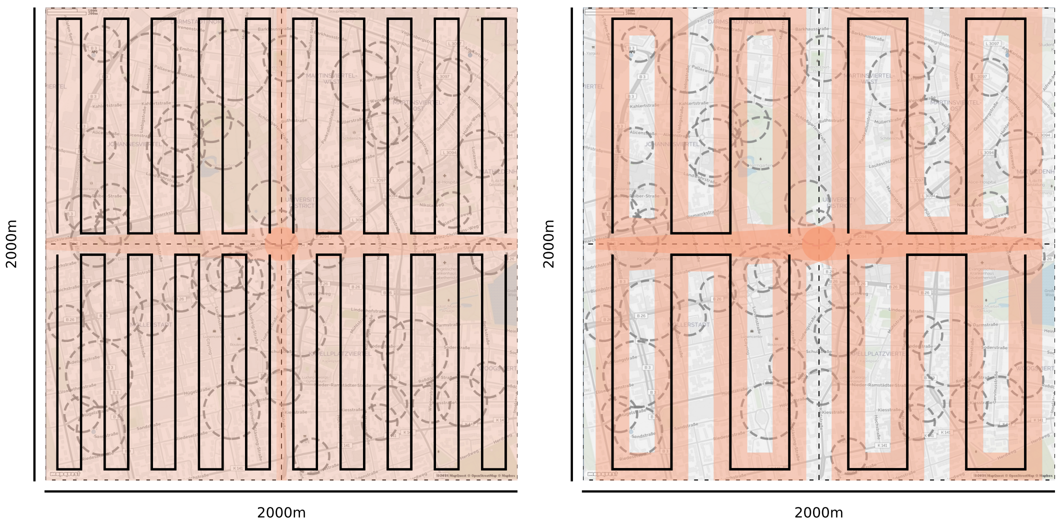
AGE-OF-INFORMATION ON BASE ARRIVAL This Age-of-Information metric denotes the age of node information when arriving at the base station. In our case, information can already have a certain age when picked up by the monitoring UAV. In case of multiple detections, only the latest information is considered.

LOCATION ERROR ON BASE ARRIVAL This metric denotes the spatial error of node information when arriving at the base station. The error is the absolute difference between the location given in the information compared to the actual node location at the time of base arrival. In case of multiple detections, only the latest information is considered.

FIRST DETECTION DELAY ON BASE The delay between the start of the first monitoring UAV until the arrival of node information at the base. Thus, this metric measures the time required for an initial node detection.

Approach

As described in Section 4.3, CAMON endeavors to overcome the required spatio-temporal overlap of monitoring UAVs and monitored DTN nodes. The goal is to increase the efficiency of the monitoring UAS by achieving a partial decoupling of area coverage and node coverage. To alleviate the assessment of CAMON and the monitoring performance, we adapt the lawnmower pattern coverage path by the number of lawnmower strips and the strip clearance, as sketched in Figure 6.4 for two examples. The reduction of strips with larger spaces in between results in a reduction of area coverage and, consequently, a reduction in path length and the required traversal time.



(a) C_{100}: 10 strips, 100 m clearance, 100% coverage.

(b) C_{60}: 4 strips, 250 m clearance, 60% coverage.

Figure 6.4: Monitoring areas are traversed using the lawnmower pattern. Area coverage is reduced by using fewer strips and a larger clearance.

Impact of coverage path

The calculation of the lawnmower pattern is only based on the monitoring area and, thus, results in the same pre-defined coverage path for all random seeds. At the same time, the OSM mobility scenario has pre-defined areas of interest that do not differ between the seeds; only node mobility itself differs. Consequently, we would only measure the influence of node mobility but neglect any influence of favorable or unfavorable area locations. Therefore, OSM is unsuitable for assessing CAMON, and we resort to the RND_T mobility scenario instead, since each simulation considers entirely different area and node distributions. In the background of Figure 6.4, the simulated areas of interest for all ten random seeds are visualized by circles. Clearly, the reduction of area coverage leads to gaps between the lawnmower strips. The random placement and size of areas provide a large coverage variance.

Area coverage adaptation

In this evaluation, we consider four lawnmower paths resulting in a coverage of 100% (C_{100}), 75% (C_{75}), 60% (C_{60}), and 35% (C_{35}). A visualization of all four variants is given in the appendix (Figure A.1), while Table 6.3 provides an overview of their properties. Note that the provided distances already include the required flight to approach the first waypoint and return to the base from the last. The baseline coverage path C_{100} with ten strips and a clearance of 100 m provides full area coverage while requiring nearly 18 minutes to complete a single monitoring flight. This coverage path also exhausts the flight capability of the utilized UAVs and, therefore, constitutes the upper bound for the monitoring area size for which the utilized UAVs can provide full area coverage. C_{75} provides a decreased coverage with 200 m clearance and an 11-minute flight. A further increase to a 250 m clearance by C_{60} reduces the flight time to around 9 minutes and a coverage of 60%. The lowest coverage of 35% is provided by C_{35} with a clearance of 500 m, resulting in a 5:30-minute flight.

Table 6.3: Resulting coverage paths and properties.

Coverage Path	Strips	Clearance	Time	Distance	Coverage
C_{100}	10	100 m	17:45 min	11.02 km	1.00
C_{75}	5	200 m	11:00 min	6.75 km	0.75
C_{60}	4	250 m	8:50 min	5.41 km	0.60
C_{35}	2	500 m	5:30 min	3.34 km	0.35

6.2.2 *Communication Overhead and Impact of Beacon Interval Size*

We introduced the different CAMON protocols and discussed their anticipated implications on the bandwidth requirements due to the additional overhead in Section 4.3. In this section, we take a closer look at the introduced overhead traffic concerning the DTN beacon interval. This interval also influences the time that cluster information is considered valid on nodes and, thus, the time it takes DTN nodes to detect major changes in the network topology. Based on the work of Baumgärtner et al., the *Information Validity Interval* (cf. Table 6.2) is used as ten times the *Beacon Interval* [30].

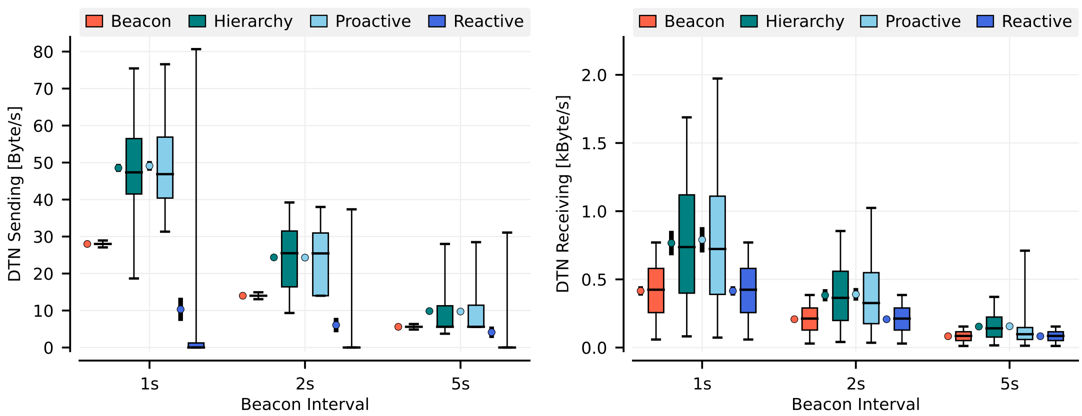
The resulting overhead traffic for the four protocols — Beacon, Hierarchy, Proactive, and Reactive — in combination with the applied beacon intervals, is shown in Figure 6.5. A complete comparison of sending and receiving traffic with and without UAV contact, respectively, is provided in Figure A.2 in the appendix. Naturally, the trend that a larger interval reduces the amount of generated traffic is clearly visible in both plots. However, note that Figure 6.5a shows the generated traffic in the presence of monitoring UAVs, while Figure 6.5b shows the overhead traffic without a UAV in contact. This distinction is especially important for the Reactive protocol due to the differences in protocol design: other protocols continue their regular behavior in the presence of UAVs while the Reactive protocol switches to data collection. As a result, the average traffic generated per node in this phase is severely reduced, while the large amplitude of the 97.5th percentile in Figure 6.5a indicates the quick flooding of information through the network at the same time. Nevertheless, the sharp increase during this phase must be taken with care, as it could disrupt other critical services. Without a UAV contact, however, the Reactive protocol behaves similarly to the non-cooperative Beacon protocol (cf. Figure 6.5b).

Less traffic with larger interval

Clear distinction of Reactive

Overall, Proactive and Hierarchy generate considerably more traffic and in a higher variance than their counterparts for both sending and receiving traffic without a UAV in contact. On the sending side, Proactive sends more data as indicated by the higher 2.5th, 75th, and 97.5th percentiles for a beacon interval of 1 s than Hierarchy, but the difference reduces with a larger beacon interval. Similarly, Proactive can outweigh Hierarchy in the receiving traffic since messages are sent to all nodes and not just within the hierarchy. Nevertheless, the median receiving traffic decreases faster for Proactive than for Hierarchy with increasing beacon interval, presumably as the constantly required maintenance messages excel the less occasionally sent

More traffic with Proactive, Hierarchy



(a) Sending, during UAV contact.

(b) Receiving, without UAV contact.

Figure 6.5: Overhead traffic per node with different beacon intervals.

data messages. Both features indicate that the network clusters are well-connected and information propagates quickly to a large number of neighbors, reducing the necessity for frequent rebroadcasts of information. Though, large-scale rebroadcasts are still happening, as indicated by the 97.5th percentile for Proactive. Maintenance messages are, nevertheless, needed and, thus, exceed the information messages.

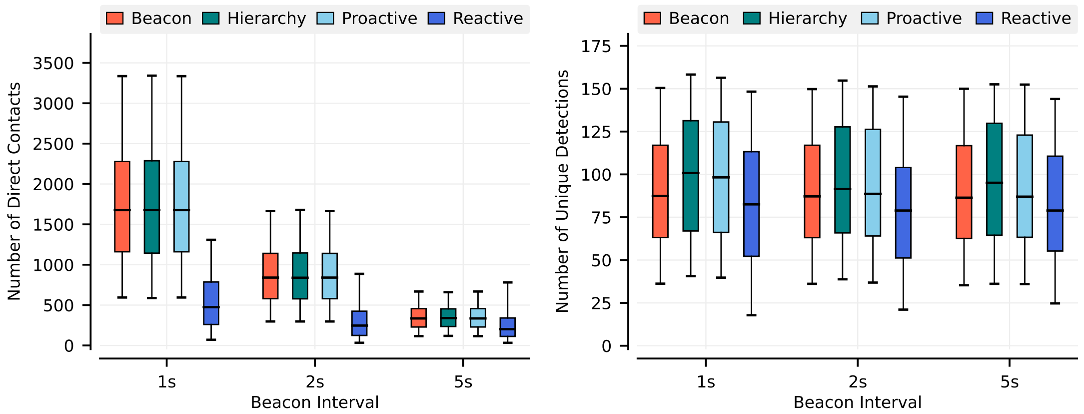
Interval influences contacts...

Expectably, the beacon interval also directly influences the number of beacons that can be received by monitoring UAVs, as shown in Figure 6.6a. Here, the number of direct contacts — similar to the overhead traffic — reduces with a larger interval. Furthermore, Beacon, Proactive, and Hierarchy also result in similar direct contacts, with only a slightly increased number for Hierarchy, probably due to additional maintenance messages being received. Reactive, on the other hand, has a significantly lower number of direct contacts than the rest, again because of the protocol design in the presence of a monitoring UAV. However, neither this different design nor the different beacon interval strongly influences the number of node detections, as indicated by Figure 6.6b. Despite some minor fluctuations, there is no general decrease in node detections perceivable with a larger interval.

...but not node detections.

In conclusion, we see the beacon interval's expected influence on the bandwidth requirements in general. However, the different protocols do not show a largely different behavior as a result of changing beacon intervals. The largest dissimilarity arises between the Proactive and Hierarchy protocols for the largest interval. The former sends fewer beacons with full information and, thus, has lower quartiles yet retains a large maximum bandwidth. The latter, on the other hand, requires more bandwidth in general but with a significantly lower maximum. It is worth noting that their mean values are still similar, indicating less fluctuating bandwidth usage per node with Hierarchy than with Proactive. To remain comparability and readability, a beacon interval of 1 s is used for the rest of this evaluation if not stated otherwise, which is a typical value for practical implementations [15, 30, 166].

Beacon interval = 1 s



(a) Direct node contacts.

(b) Unique node detections.

Figure 6.6: Contact metrics on monitoring UAVs (C_{100}) for full coverage with different beacon intervals.

6.2.3 *Impact of Area Coverage Reduction on UAV-DTN Contacts*

After assessing the performance of the communication network with varying communication parameters, we now focus on CAMON and the ability to detect DTN nodes in the monitoring areas. As described in Section 6.2.1, we decrease the area coverage to investigate the ability of the cooperative monitoring approach to maintain detection performance with reduced coverage. Consequently, it is to be expected that the number of contacts and detections decreases with reduced coverage, i.e., with gaps in the coverage path. Note that similar to before, metrics provide aggregated results per UAV and monitoring area flight to investigate the interaction between UAVs and DTN nodes.

View on UAV-DTN interaction

Figure 6.7 shows the number of direct contacts for the different coverage paths and protocols. The overall high variance in the direct contacts reveals the uneven distribution of nodes in the different monitoring areas. A similar spread must, therefore, also be expected for node detections. The Reactive protocol again results in considerably fewer contacts with monitoring UAVs, similar to the behavior already shown in Figure 6.6a, due to the protocol design in the presence of a UAV. For all protocols, direct contacts are expectedly decreasing with lesser area coverage. Nevertheless, this decrease is generally larger between C_{100}, C_{75}, and C_{60}, respectively, than it is between C_{60} and C_{35}. More importantly, the 97.5th percentile for C_{35} is increasing. This hints at some cases where more nodes are covered despite the lower area coverage, either due to node mobility or the distribution of the areas of interest favorably under the coverage path by coincidence. We assume that this must be mostly attributed to node mobility because of the markedly larger increase for Reactive than the other protocols since larger clusters (located in AoIs) result in less direct contacts than several smaller ones. Overall, the high number of direct contacts illustrate largely redundant beacon receptions, despite some mitigation for the Reactive protocol, as a result of the chosen beacon interval.

Less direct contacts with Reactive

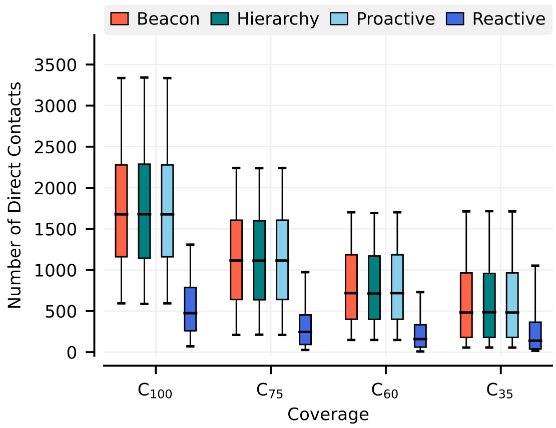


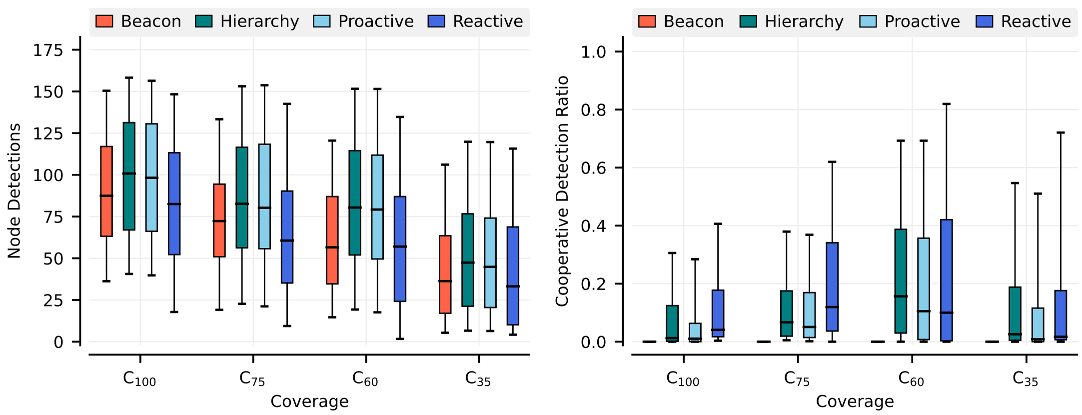
Figure 6.7: Direct node contacts with decreasing area coverage.

Until this point, we solely addressed the number of beacons and generally the traffic that is received on each monitoring UAV. Hence, we now shift our focus to the contained node information and the detection of nodes using the different protocols in more detail. Figure 6.8a visualizes the number of node detections for monitoring flights. As expected, we perceive a similar high variance for detections due to the unequal node distribution among the monitoring areas. This is best showcased by the results for BEACON with the full coverage path, where between 35 and 150 nodes are directly detected. Compared to this baseline, however, the HIERARCHY and PROACTIVE protocols increase the number of detected nodes. Since BEACON for the full coverage case (C_{100}) already covers all nodes within an area, the increase in node detections illustrates the overlap of network clusters with area borders and the cooperative detection of nodes outside the actual monitoring area. The opposite effect is observable for REACTIVE with a decrease in node detections, especially in the 25th percentile and the median. Because the pre-defined monitoring paths are symmetrical at the area borders, several UAVs can approach a network cluster that overlaps two or more monitoring areas. Depending on which UAV approaches the cluster first to trigger the topology information collection process, only this UAV receives the REP message with the information. The time difference between their arrival is presumably not big enough to allow separate collection processes for each UAV; otherwise, we would expect larger results for node detection.

Clusters overlap monitoring areas

Similar protocol differences are observable for every coverage path. However, although node detections generally decrease with less coverage as expected, HIERARCHY and PROACTIVE perceive considerably smaller losses for C_{75} and C_{60} than REACTIVE and especially the non-cooperative BEACON protocol. For C_{35}, on the other hand, the gains by cooperative behavior are still acknowledgeable but less prevalent than with higher coverage. Nevertheless, Figure 6.8a only directly compares the protocols for their impact on the overall detections. To further assess the influence of cooperation, we additionally investigate the exclusively cooperatively detected nodes as the share of all node detections, as given by Figure 6.8b. The cooperative detection ratio for BEACON is naturally zero due to the lack of cooperation. Although we would

Detections decrease with lower area coverage



(a) Detected nodes, direct and cooperative detections.

(b) Share of cooperatively detected nodes.

Figure 6.8: Node detections and the cooperative share with decreasing area coverage.

expect the same for the cooperative protocols and full coverage at first glance, up to 30% of node detections for HIERARCHY and PROACTIVE and up to 40% for REACTIVE are cooperative detections, respectively. The former can again be attributed to the detection of nodes outside the actual monitoring area as a result of overlapping clusters. The latter, however, is a combination of outside-node detection and the suppression of beacon sending during the REACTIVE collection process. Thus, a monitoring UAV rather receives some node information from the REP message than from eavesdropped beacons as in the other protocols.

Cooperation detects nodes in other monitoring areas

In general, the cooperative detection ratio increases with decreasing coverage. But this influence again reduces with C_{35} coherently to the total node detections. This indicates that a considerate share of clusters is not covered at all, i.e., not a single node is detected during the monitoring flight. Nevertheless, in the case of cluster contact, cooperation still provides a large number of detections, for example, up to 70% for REACTIVE. The largest benefit of cooperation is achieved at C_{60}. The comparison with C_{75} highlights that cooperation can achieve a similar node coverage despite a reduced area coverage, while the comparison with C_{35} demonstrates that this still requires sufficient area coverage nonetheless.

C_{35} has insufficient area coverage

Both Figure 6.8a and Figure 6.8b point out more node detections but a lower influence of cooperation for HIERARCHY and PROACTIVE compared to REACTIVE in the upper quartiles. Nevertheless, we also discussed some plausible factors of influence on these differences and continue examining these properties in the following. Furthermore, the used metrics provide UAV-specific measurements for monitoring flights and the interaction with DTN nodes on the ground. They are, hence, not descriptive of the entire aerial monitoring system, albeit providing a discernible tendency. Therefore, the next section emphasizes the system perspective and the system's node detection performance.

REACTIVE provides largest cooperative impact

6.2.4 *Impact of Area Coverage Reduction on the UAS' Node Detection Performance*

The most important aspects of aerial monitoring in a disaster scenario are *comprehensiveness* and *timeliness*. In the optimal case, the collected information state for the entire disaster area is complete, correct, accurate, and up-to-date. As discussed in Section 4.2.1, however, comprehensiveness and timeliness are typically diametrical to each other, as a comprehensive assessment of the area requires more time than a partial assessment and vice versa.

View on system-wide performance

In this section, we focus on the performance of the whole aerial monitoring system within our monitoring scenario. Because monitoring UAVs are required to return to the base station to report their collected monitoring information — due to the lack of a high-throughput long-range communication channel between base station and UAVs (cf. Chapter 4) —, the base station is the crucial part of the system to measure performance. First, we assess the information quality that is arriving at the base station via monitoring UAVs, visualized in Figure 6.9, for both the location error and the age of the incoming information. Note that information is created on the DTN nodes, and thus, both metrics measure the spatial and temporal delta, respectively, from the creation on a node until itsarrival at the base.

Information Quality

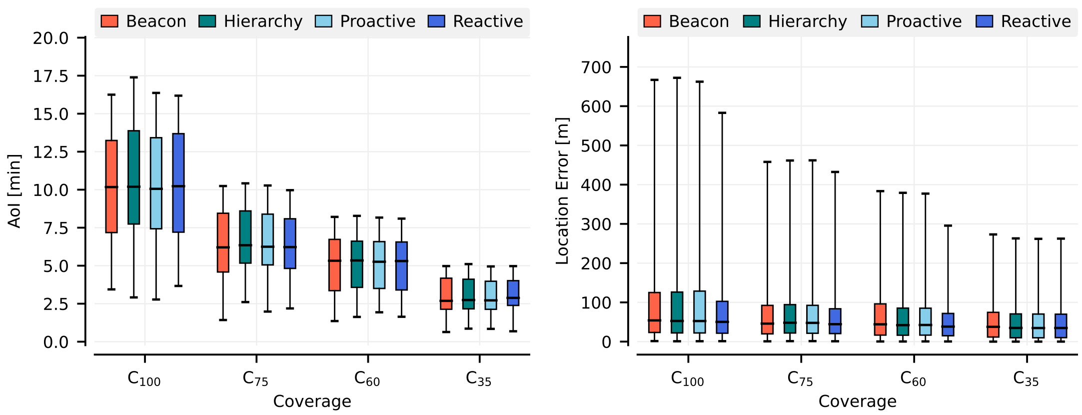
Lower information age with shorter traversal

The information quality for our aerial system is composed of the age of arriving information and the location error of that information from the actual node location when arriving at the base station. Corresponding to our expectations, the age-of-information decreases with lower area coverage and the resulting shorter traversal time (cf. Figure 6.9a). Since all information is collected between the start and return of monitoring UAVs, the flight time serves as a natural upper bound for the age-of-information. Clearly, this metric can only count arriving information and cannot assess the lack of information in general, but we will discuss more details later. However, the age-of-information metric still provides valuable insights on arriving information and the delay between their collection and the subsequent arrival at the base. Primarily, no major differences between the protocols are perceivable, which would show some disadvantages for any protocol. Minimal age-of-information is typically achieved with the non-cooperative BEACON approach, as only direct and the newest information is collected. Consequently, the maximum age-of-information is seen for the HIERARCHY protocol which has the lowest propagation of information inside clusters. In between the maxima and minima, however, the extends of the distributions and the median values are in close proximity, with a maximum deviation of 30 seconds.

Small differences between protocols

Larger errors for older data

The location error, i.e., the deviation from the arriving location information to the actual location at that same time, is visualized in Figure 6.9b. The large extent of the upper whiskers immediately highlights the considerable errors that can accumulate during the time it takes the information to reach the base station, which naturally increases with a longer monitoring path. In the case of full coverage, for example, more than 25% of errors are larger than 100 m. Note that the 75th and 97.5th percentiles



(a) Age-of-information.

(b) Error of location information.

Figure 6.9: Age and location error for incoming information at the base station.

are discernibly lower for Reactive compared to the other protocols, indicating that the protocol can provide more accurate information. However, this is not clearly supported by the provided age-of-information, although Reactive has slightly lower 97.5th and 25th percentiles than Proactive and Hierarchy for C_{100}, C_{75}, and C_{60}, respectively.

As expected, the location error is generally reduced with a reduction in travel time for the information. More than 75% of all incoming information has an error of less than 150 m. Thus, we can assume that the larger part of the nodes stayed within an area of interest until the information arrived at the base. Nevertheless, the location error for the remaining share of nodes is considerably high and reveals a clear shortcoming of our aerial system with high node mobility. Further reduction of this location error would only be possible if mobile nodes are encountered more frequently and the information arrives more quickly at the base station. With a static coverage path as used in this scenario, however, this cannot be achieved. The adaptation of monitoring routes to cover mobile nodes more frequently or using cooperatively shared information on planned trajectories of DTN nodes are interesting research topics, but they are left open for future work.

Considerable location errors remaining

Node Coverage

After evaluating the quality of the incoming monitoring information, we shift our focus to the actual node detection. For that, we assess the performance of the monitoring system with *(i)* the delay for the initial node detection at the base station and *(ii)* the collected number of detected nodes over time. Both metrics primarily enable us the assessment of node coverage and, by that, node detection performance.

Figure 6.10 depicts the first base detection delay, i.e., the time from the start of the monitoring system until the first arrival of node information. For C_{100}, the results clearly mark the time to traverse the monitoring path, as detailed in Table 6.3. No nodes are found after the first flight, which suggests full node coverage — as expected for full area coverage — and is confirmed by the results given in Figure 6.11.

Comparison of detection delay

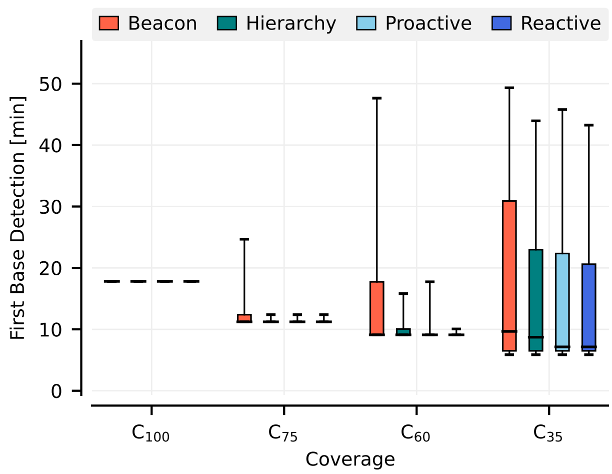


Figure 6.10: Delay for initial node detection at the base station.

More delayed node detection with lower area coverage

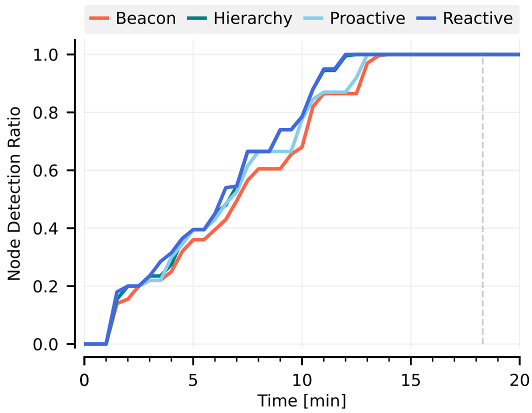
In contrast, not all nodes are found at the first flight with C75 due to the increased detection interval, demonstrating a later detection of some nodes. Based on the shown percentiles, only a minor fraction of nodes was not detected within the first flight using the cooperative protocols, while BEACON requires multiple flights to detect more nodes. Similarly, the detection delay further increases with lower area coverage and, thus, also highlights lower node coverage within single flights. Especially for C35, this can lead to tremendous detection delays, for example, more than 30 minutes for around 25% of detections in the case of using the BEACON protocol. The direct comparison between the CAMON protocols reveals slight differences, mostly in the 75th and 97.5th percentiles, with REACTIVE providing the lowest node detection delay.

Comparison of total node detection

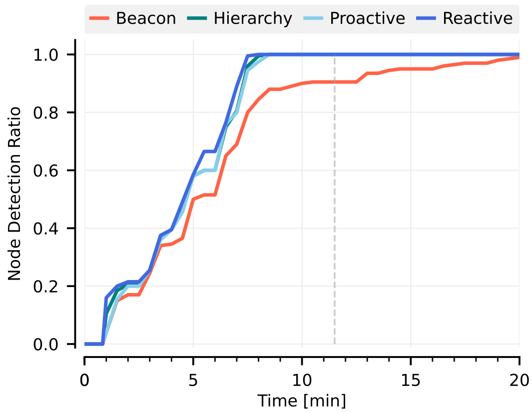
Besides the initially required time to detect nodes, it is also of utmost importance whether nodes are detected in the first place and can be monitored afterwards. To address this issue, we compare the overall number of detected nodes by the aerial system for the different CAMON protocols in Figure 6.11. For better readability and to allow a direct comparison of the full coverage flight with the other paths, Figure 6.11 visualizes only the first 20 minutes. This also facilitates the evaluation of the initial node detection performance — which is crucial for the initial assessment of the network's actual size in a disaster area. Furthermore, we discuss only the median node detection performance within this section to highlight the most significant aspects. More detailed evaluation results are provided in the appendix, Section A.2.3, together with a larger visualization that directly relates all performance measurements.

Full area coverage results in full node coverage

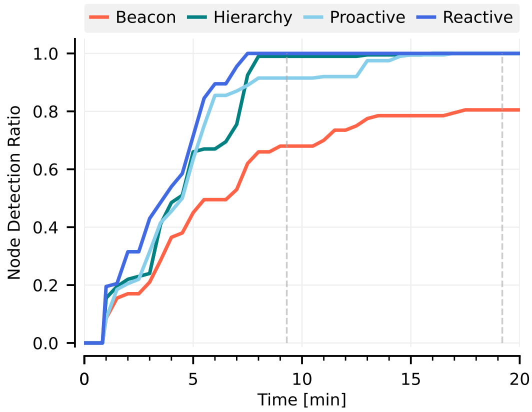
According to our expectations, full area coverage provides a comprehensive node detection within one flight, as visualized in Figure 6.11a. At the same time, the applied CAMON protocol is not important for full detection. All cooperative protocols provide only slight improvements to the initial detection time, which would only be a benefit if monitoring UAVs were able to transmit information of detected nodes to the base station directly. Despite these minor differences, however, they provide the same end result.



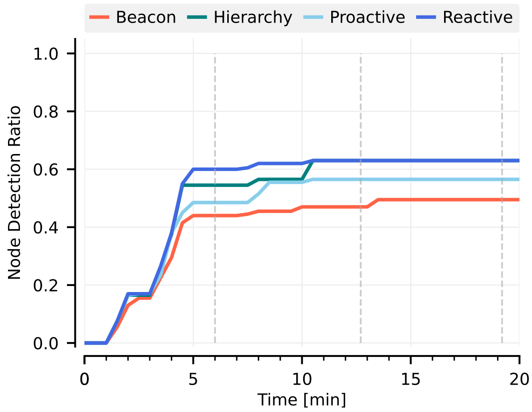
(a) C_{100}.



(b) C_{75}.



(c) C_{60}.



(d) C_{35}.

Figure 6.11: Comparison of the median node detection over time for the assessed protocols using different coverage paths. Grey vertical lines indicate the end and consecutive start of the coverage path traversal.

C_{75}: cooperation remains full node coverage

With an area coverage of 75% (C_{75}), a first disparity between the non-cooperative and the cooperative protocols is emerging (cf. Figure 6.11b). The Beacon protocol reaches an average of 90% within the first flight and requires consecutive flights to detect more nodes (cf. Figure A.4). By using CAMON, all nodes are detected within approximately 9 minutes in the first monitoring flight.

C_{60}: increased benefit of cooperation

This difference is further amplified by another reduction of the coverage, as shown in Figure 6.11c. Only 68% of nodes are found with Beacon after the first flight, while Proactive detects an average of 91% of nodes, Hierarchy 98%, and Reactive provides a full detection at the same time. Overall, Reactive differs from the other two cooperative protocols by a faster, more comprehensive detection throughout the evaluation. Our initial results did not clearly reveal this behavior since Reactive typically performed worse than the other protocols, which led to the anticipation that it would also perform worst at the overall system performance (cf. Figure 6.8a). Nevertheless, the opposite is the case when contemplating the entire system and not each monitoring flight separately.

Previous results for C_{35} already revealed a considerable performance decrease with such low area coverage. Figure 6.11d confirms this anew, as none of the protocols achieves an average detection rate of more than 65% within three monitoring flights. Clearly, the gaps in the coverage path are too large, and monitoring UAVs are less likely to encounter even a single node of a cluster. Although the lack of node contacts also diminishes the beneficial capabilities of CAMON, cooperation always outperforms no cooperation.

C_{35}: node coverage too low

In this section, we highlighted the benefits of cooperative behavior facilitated by *Cooperative Aerial-Ground Monitoring* (CAMON) and its positive impact on the aerial monitoring system's performance. In particular, CAMON achieves our goal of decoupling area coverage and node coverage. This allows a more coarse-grained monitoring of the disaster area, which reduces the traversal time of the monitoring path and allows a higher monitoring frequency. Simultaneously, however, CAMON can maintain the node detection performance and, thus, provides more accurate and more timely information. Additionally, CAMON can achieve a reduction of the initial detection time by more than 50%. Nevertheless, this evaluation also highlights the problematic nature of the area coverage reduction in combination with a static coverage path. Depending on the actual distribution of nodes, we expect the existence of an optimal tradeoff between area coverage and the possibility of encountering at least a single node of a cluster. For future work, this tradeoff could be determined by performing an initial full coverage flight and using the resulting comprehensive dataset to determine an optimal monitoring path. Similarly, several monitoring paths covering different partitions of a monitoring area could be defined and traversed consecutively, providing full area coverage with multiple flights. CAMON could be utilized for both cases to maximize node coverage on the monitoring paths, as shown in this evaluation. Overall, the cooperative CAMON protocols HIERARCHY, PROACTIVE, and REACTIVE provide comparable results despite their differences in the protocol design. This is especially important since we intended CAMON to be implemented as an extension to typical DTN protocols, as discussed in Section 4.3. The evaluation of CAMON shows that it is applicable and easily integrated into existing protocols without significant drawbacks besides generally larger bandwidth requirements.

Decoupling of node and area coverage

Open issues

6.3 CLUSTER ESTIMATION ON UNSTRUCTURED DATA

To facilitate communication support, our aerial system needs to identify static network clusters and differentiate them against node mobility. In this section, we evaluate our prototypical implementation for the estimation of clusters on unstructured detection data, following the design specifications discussed in Section 4.4. In addition to the common evaluation settings, Section 6.3.1 provides further evaluation parameters and metrics for the evaluation of the cluster estimation on unstructured data. Within this estimation scenario, we evaluate the influence of the data source with a focus on the update interval in Section 6.3.2, followed by the evaluation of the cell size's impact in Section 6.3.4, respectively.

Table 6.4: Parameter set for the cluster estimation scenario.

PARAMETER	VALUE
Mobility	RND_S, RND_T, OSM
Communication Support	1 UAV, Cyclic Data Ferry strategy[a]
Route Scaling Factor (f)	0.0, 0.5, 1.0, 1.5, 2.0
Aerial Monitoring	4 UAVs, full coverage lawnmower CPP[b]
Data Source	ORACLE (O), AERIAL MONITORING (AM)
Update Interval	O — 10 min (O_{10}), 20 min (O_{20}), 30 min (O_{30}) AM — after completed monitoring ($\approx$ 19 min)
Cell Size (d_{cell})	50 m, 75 m, 100 m, 125 m, 150 m

[a] cf. Section 4.2.2; [b] cf. Section 6.2.1

6.3.1 *Estimation Scenario*

Similar to the monitoring scenario used in the previous section, we require additional metrics, parameters, and simulation features to evaluate the cluster estimation performance on unstructured data. The used evaluation parameters for the estimation scenario are summarized in Table 6.4.

Mobility For node mobility, we compare the random area of interest placement with transit mobility (RND_T) and without (RND_S), as well as the disaster-related public areas of interest (OSM). As RND_S and RND_T use the same areas of interest, but only the latter provides transit mobility between them, we anticipate that both provide comparable results but a possible performance decrease for RND_T due to the additional mobility. The OSM node mobility provides a challenging environment with more and only temporally existing AoIs, which could result in reduced performance. For the rest of this evaluation, it is important to note that newly created AoIs with the OSM mobility are empty and are getting populated over time. Thus, performance drops are to be expected before a sufficient population allows the identification as a cluster. *UAS* A single UAV performs aerial communication support by applying the Cyclic Data Ferry strategy (cf. Section 4.2.2) to connect all identified network clusters. For the evaluation of cluster estimation, the communication UAV uses the direct route between clusters. Furthermore, the data ferry UAV does not collect monitoring information to prevent any interference with the evaluation of the data sources. Co-existing monitoring and communication support mechanisms are further detailed in Section 6.5. For the evaluation of the in-transit node coverage, which is performed later on in Section 6.4, however, we apply different route scaling factors already listed in Table 6.4 for completeness.

Data Sources The identification of clusters is performed using the specified design proposed in Section 4.4, which uses an arbitrary data source as input for the unstructured data. To evaluate the influence of data sources with varying input intervals, we compare an *Oracle* (O) against the *aerial monitoring system* (AM) already known from the previous section. The oracle provides the exact location of all nodes within a fixed interval of 10 minutes (O_{10}), 20 minutes O_{20}, or 30 minutes (O_{30}), respectively. Aerial monitoring, on the other hand, supplies the monitored node locations after each concluded monitoring flight. We employ four monitoring UAVs with a full coverage lawnmower path; thus, updated location information is available with an interval of approximately 19 minutes. The size of the gridmap cells d_{cell} is altered between 50 m and 150 m in 25 m steps, respectively. The 1σ distance for the kernel is defined as 50 m to resemble the similarly distributed transmission ranges that are to be expected in the urban scenario [15], which results in a kernel size of 5x5 cells for 50 m and 75 m, and a kernel size of 3x3 cells for larger cells, respectively.

Gridmap Adaptation

Estimation Metrics

The evaluation of the cluster estimation requires additional metrics we use specifically in this scenario. The following metrics are measured for each estimated cluster, compared against the actual areas of interest, and eventually aggregated to provide a global performance measurement.

ESTIMATION RECALL The estimation recall is defined as the ratio of correctly estimated clusters out of the set of all existing clusters. Optimally, recall resembles a value of or close to 1.0.

ESTIMATION PRECISION The estimation precision is defined as the ratio of correctly estimated clusters out of the set of estimated clusters. Similarly, a precision value of or close to 1.0 is optimal.

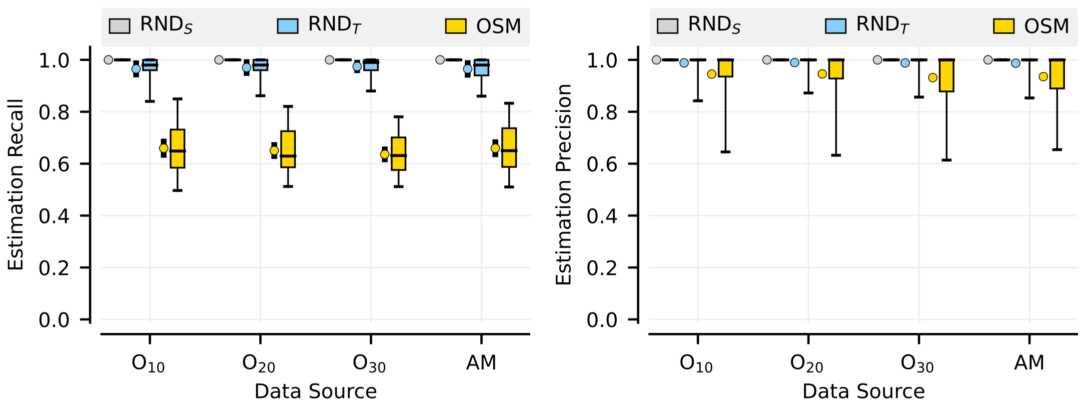
ESTIMATION COVERAGE METRICS In addition to the sole estimation of clusters, we also measure the estimations' coverage compared to the actual clusters. Specifically, we provide three coverage metrics: *(i)* the cluster area that is covered by an estimation, *(ii)* the area that is incorrectly estimated to be within a cluster, and *(iii)* the nodes within a cluster that are covered by an estimation (at the time of the estimation).

6.3.2 *Impact of Data Source and Update Intervals on the Estimation*

The first step of our evaluation compares the aerial monitoring system against the oracle with different information update intervals as data sources. By that, we evaluate whether the designed cluster estimation is susceptible to the available data sources and update intervals of information. Within this section, we use a cell size of 100 m for the comparability of data sources and intervals. In contrast, the impact of different cell sizes is evaluated separately in the subsequent section.

Figure 6.12 visualizes the estimation recall and precision for the different oracle systems and the aerial monitoring, respectively. In general, we perceive only small variations between data sources but a much larger impact of node mobility on the overall performance. Especially the OSM mobility provides a challenging environment with an average estimation recall between 0.6 and 0.7, while the average estimation precision is better with more than 90%. Cluster estimation with RND_T mobility performs much better with nearly ideal recall and precision; the best estimation

Mobility impacts estimation



(a) Recall. (b) Precision.

Figure 6.12: The estimation performance does not differ considerably for different data sources but is lower for more dynamic scenarios. Plots exemplary show the results for a cell size of 100 m.

performance is achieved with RND$_S$ mobility. From this initial assessment, we infer that our estimation approach is missing an estimation for entire areas more often than wrongly identifying mobile nodes as a cluster. However, the interval in which the oracles provide up-to-date information has only a minor impact on this feature.

Minor impact of oracle interval

The largest decline in performance was achieved with an interval of 30 minutes and the OSM mobility, most probably due to the slower adaptation to the changing areas as a result of the larger interval. Interestingly, the performance is worse for static areas with transit mobility (RND$_T$) at a shorter interval. This points out some fluctuations within the areas, negatively influencing their correct estimation. With a larger information update interval, the possibility of receiving information that depicts such a fluctuation is lower, and the estimation generally is more robust. Consequently, a less static scenario requires more adaptability and, thus, a smaller update interval, as supported by the results for the OSM mobility. More importantly, however, recall and precision for the aerial monitoring system — which has to collect the information by UAV and, therefore, provides it with a delay of up to 19 minutes — are comparable to that of the oracle systems, which provide the optimal locations instead. Thus, we use the more realistic and actively collecting AM data source as the standard for the remaining evaluation of the estimation performance with varying cell sizes.

Aerial monitoring system comparable to oracles

6.3.3 *Revising Cluster Estimation in Mobile Environments*

Before continuing with a thorough investigation of the cell size impact, we take a deeper look into the imperfect estimation recall for the environments with transit mobility. Naturally, the correct identification of existing clusters is extremely important for the realization of our aerial communication support system — much more important than the incorrect identification of clusters. The relatively low recall, however, must be attributed in large parts to the metrics for the estimation measurements,

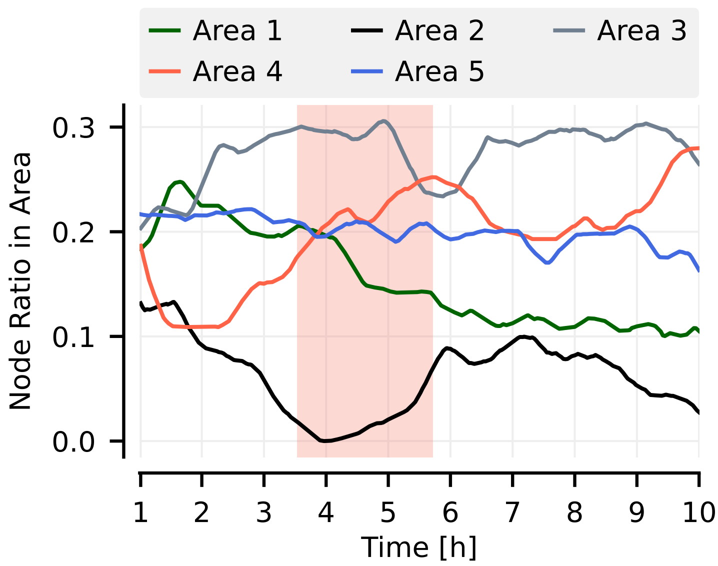


Figure 6.13: Detailed node distribution of one exemplary simulation run for five areas of interest using RND_T mobility and a cell size of 100 m. The red area marks the time frame in which Area 2 was not detected.

Problematic recall definition based on AoIs

especially for OSM mobility. To measure the estimation performance, we compare the actual areas of interest against the estimations. Incorrect estimations can be easily identified since they are located entirely outside of the simulated AoIs. Correct estimations, on the other hand, are denoted to overlap with an AoI. The transit mobility with RND_T, but even more so the changing, emerging, and dissolving AoIs in the OSM mobility, are, thus, problematic to some extent, as the actual areas of interest can be temporarily populated only sparsely or not at all. Such a phenomenon is visualized in Figure 6.13 for one exemplary distribution of five areas with RND_T mobility. The graphs show the ratio of simulated nodes currently within each area over time. The red area marks the time frame of approximately two hours, where Area 2 (black) is not estimated, while all other areas are estimated all the time. However, Area 2 is also sparsely populated within that time frame and is even empty at roughly four hours of simulation time. After more nodes are arriving in the area, it is again estimated as expected.

Empty AoIs cannot be detected

Therefore, the lack of an estimation within that time frame is actually correct and cannot be depicted sufficiently without initial recall measurements. To address this issue, we adjust the estimation recall metric by a direct comparison with the node ratio in each area. Whenever the node ratio undercuts a certain threshold, the lack of an estimation is counted as correct. In our case, we decided on a ratio of < 0.03 as the threshold. This results in a clipping below ten nodes within an area, approximating the same functionality as the implemented high-pass filter for the initial cluster detection. The adjusted estimation recall is given in Figure 6.14, showing an apparent increase in performance compared to Figure 6.12a. Now, most areas are correctly estimated for the whole time of their presence with an average recall value on or close to 1.0, independent of the data source, and only minor fluctuations down

Adjust recall metric to incorporate node density

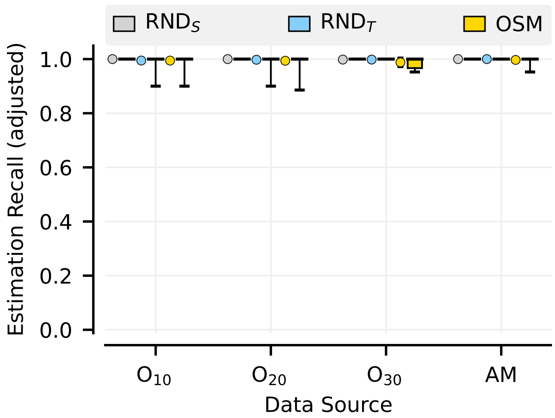


Figure 6.14: The adjusted estimation recall incorporates the lack of nodes within an area. Plot exemplary shows the results for a cell size of 100 m.

to an approximate 0.85 recall. Additionally, the AM data source provides the overall best performance with small deviations. This small difference to the other data sources, however, could be just coincidental and not generally representative. Due to the temporal displacement between information collection and processing using the aerial monitoring system, an already estimated cluster could remain estimated until the next monitoring UAV traverses the area and has returned home. The oracles, on the other hand, provide current information without delay, which seems to have a minor disadvantage. The adjusted estimation recall is utilized for the remainder of this evaluation.

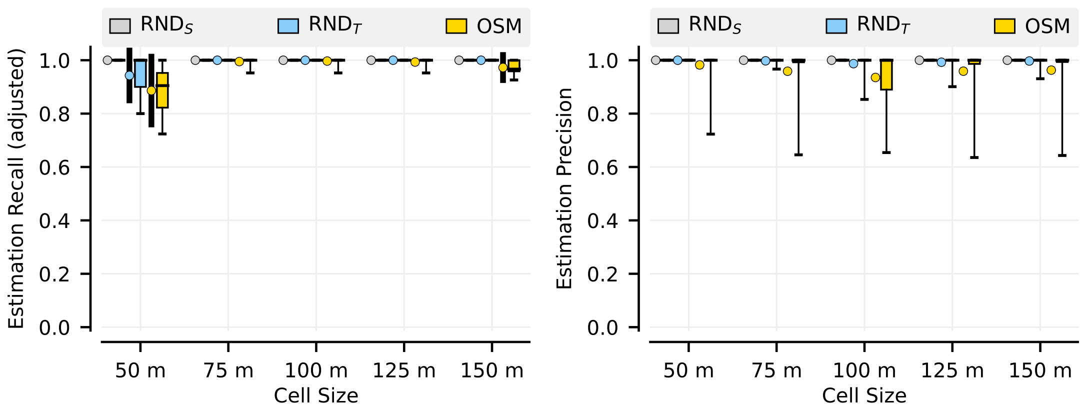
Correct estimation of empty AoIs

6.3.4 *Impact of Cell Size*

One of the most influential aspects of our approach is the choice of cell size. This defines the extent of our gridmap and the estimation kernel, which eventually also determines the size of possible cluster estimations. Thus, we need to investigate the impact of the cell size on the estimation performance. All results shown use aerial monitoring (AM) as data source.

First, we assess the cluster estimation recall and precision for the different cell sizes, depicted in Figure 6.15. For the recall, we see that nearly all clusters are correctly identified for cells of 75 m, 100 m, and 125 m; only the OSM mobility scenario provides non-optimal results. For 50 m, however, larger drops are observed for RND$_T$ and especially OSM mobility with 80% and 70% correct cluster estimations in the worst case, respectively. Apparently, large clusters spread over many cells, especially if cells are small. This leads to a dispersion of node measurements, which hampers the detection of that cluster if too many cells are involved and the measured node density per cell is small as a result. The opposite, i.e., that clusters are too small to be detected with large cells, is observed for 150 m and OSM mobility. Therefore, the chosen cell size should be roughly within the size of the expected clusters size. Conversely, the precision provides partially worse results with mid-size cells, where the

Cell size should approximate cluster size



(a) Recall. (b) Precision.

Figure 6.15: Estimation recall and precision for different cell sizes.

Precision worse when recall better

lowest precision is achieved with 100 m. This indicates that this size is most favorable for the false identification of mobile nodes as clusters, probably as large groups in transit can increase node density in a cell over the applied high-pass filter threshold. For small cells, however, this is spread over multiple cells and attenuated by the smoothing process for large cells. Conclusively, the best cell size setting based on precision and recall cannot be clearly defined. In our case, the correct estimation of clusters is more important than the occasional wrongful identification of mobile groups as clusters, which suggests using a cell size between 75 m and 125 m, even despite the low precision for 100 m.

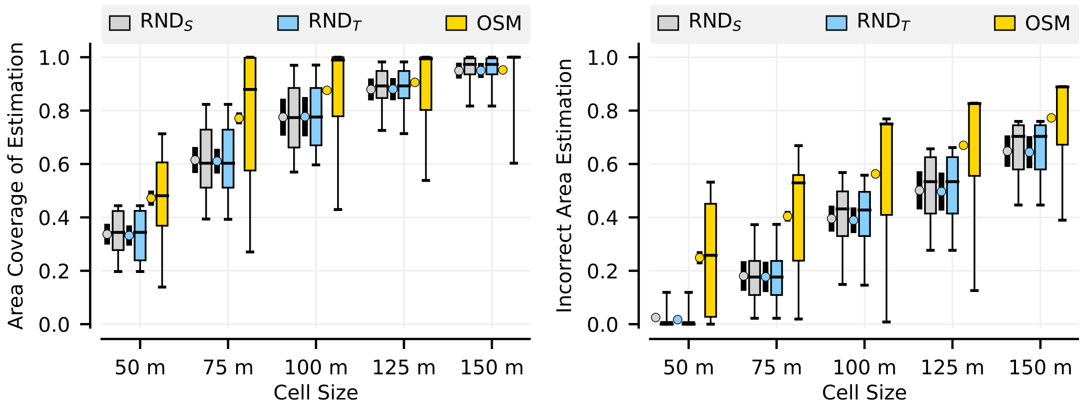
Area estimation

Larger cells increase correct...

...but also incorrect coverage.

Furthermore, the cell size also determines the estimation extent due to the adaptive kernel size. Thus, we investigate the spatial estimation performance by comparing the area overlap between our estimations and AoIs. Figure 6.16 visualizes the correct and incorrect area overlap of estimations, respectively. As expected, the area coverage increases with a larger cell size due to the similarly larger kernel. However, this also increases the possibility of incorrect estimations. Most prominently, this can be observed for OSM mobility. Since areas are generally smaller than for the RND mobility scenarios, larger estimations not only increase the probability of correct overlap of estimation and cluster, but also increase the incorrect overlap. This results in extreme cases in which the actual area is fully encompassed by the estimation but actually represents only a small fraction of that area. A cell size of 150 m naturally provides the largest estimation area and, therefore, also the largest overestimation, which results in half of all estimations overestimating the cluster size by a factor of ten (cf. Figure 6.16b). Clearly, larger cell sizes provide a very rough estimation that cannot accurately depict especially smaller clusters. We, therefore, recommend against using larger cell sizes despite the similarly better coverage of the actual areas.

As shown in Figure 6.16a, the estimations at 75 m or 100 m cell size could provide a reasonable tradeoff between the correct and incorrect area estimation. Similar to precision and recall, the eventual choice for the cell size depends on the targeted system performance. In our case, the actual estimation and overlap of our estimation with the areas of interest is only a subsidiary objective to provide stable estimations for



(a) Correct area estimation. (b) Incorrect area estimation.

Figure 6.16: Spatial estimation performance for different cell sizes.

a robust long-term deployment of our aerial communication support system. The primary objective, by contrast, seeks the preferably exhaustive coverage of actual DTN clusters by our estimations. Furthermore, nodes are not uniformly distributed within the areas of interest. Thus, node coverage does not necessarily correlate with area coverage. This issue is further investigated by comparing the estimations' node coverage with that of the actual areas of interest. As provided in Figure 6.17, larger cell sizes result in larger estimation areas and, thus, an increased coverage of nodes. Nevertheless, the estimation resembles the highly populated parts of areas better than the entire areas since the estimations' node coverage is significantly higher than their respective area coverage. This also holds for smaller cell sizes. For example, estimations for a cell size of 50 m in the RND environment cover only approximately 20% to 45% of the area but 45% to 95% of nodes. Thus, the estimation still performs considerably better than initially expected when considering only the correctly estimated area.

Area coverage ≠ node coverage

Higher coverage of nodes

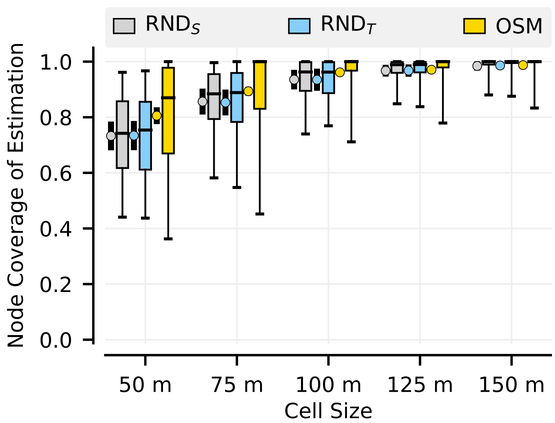


Figure 6.17: Node coverage of estimations using different cell sizes.

Successful cluster estimation

In conclusion, we achieved cluster estimation based on unstructured data — especially from an actively collecting aerial monitoring system. The important influence factors on the performance are the cell size and the mobility characteristics of the nodes. Expectedly, larger areas of interest are better detected using larger cell sizes and vice versa. Furthermore, a higher mobility and generally lower or varying concentration of nodes at one location, like for OSM mobility, constitutes a more challenging environment for cluster estimation. In our specific disaster scenario, a cell size of 100 m provides the overall best results considering estimation recall, area coverage, and especially node coverage. However, this comes with the drawback of reduced precision and larger incorrect area estimation. Using a cell size of 75 m could, thus, be a reasonable alternative with the tradeoff of a lower node coverage, depending on the aspired performance. The provided estimation of network clusters is the necessary prerequisite for deploying aerial communication support in the first place. Additionally, our approach is also capable of providing a current information state, In our specific disaster scenario, a cell size of 100 m provides the overall best results which is necessary for long-term deployment in an unstable and changing scenario. In this section, we specifically focused on using the information on the estimated clusters, which are our main focus points in the disaster scenario. Nevertheless, this also allows extracting mobility information from the same data, as discussed in Section 4.4, which we apply in the following section to increase the node coverage outside of areas of interest.

Choice of cell size with tradeoff

Facilitates long-term topology assessment

6.4 INCREASING TRANSIT NODE COVERAGE WITH ADAPTIVE TOPOLOGY-AWARE ROUTING

The most efficient flight path in terms of flight distance and duration for communication support UAVs, naturally, is a straight line between clusters that are to be connected. Nonetheless, the same is usually not possible for civilians in transit between areas of interest. Therefore, they are typically disconnected from the larger disaster DTN for the entire time of their transit if they are not coincidentally crossing the path of the UAVs. In this section, we assess our approach for *adaptive topology-aware routing* to increase the coverage of transit nodes, as proposed in Section 4.5.

Scenario setup

We utilize the same scenario as the previous section (cf. Table 6.4), but this time focus on the evaluation of aerial communication support instead of aerial monitoring. Thus, we deploy four monitoring UAVs with full area coverage and one communication support UAV. To reduce any influence of incorrect cluster estimation, communication UAVs traverse the actual network clusters provided by an oracle. Nevertheless, topology data is provided by the aerial monitoring system, and node mobility in the disaster area is identified using the cluster estimation approach, as discussed in Section 4.4. The gridmap for the estimation and our route calculations uses a fixed cell size of 100 m. Since transit nodes are missing for the RND_S mobility, only RND_T and OSM mobility settings are used. As discussed in Section 4.5, the scaling factor f balances the increase between node coverage and route length; thus,

Scaling factor

a higher f allows longer routes to increase node coverage. The scaling factor f is used as 0.0 (direct flight baseline), 0.5, 1.0, 1.5, and 2.0, respectively.

Scenario metrics

For this evaluation, we introduce two additional metrics to assess the influence of our approach with varying scaling factors:

ROUTE LENGTH The route length determines the distance covered by a communication UAV, measured for each flight from the start at the base station until its return.

TRANSIT NODE COVERAGE Transit node coverage is measured per each flight of the communication UAV. Transit nodes are not connected to any network cluster in an area of interest and, as determined by the mobility model, are also in an active transit state. Coverage is determined by at least a single beacon or message exchange between a transit node and communication UAV.

Route Length

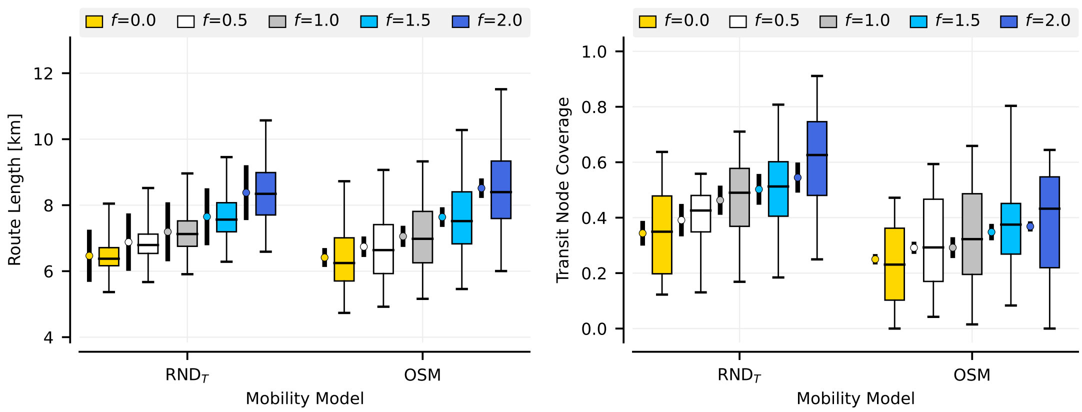
Longer routes with higher scaling factor

Initially, we assess the impact of the used scaling factor on the route length. The resulting lengths of communication support routes are depicted in Figure 6.18a. In general, we observe the expected length increase with higher scaling factors. Nonetheless, route calculation between areas of interest and their adaptation for transit node coverage is highly dependent on the found topology information. Therefore, OSM route lengths spread over a wider range than RND_T due to the more dynamic scenario with changing numbers of areas and high mobility in-between. The standard deviation, on the other hand, is stable across all simulations for OSM, while considerably larger for RND_T since AoIs are placed differently for each seed. The overall spread of route lengths for each set of parameters must be attributed to a lower number of estimated areas in case of shorter routes and an overestimation or misinterpretation of mobility as a network cluster in case of longer routes, respectively. The longest route is observed for $f = 2.0$ with OSM mobility, resulting in a route length of 11.51 km. Although this route did not exceed the maximum flight range of 12 km for the applied UAVs in our case, the remaining margin of less than 500 meters is relatively small. Thus, the extent of the route adaptations must be regarded carefully with respect to the available flight capacity — especially when factoring in additional environmental factors like temperature or wind that can influence the flight range of a UAV in situ.

Transit Node Coverage

Better transit coverage achievable, ...

The most important aspect of our approach, however, is the coverage of transit nodes. Figure 6.18b visualizes the increase of transit node coverage with a larger scaling factor. Therefore, we conclude that our approach, in general, works as intended. Nevertheless, the increase in coverage is not as unambiguous as the increase in the route length is. The results show several occurrences of a deterioration instead of an advance, for example, a reduction of the fourth quartile for RND_T and $f = 0.5$ or the



(a) Route length.

(b) Transit node coverage.

Figure 6.18: Route length and transit node coverage generally increase with a larger scaling factor.

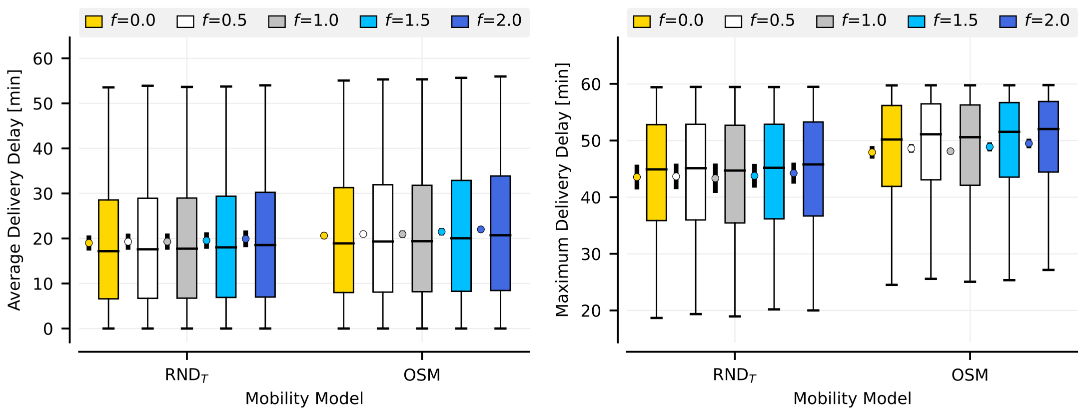
third quartile for OSM and $f = 1.5$. The latter case, however, also perceives an increase in the fourth and second quartile compared to the shorter route. Especially for the dynamic OSM scenario, this highlights the considerable influence of the node mobility and a coincidental overlap of estimated and actual transit routes. We assume this also influences the overall better transit node coverage for RND_T with fewer and more aligned routes than the several complex routes with OSM mobility. Despite an average increase of the resulting coverage, this still results sometimes in a very low transit node coverage. In the case of $f = 2.0$, the coverage in the 2.5th percentile even reaches 0.0, similar to the direct approach. This again shows the influence of node mobility and demonstrates that the longer route not necessarily provides more transit node coverage than a shorter route, only that it is more likely.

...but high influence of mobility.

Communication Performance

The question remains whether the increase in the route length and the higher transit node coverage results in differences for the overall communication network. For that, we first assess a possible impact on the delivery delay, which we expect to generally increase due to the higher time requirements for flights between network clusters. Figure 6.19a depicts the average delivery delay compared to the maximum delivery delay in Figure 6.19b. Although an increase is apparent for both metrics with a larger scaling factor, it is only within the range of a few minutes and comparable with the expected increase in flight time with an increased route length. The overall largest difference is perceivable between the different mobility models, with OSM having a considerably larger average and, more so, a larger maximum delay than RND_T as a result of the increased node mobility and number of AoIs. In conclusion, the increased route lengths do not considerably deteriorate the delivery delay for messages, neither for the average nor the maximum delay. In some cases the increased transit node coverage even results in slightly shorter maximum delivery delays, due to an earlier message delivery to them.

Slight increase of delivery delay with longer routes



(a) Average delivery delay.

(b) Maximum delivery delay.

Figure 6.19: Delivery delay with increasing route length. Only a slight increase is observed.

Message spread

Nevertheless, longer routes result in less time for message spread, which the delivery delay cannot easily depicted since only successful receptions can be measured. On the other hand, these longer routes also increase the transit node coverage and could, thus, increase message spread nonetheless. To assess the message spread in the DTN and the influence of the scaling factors in more detail, Figure 6.20 depicts the recall distribution of all messages over their lifetime (TTL) for one representative seed using RND$_T$ mobility. Most clearly, no considerable differences can be observed for all scaling factors from the first (Q1) to the fourth quartile (Q4). In some instances, longer routes provide an increased recall compared to the baseline $f = 0.0$ at that time, such with Q1 around 20 minutes lifetime, while it is reduced in other cases, such as after 30 minutes at the same quartile. Eventually, Q1 and Q2 provide the same recall values after approximately the same time. For Q3 and Q4, however, a recall of 1.0 was reached between approximately one and five minutes faster for enlarged routes compared to the baseline. Thus, increasing transit node coverage can provide faster dissemination for a fraction of messages, despite the end result being the same. The overall differences, though, are marginal, probably due to the relatively small amount of receiving transit nodes compared to the majority of nodes in the connected network clusters.

No considerable difference for Q1 to Q4

Increased performance in Q0

This feature, however, changes for the messages with the worst spread shown by Q0, presumably due to the higher share of transit nodes as recipients. Here, we observe a clear distinction between $f = 0.0$ and $f = 2.0$ on the one hand, and $f = 0.5$, $f = 1.0$, and $f = 1.5$, on the other. The former two result in roughly the same relatively low recall, albeit the direct route with around 50% actually provides a 3% better recall than the longest route with $f = 2.0$. Clearly, the longer route does not necessarily provide a better recall. The latter group, however, results in a considerably larger recall of more than 80%. Furthermore, recall in Q0 increases heavily only after 35 minutes; before that, messages are not widely disseminated. Compared to $f = 1.0$ and $f = 1.5$, $f = 0.5$ is a few minutes faster, but provides a similar end recall. We attribute the late increase in recall to two features. First, messages that are created on transit nodes are carried around a long time before reaching other nodes or

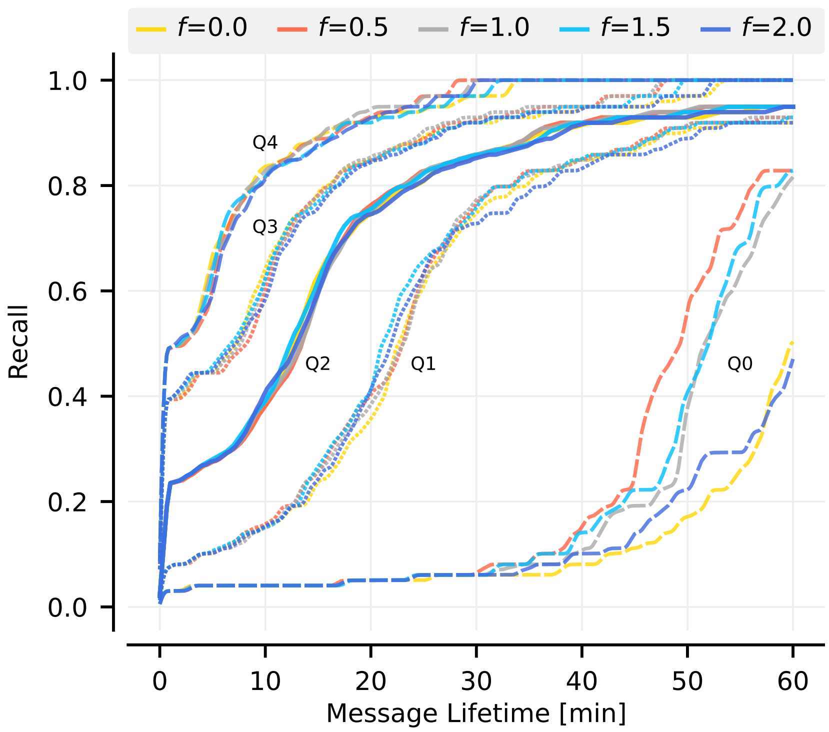


Figure 6.20: Distribution of message recall over their lifetime. Annotations mark the representing quartiles.

larger network clusters. A higher transit node coverage increases the probability that communication support UAVs can collect such messages and spread them further on the next approached network clusters. Second, a higher transit coverage also allows UAVs to distribute messages to nodes crossing their paths, which are on route to a different cluster than the UAV. This allows a delayed delivery to that cluster, in case of nodes arriving earlier than the UAV and the expiration of the TTL. Still, this large increase is only perceivable for the lowest quartile, suggesting message delivery via DTN nodes to play only a minor role compared to the more impactful aerial communication support.

Better connectivity of transit nodes

In conclusion, transit node coverage was increased with adaptive topology-aware routing using mobility estimations of nodes. On the example of the RND_T mobility scenario, between the direct flight and the adapted routes with $f = 2.0$, the median route length was increased by 31.5%, from 6.4 to 8.4 km. At the same time, transit node coverage was significantly increased by 85.3% compared to the direct flight baseline, which is state-of-the-art (cf. Section 3.2). Our approach for adaptive topology-aware routing, therefore, achieves increased connectivity and message spread to otherwise disconnected DTN nodes. This is especially important for the distribution of impactful and possibly life-saving messages like hazard warnings or evacuation notices. Similar improvements were observed with the OSM mobility, despite a larger influence of the dynamic mobility on the overall communication

Significant increase in transit node coverage achieved performance, leading to a larger variation in the resulting routes and coverage measurements. With the different scaling factors, a tradeoff between coverage and delay must be considered. Naturally, the prolonging of routes results in a slower distribution for a large fraction of all DTN nodes for most messages while covering possibly only a few more nodes. Nevertheless, we showed that the increase in the average and maximum delay is small compared to the possible increase in transit node coverage. However, different scaling factors provide different route lengths. In our case, routes did not exceed the maximum flight range of UAVs despite a relatively small margin in some cases — but this highlights that adaptations must always be regarded with care. Thus, route adaptation should only be used with available flight capacity and dissemination time left. Overall, our adaptive topology-aware transit node coverage approach constitutes a valuable addition to aerial communication support whenever mobility data like preferred or more likely routes of nodes are available, facilitating a significant increase in transit node coverage with reasonable expenses.

Tradeoff with scaling factor

UAV flight range must allow longer routes

6.5 coexistence of monitoring and communication mechanisms on uavs

Different variants of coexistence for monitoring and communication support in the UAS were discussed in Section 4.2.3. Throughout this thesis, we applied a split approach with dedicated strategies and UAVs for either monitoring or communication support appliances, respectively. However, we also discussed the possibility of secondary, concurrent mechanisms on UAVs, such as communication support running in the background of a monitoring UAV and vice versa. This section, therefore, specifically assesses the coexistence of monitoring and communication support mechanisms on the same UAVs instead of a clear separation of monitoring and communication UAVs that was used until now.

Scenario setup

The evaluation scenario is similar to before, with four monitoring UAVs traversing a full coverage monitoring path in each of the $1\,\text{km}^2$ areas and a single communication support UAV, sequentially approaching all areas of interest. To rule out cross-influences, we utilize an oracle to provide the exact network cluster locations from the simulator, and a straight flight line is used between the AoI centers. Each simulation run is repeated with one of three settings for the UAS: *(i) Monitoring* only deploys the four monitoring UAVs with DTN communication running in the background, *(ii) Ferry* only deploys the communication support UAV to ferry messages between AoIs with the monitoring mechanism running in the background, and *(iii) Coexistence* executes both strategies with their respective UAVs in parallel and the background mechanisms included. Each setting is assessed with both RND_T and OSM mobility.

Strategy and mechanism combinations

Monitoring performance

We start the evaluation with regard to the influence of the coexistent application on the monitoring performance. Naturally, a long-term application of monitoring UAVs aims at providing up-to-date information on all nodes for the aerial system. As a result of the chosen monitoring path with full area coverage — similar to the evaluation performed in Section 6.2 —, full node coverage is achieved for *Monitoring*

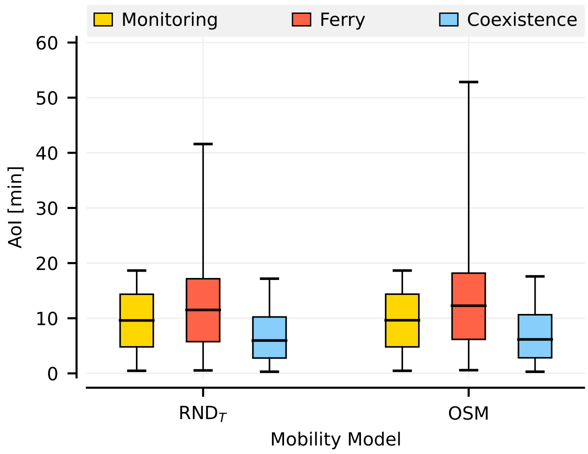


Figure 6.21: Age of monitoring information on base station.

Varying node coverage for Ferry

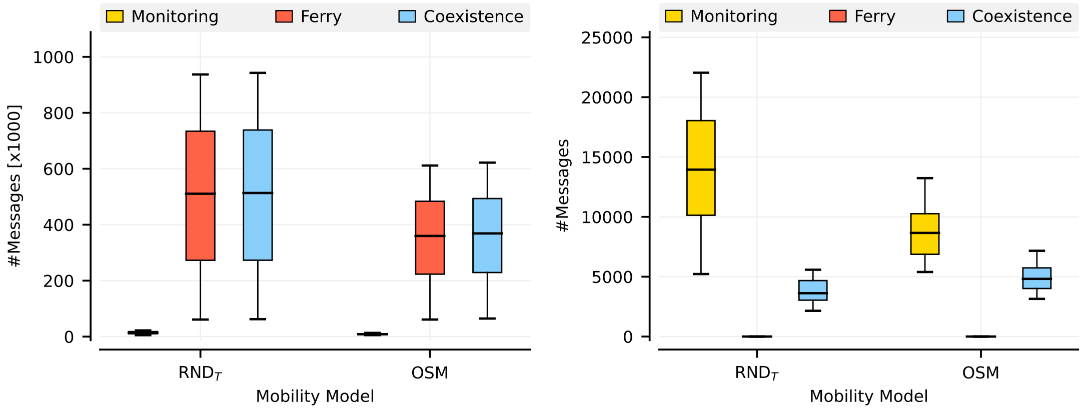
and *Coexistence* with the monitoring UAVs. For *Ferry*, however, the share of network nodes seen in each ferry flight differs significantly: Between 58% and 91% of nodes are encountered in the RND_T mobility scenario, less in OSM mobility with 46% to 85% of nodes. Nevertheless, the ferry UAV encounters at least 95% of nodes within the first 120 minutes of deployment, which highlights the high concentration and mobility of nodes in the areas of interest.

Lower information age with Coexistence

The important metric for the monitoring application is the Age-of-Information within the system, depicted in Figure 6.21. *Monitoring* and *Coexistence* provide a very similar Age-of-Information with both RND_T and OSM mobility, only with minor increases in the age for OSM. The direct comparison, however, shows that the average Age-of-Information decreases for *Coexistence* by three to four minutes, which discloses a positive impact of monitoring data collection on the ferry UAV. But as expected for *Ferry* without monitoring UAVs, a large portion of the available information at the base becomes considerably older as many nodes are not encountered during each ferry traversal. This factor could be reduced by utilizing the cooperative monitoring approach, presented in Section 4.3, but is not within the scope of this evaluation. Furthermore, we observe a larger fourth quartile with OSM mobility due to the typically longer routes with the more complex scenario. In conclusion, coexistent monitoring on data ferry UAVs can be beneficial by providing more recent information than monitoring alone. Especially in the considered case, passive monitoring comes with no additional communication effort. As it requires only more computational resources on the UAVs, this constitutes an inexpensive and straightforward addition to any aerial network assistance system.

Communication performance

Next, we assess coexistence with regard to communication support and specifically focus on the impact of monitoring UAVs on message dissemination. As discussed in Section 4.2.3, we expect a rather small advantage due to the relatively long traversal time of monitoring routes and only sporadic message exchanges between UAVs to spread into other monitoring areas. At first, we contemplate the number of messages delivered by UAVs, as visualized in Figure 6.22. Figure 6.22a provides data for all UAVs, while Figure 6.22b specifically only counts messages delivered by monitoring



(a) Messages delivered to the DTN.

(b) Messages delivered to the DTN by monitoring UAVs only.

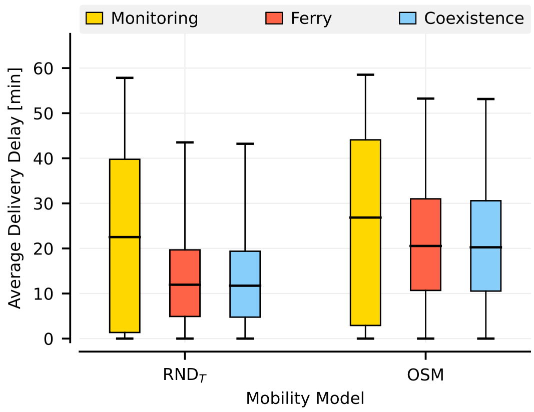
Figure 6.22: Message dissemination of coexistent applications.

UAVs. For several reasons, *Monitoring* results in tremendously less message deliveries than *Ferry* and *Coexistence*. For once, larger clusters can be encountered several times by monitoring UAVs (cf. Section 6.2.3); therefore, messages are already known and no exchange is happening. Furthermore, messages spread poorly between monitoring areas, shown later on, which also reduces the number of messages that are actually able to be delivered by the monitoring UAVs. Additionally, communication support UAVs hover over areas of interest for a short time. Then, they actively forward and disseminate newly created and unknown messages to all nodes in range, considerably increasing the number of deliveries counted at the UAVs. The limitation to only monitoring UAVs in Figure 6.22b also highlights the small fraction of *Coexistence* message deliveries by monitoring UAVs, compared to the large number shown in Figure 6.22a. Comparing RND_T and OSM, *Monitoring* has fewer message deliveries in the OSM scenario, while more messages are delivered with the *Coexistence* approach. Apparently, monitoring UAVs generally have fewer contacts and, thus, fewer message deliveries with nodes due to their higher mobility. On the other hand, the increased mobility also seems to reduce the efficiency of data ferry UAVs, which provides more opportunities for monitoring UAVs to deliver messages in the OSM scenario. Nevertheless, message deliveries by monitoring UAVs still contribute less than 1.5% to the overall deliveries (cf. Figure 6.22a), and, up to this point, it is unclear whether they contribute to the message spread or provide only a slightly faster delivery.

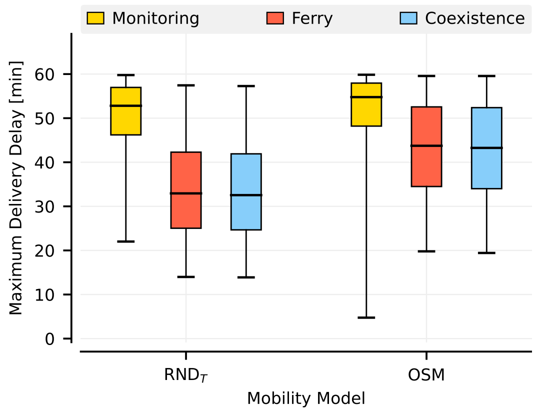
Minimal message deliveries by monitoring UAVs

Minor impact of monitoring UAVs

Therefore, we now consider the delivery delay of messages as shown by Figure 6.23. As expected, due to the different mobility, delays for RND_T are lower than for OSM. Furthermore, there are only slight differences between *Ferry* and *Coexistence* as a result of the quite small contribution of the monitoring UAVs on message deliveries. For *Monitoring*, however, delivery delays are significantly worse than for the rest. The large spread of the delivery delay, especially the averages as shown in Figure 6.23a, demonstrate a very slow spread of some messages on the one hand and no spread at all for other messages beyond the local network cluster on the



(a) Average delivery delay.



(b) Maximum delivery delay.

Figure 6.23: Delivery delay of coexistent applications.

other hand. Although mobility influences performance with *Monitoring* less due to the static monitoring path with full area coverage, provisioning communication support solely by monitoring UAVs should only be done with no resources left available for dedicated communication support.

Similar results are observable for the recall in general, as shown in Figure 6.24a, and the message spread over time given in Figure 6.24b, respectively. Especially for the OSM mobility scenario, 50% of messages do not reach more than 49% of recipients, despite that the highest achieved recall is 96% for *Monitoring*. The message spread clearly visualizes the tedious and only gradual dissemination of messages, which stands in stark contrast to the ferry-based dissemination. For *Ferry*, most messages are distributed to the majority of nodes, despite remaining room for improvement, especially for OSM mobility. However, as exemplarily shown in Figure 6.20, this issue could be mitigated with route adaptations for increased transit node coverage. In our case, the coexistent communication support on monitoring UAVs does only provide minimal advantages to a pure *Ferry* application. For both mobility models, the 2.5th percentile is increased by only 1% from 0.92 to 0.93 in RND_T, and 0.5 to 0.51 in OSM, respectively. Overall, recall and message spread are in accordance with our earlier results showing a slightly better and slightly faster message distribution.

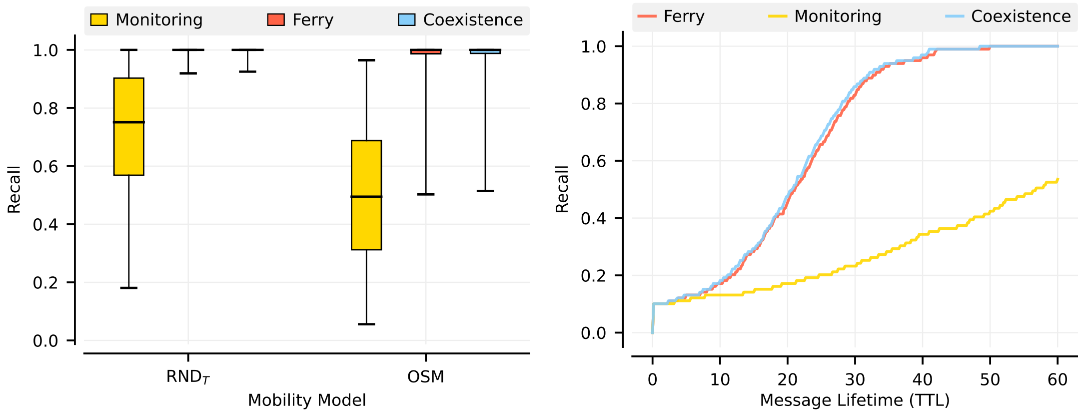
Insufficient message spread via monitoring UAVs

1% increased recall with Coexistence

In conclusion, the coexistence of monitoring and communication support as respective secondary functionality on the deployed UAVs can be beneficial, even though minimal in its impact, which confirms our earlier assumptions. Nonetheless, every slight increase in performance may be helpful for the considered disaster scenario, specifically in the case of extremely important messages like hazard warnings or evacuation notices with significant implications for the affected population. In general, it is clear that the deployed UAVs perform strategies that were specifically designed to either monitor areas or ferry messages between clusters. The low impact is, therefore, likely a result of a misaligned strategy with the applied mechanism. Performance could be significantly higher in strategies that purposefully combine both objectives directly in a single implementation. Nevertheless, the results highlight

Mechanism coexistence with minimal benefits

Strategies not designed for joint application



(a) Recall. (b) Message spread for OSM mobility.

Figure 6.24: Recall and message spread over TTL.

that UAV strategies tailored to a single specific application or target can generally be expected to perform better than multi-objective strategies. Similar features were highlighted in previously published material [312].

In this evaluation, we demonstrated and evaluated the proposed and implemented system design of our Aerial Network Assistance System, providing coexistent aerial topology monitoring and communication support. In particular, we assessed our three contributions to the collection, processing, and utilization of topology information in the aerial system, respectively. These contributions enable the system to *(i)* increase the initial node detection and the overall monitoring performance by *Cooperative Aerial-Ground Monitoring* (CAMON), *(ii)* reliably estimate network clusters based on topology information and constantly adapt the deployed mechanisms to a dynamic disaster environment, and *(iii)* increase the coverage of transit nodes with *adaptive topology-aware routing* for data ferry UAVs. The results are summarized and discussed together with the conclusion of this thesis in the following chapter.

7 SUMMARY, CONCLUSIONS, AND OUTLOOK

Aerial network assistance systems are a key enabler for the effective usage of infrastructure-independent communication systems in dynamic disaster areas by utilizing Unmanned Aerial Vehicles (UAVs) as relays or data carriers between otherwise disconnected parts of the communication network. In this chapter, we summarize the content of this thesis and the main contributions to the application and simulation of aerial network assistance systems. Furthermore, we discuss the obtained results and conclude this thesis with an overview of open scientific questions and potential future work.

7.1 SUMMARY OF THE THESIS

In Chapter 1, we described the challenges of intermittent infrastructure-independent networks, like Delay-Tolerant Networks (DTNs), in post-disaster scenarios and motivated the application of UAVs to support communication between disconnected network parts. Furthermore, we highlighted the challenges for such an aerial system that emerge with the disaster scenario. Chapter 2 provides background information on smartphone-based DTNs to provide infrastructure-independent communication services for disaster relief and an example of a real-world application. Unmanned Aircraft Systems (UAS) and UAVs were studied in Chapter 3. We discussed mechanisms for UAV-based communication support and topology monitoring, respectively, and highlighted their often-neglected affiliation. Specifically, we discussed the necessity of communication support to constantly adapt to the changing network topology in a disaster and the necessity of aerial monitoring to provide the required information. In conclusion, an aerial system for communication support of infrastructure-independent networks in post-disaster scenarios needs to combine both mechanisms to address the identified issues. Therefore, we defined three research goals that were addressed in this thesis: *(RG1)* coexistent topology monitoring and communication support for post-disaster networks, *(RG2)* adaptability of the aerial system to dynamic disaster network topologies, and *(RG3)* evaluation of aerial systems, their strategies, and mechanisms. We summarize the contributions that cover the individual research goals and the results of this thesis in the following.

Contributions

Chapter 4 initially analyzed disaster scenarios and identified requirements for the application of UAV-based aerial monitoring and communication support. Based on this analysis, we combined network monitoring with communication support mechanisms into a single *Aerial Network Assistance System* for post-disaster DTNs, addressing our *first research goal*. The coexistent execution of the respective individual strategies in the same system allows utilizing a wide variety of existing or upcoming strategies and studying potential inter-dependencies. In contrast to existing work with separate mechanisms, the coexistent design specifically facilitates the direct usage of information gained by the monitoring application to adapt the communication support application, which is required to achieve the necessary adaptability of the aerial system to the constantly changing disaster environment. Furthermore, we successfully addressed specific issues in a combined Aerial Network Assistance System. *(i)* With *Cooperative Aerial-Ground Monitoring* (CAMON), we achieved a partial decoupling of area coverage and node coverage, enabling a faster and more frequent monitoring area traversal without considerable drawbacks to the monitoring results. *(ii)* We facilitated the estimation of network clusters and constant assessment of the present topology on unstructured monitoring information, which is necessary for the long-term deployment of the aerial system and its adaptability to topology changes. *(iii)* Lastly, we proposed *adaptive topology-aware routing* of data ferry UAVs by incorporating topology data to increase the coverage and connectivity of transit nodes between areas of interest. These contributions cover our *second research goal*.

We generalized our system architecture in Chapter 5 by integrating it into the Simonstrator.kom evaluation platform. Common strategies for aerial monitoring and communication support were added as well as our proposed contributions to different parts of the aerial system. To increase the expressiveness of simulations, we additionally contributed two different models. First, we identified the flight characteristics and energy consumption of a real-world multicopter and used the results to design a thrust-based movement model for multicopter UAVs. Second, we analyzed human mobility trace data from a field test to create a civilian disaster mobility model. The resulting evaluation platform for Unmanned Aircraft Systems — this thesis's contribution to address our *third research goal* — establishes the necessary foundation for the evaluation of our Aerial Network Assistance System in Chapter 6.

Conclusions

Aerial Network Assistance Systems, combining UAV-based topology monitoring and communication support mechanisms in a single UAS, are a necessary step towards the autonomous and adaptive aerial support of civilian disaster communication networks. The availability of information is a prerequisite for deploying communication support UAVs in the first place, which clearly requires the involvement of its acquisition in the process. In our extensive simulation-based evaluation, we showcased that our system design successfully addresses the identified challenges for applying aerial systems in different post-disaster scenarios. The Aerial Network Assistance System can identify and monitor the network topology autonomously while simultaneously deploying and adapting aerial communication support according to the present situation based on the obtained information.

Furthermore, we evaluated our contributions to the collection, processing, and utilization of topology information. In Section 6.2, we showed that *Cooperative Aerial-Ground Monitoring* (CAMON) allows the decoupling of area and node coverage. Thus, our approach increases the initial detection performance and the monitoring traversal frequency despite reducing the overall area coverage for monitoring UAVs. The results demonstrate the positive impact of cooperative behavior on information collection and motivate its application despite the increased communication overhead. Additionally, we demonstrated the applicability of the proposed topology information processing approach in Section 6.3. It facilitates the identification of DTN clusters based on error-prone and imprecise information and allows identifying and reacting to changes in the network topology over time, which is the main enabler for an adaptive and efficient long-term deployment of aerial communication support. Furthermore, Section 6.4 evaluated our adaptive routing approach for data ferry UAVs. We highlighted that utilizing available topology information increases the coverage of transit nodes that were otherwise disconnected from the network. With relatively small adaptations of data ferry routes and acceptable costs for the majority of nodes in the network, *adaptive topology-aware routing* provides a significant increase in transit node coverage. Finally, in Section 6.5, the evaluation of coexistent mechanisms on UAVs showed the necessity for application-specific strategy designs. If the applied strategies are not properly aligned to the utilized communication or monitoring mechanisms on UAVs, respectively, the system performance will be low. Nevertheless, concurrently executed mechanisms on UAVs can still provide a small benefit to the overall performance.

7.2 OUTLOOK

The results presented in this thesis provide the foundation for further research in Aerial Network Assistance Systems. The evaluation platform constitutes the ability to model and simulate a variety of aerial system applications and their interaction with possibly different communication networks. In this thesis, we utilized typical monitoring and communication support strategies and contributed to the collection, processing, and utilization of topology information. In the future, the platform could be further extended with existing or newly created approaches, strategies, or mechanisms to assess and identify their impact on monitoring or communication support of infrastructure-independent communication networks.

Especially in the field of aerial monitoring and its adaptive and situation-aware application, there is a considerable number of open issues. Section A.4 highlights some problems and ideas for solutions from previously published material [316], which we want to track further in future work. Briefly summarized, monitoring could be considerably improved by adapting monitoring routes or monitoring areas based on available topology data, or by contemplating the coexistently covered area by communication support to adapt monitoring areas appropriately [246]. Particularly the last approach is made possible by the proposed Aerial Network Assistance System.

The provided implementation of the UAV movement only considers multicopter types and the respective propulsion model for the Intel Aero RTF drone. Future work should encompass the inclusion of fixed-wing and hybrid movement models, which are then backed by different models for real-world flight behavior and power consumption, to evaluate systems and approaches with a wide variety of different UAVs. Furthermore, we simplified the autonomous flight of UAVs and did not incorporate properties like near-field object detection, collision avoidance, or close-proximity joint maneuver coordination between UAVs. In reality, however, these features are critical parts of any autonomous deployment [39].

This thesis focuses on a centralized system approach with minimal individual decisive power on UAVs. A partial strategy decentralization, however, could greatly improve the system's adaptivity to changes in the disaster environment by allowing UAVs to independently assess information and react to it. This could include the adaptation of monitoring routes to localized topology changes or re-routing of data ferries based on received messages [170, 177, 191]. A jointly used data channel between all UAVs and the base station could also facilitate better adaptivity. Nevertheless, it needs to be assessed which capacity would be required for such a channel, in which way data may need to be aggregated, and what the probable influence of an imperfect communication channel would be [40].

The recent disaster events, for example, in Puerto Rico and the Ahrthal in Germany, highlight the vulnerability of infrastructure-dependent communication systems. Despite the clearly visible necessity for infrastructure-independent systems like DTNs, as applied and supported by our aerial system in this thesis, as well as their practical applicability, shown in the Smarter field test [15, 166], there still exists no viable, publicly available smartphone application which provides the necessary functionality. Nevertheless, such an application would be of tremendous value in the case of a disaster and should be available on every smartphone by default. This could also be accompanied by a standardization of DTN communication between every smartphone, which could be further applied for a vast number of disaster- and non-disaster-related applications as well [123, 124, 235, 238, 273].

The proposed Aerial Network Assistance Systems and the provided contributions to the adaptive collection, processing, and utilization of topology information in this thesis constitute the foundation for further research in the field of aerial systems, aerial topology detection and monitoring, and aerial communication support. Furthermore, we provide our evaluation platform to other researchers to facilitate future developments of concepts, mechanisms, and aerial system applications and their assessment in a simulation environment.

ACKNOWLEDGMENTS

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A
APPENDIX

A.1 OSM: DISASTER-RELATED AREAS WITH TRANSIT MOBILITY

The evaluations performed in Chapter 6 use different distributions for Areas of Interest (AoIs) to depict different scenarios. Besides the RND scenario with five randomly placed AoIs, we utilize the OSM scenario to depict a more dynamic, more distributed, and less stable scenario than RND provides. The OSM scenario utilizes a total of 14 disaster-related locations taken from OpenStreetMap (OSM) data — hence the name. Six locations are active throughout the entire simulation and nodes are placed therein at the beginning of the simulation. The rest of the location are only temporarily active, thus, they have a limited lifetime in which simulated nodes will approach and roam these areas. Active times are chosen arbitrarily to induce mobility and achieve a varying distribution of nodes over the areas of interest.

Table A.1: Areas of interest for the OSM scenario.

Name	Type	Active Time
Shelter West	School	always
Shelter North	School	always
Shelter East	School	always
Shelter South	School	always
Herrngarten	Park	always
Elisabethenstift	Hospital	always
Alice Hospital	Hospital	5h – 10h
Klinikum	Hospital	2h – 7h
Resource Depot North	Supermarket	3h – 6h
Resource Depot South	Supermarket	5h – 7h
Resource Depot West	Supermarket	2h – 6h
Luisenplatz	Plaza	1h – 8h
Marktplatz	Plaza	1h – 2h; 6h – 8h
University	Plaza & Hall	3h – 7h

A.2 Cooperative Aerial Monitoring (CAMON): Additional Material

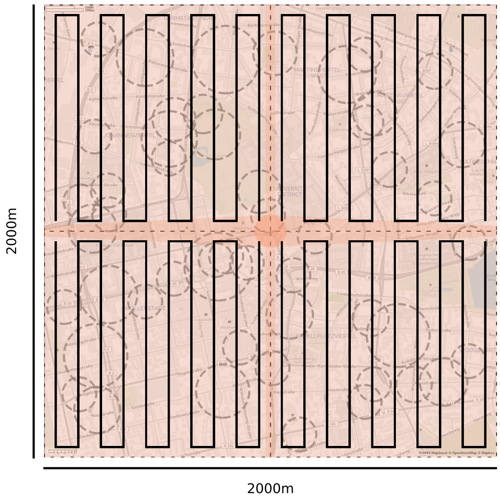
This section provides additional material and results from the evaluation of *Cooperative Aerial Monitoring* (*Cooperative Aerial-Ground Monitoring*). The utilized simulation and system parameters are the same as discussed in Section 6.2. In the following, we discuss the static monitoring routes for each scenario in more detail, give an extended view on the generated traffic with *Cooperative Aerial-Ground Monitoring*, and furthermore provide an in-depth analysis of the node detection performance of the respective *Cooperative Aerial-Ground Monitoring* protocols.

A.2.1 *Monitoring Areas*

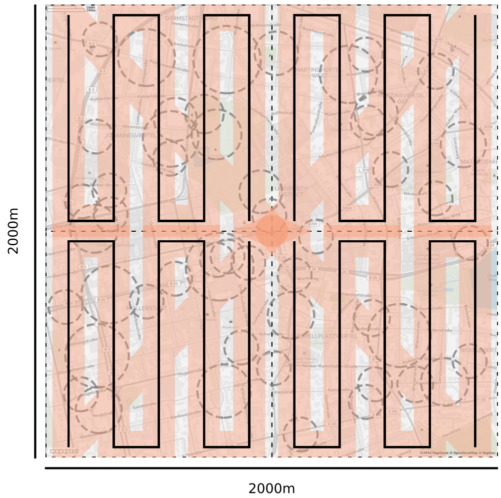
The utilized monitoring areas in our simulative evaluation are four square-shaped areas, each 1000x1000 m^2 in size. As discussed in Section 6.2.1, this size constitutes the upper boundary for an area that can be monitored with full area coverage, due to the limited flight time of the utilized UAVs. Within the evaluation, we adapt only the monitoring routes to facilitate a faster and more often traversal; the monitoring areas are static and not altered. Figure A.1 depicts the monitoring areas in the simulation with the monitoring routes as a result of the respective area coverage. Additionally, the colored surfaces denote the anticipated area coverage based on the actual UAV flight route.

Area coverage depends on the Wi-Fi model, as discussed in Section 6.1.3, which provides a theoretical maximum communication range of around 88 m, and the monitoring UAVs flight altitude, which is set to 30 m throughout this evaluation. The theoretical area coverage of a monitoring UAV, thus, can be approximated by a circular area with a radius of around 82 m. Nevertheless, we measured the maximum ranges when receiving DTN beacons between a moving UAV and DTN nodes within the simulator to usually be around 80 m, varying depending on the number of nodes in the vicinity. We attribute this attenuation to the utilized WiFi model from ns-3, that also incorporates properties like signal interferences between senders [122, 236] as well as the swift movement of UAVs. Therefore, we approximate the possible coverage to a radius of 75 m on the ground around the monitoring UAV. Simulation results for node coverage, however, are independent of this approximation and rely solely on the received beacon messages.

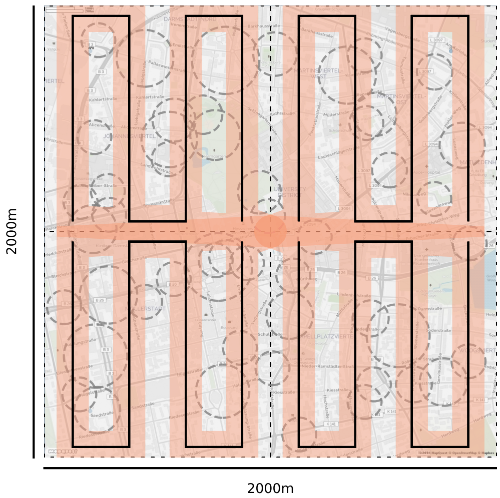
Figure A.1a shows full coverage of the area, including possible overlaps at common borders between monitoring areas, around the base station in the center, and at the return path of monitoring UAVs from the last route waypoint to the base station. Figure A.1b reveals that parts of each monitoring area are not covered. Due to the odd number of strips, the return path runs diagonally. Some overlap remains at the vertical border. The coverage is further decreased in Figure A.1c and Figure A.1d, again with some overlap at the vertical border mostly covered by the return path.



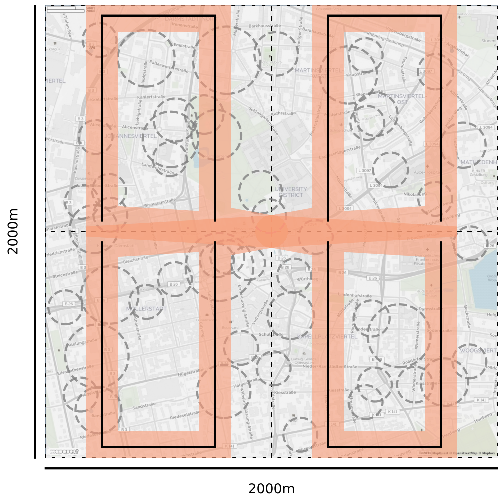
(a) C_{100} — 100% coverage, 100 m clearance, 10 strips per monitoring area.



(b) C_{75} — 75% coverage, 200 m clearance, 5 strips per monitoring area.



(c) C_{60} — 60% coverage, 250 m clearance, 4 strips per monitoring area.

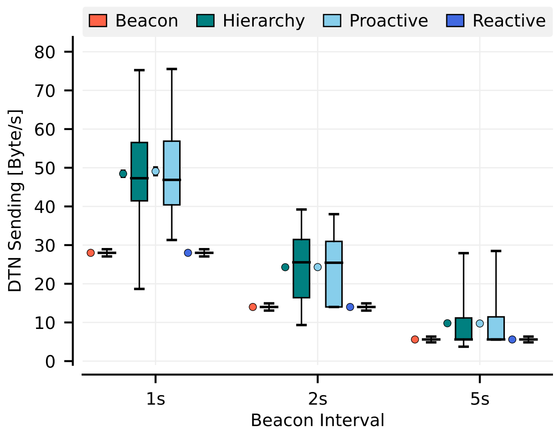


(d) C_{35} — 35% coverage, 500 m clearance, 2 strips per monitoring area.

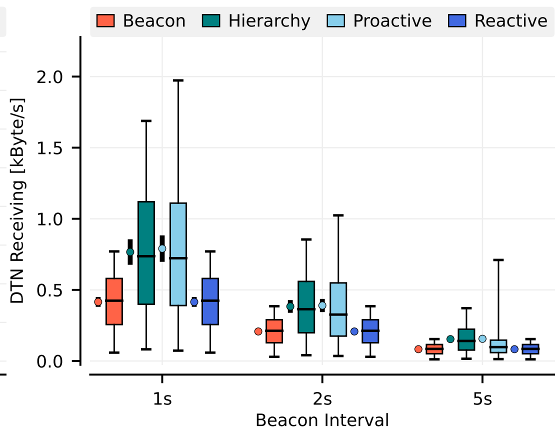
Figure A.1: Monitoring areas with lawnmower monitoring route. Circles denote areas of interest accumulated from all simulation runs. Colored areas denote the anticipated area coverage.

A.2.2 *Overhead Traffic (Extended)*

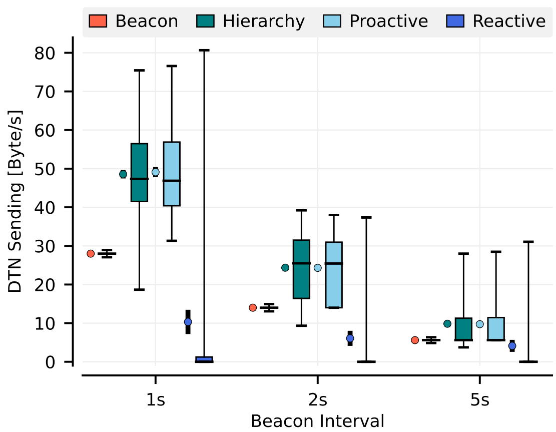
The communication overhead of *Cooperative Aerial-Ground Monitoring* and the impact of the beacon interval was extensively discussed in Section 6.2.2. However, overview based on the overhead traffic was shortened in the main evaluation. Therefore, we use this section as an addendum, to specifically provide a direct comparison of the sending and receiving traffic for both the DTN nodes with and without UAV contact. In particular, the direct comparison highlights the important differences of the Reactive protocol in the presence of monitoring UAVs, in contrast to the other protocols that do not incorporate a different behavior when encountering a UAV. Therefore, the overhead traffic for Beacon, Hierarchy, and Proactive does not change discernibly between Figure A.2a and Figure A.2c, or Figure A.2b and Figure A.2d, respectively.



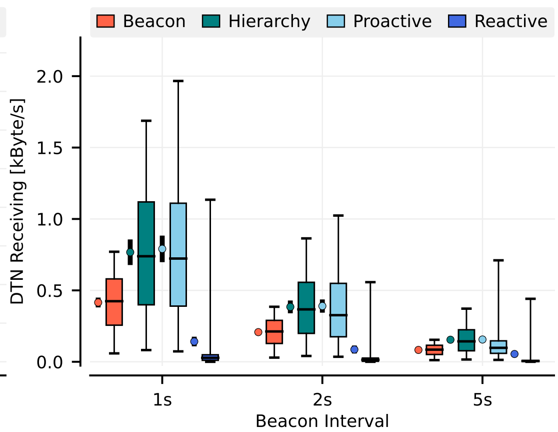
(a) Sending, without UAV contact.



(b) Receiving, without UAV contact.



(c) Sending, with UAV contact.



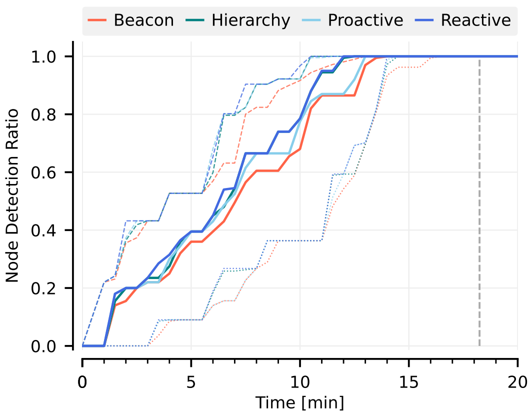
(d) Receiving, with UAV contact.

Figure A.2: Overhead traffic of *Cooperative Aerial-Ground Monitoring* protocols with different beacon intervals. Separate measurements for traffic with and without UAV contact.

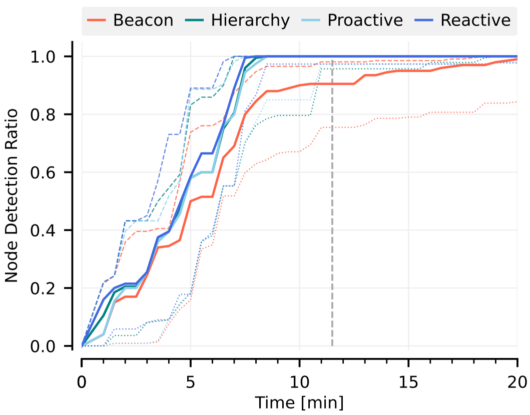
A.2.3 *Node Detection Performance (extended)*

The system performance of node detection was discussed in Section 6.2.4. Nevertheless, the evaluation was confined to median values, focusing on conveying the most important features. In this section, we extent our evaluation by incorporating the 97.5th and 2.5th percentiles, respectively, into our assessment. Figure A.3 similarly extends the visualization provided by Figure 6.11. Furthermore, we provide an aggregated visualization of all medians over the first 60 minutes in Figure A.4.

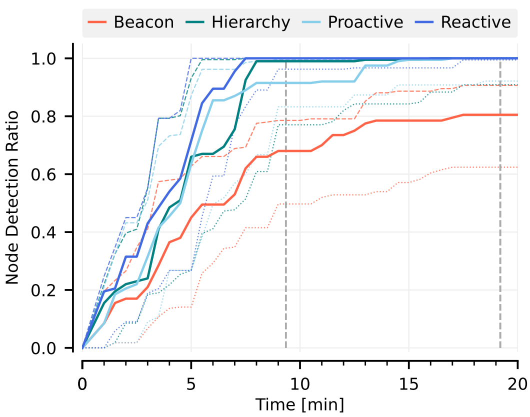
UAVs on the full coverage route (C_{100}) detect all nodes within a single flight, as shown in Figure A.3a. The applied *Cooperative Aerial-Ground Monitoring* protocol is not important for a full detection; Beacon also provides full node detection. Cooperative protocols can provide slight improvements to the initial detection time compared to the baseline, in the range of a few minutes. In the median, Hierarchy and Reactive are also faster than Proactive, as already discussed, but show



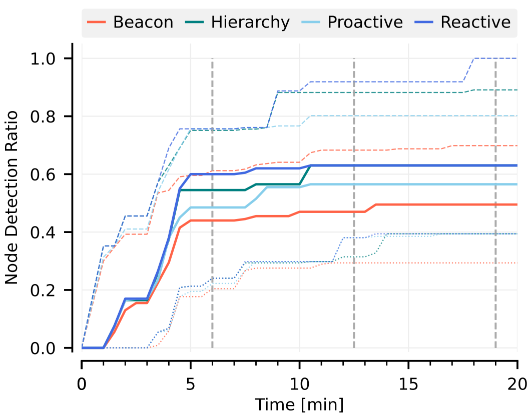
(a) C_{100}.



(b) C_{75}.



(c) C_{60}.



(d) C_{35}.

Figure A.3: Comparison of the node detection over time for the assessed protocols using different coverage paths. Grey vertical lines indicate the end and consecutive start of the coverage path traversal. Dashed and dotted lines show the 97.5th and 2.5th percentiles, respectively.

slighter variations for the 97.5th and 2.5th percentiles, respectively. In most cases for the upper and lower quartiles, Reactive shows a minimally better performance.

With the reduced area coverage in C_{75}, we perceive a positive impact of cooperative behavior, depicted in Figure A.3b. The Beacon protocol can achieve a node detection ratio between 75% and 97%. The maximum is slightly above the lowest performance of the cooperative protocols. In the worst case with *Cooperative Aerial-Ground Monitoring*, 96% were detected by Proactive and Reactive, 94% by Hierarchy. At average, all nodes are found after approximately 9 minutes; even earlier for the best cases.

This difference is further amplified by another coverage reduction, shown in Figure A.3c. Between 49% and 78% of nodes, with a median of 68%, are found with Beacon after the first flight. Another 10% are found for a consecutive monitoring flight, but full detection is typically not reached (cf. Figure A.4). At the same time, Proactive detects an average of 91% of nodes, Hierarchy 98%, and Reactive provides a full detection after the first flight. In the worst case, Proactive and Hierarchy perform as good as Beacon at its best, clearly emphasizing the general benefit of cooperation. Nevertheless, we are not sure what causes the considerably lower median performance of Proactive in this case. Presumably, the network topology changes at the time when the monitoring UAV arrives at clusters, which could also be indicated by the higher performance of Reactive, especially in the 2.5th percentile, compared to the much slower-reacting protocols Hierarchy and Proactive.

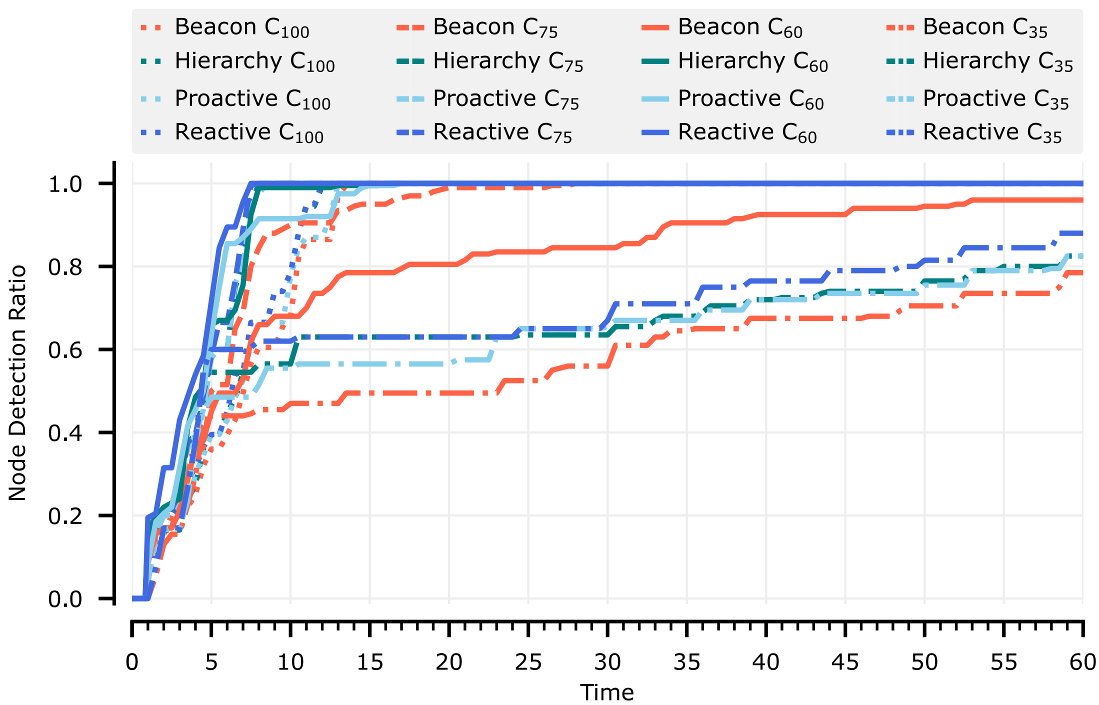


Figure A.4: Median node detection performance over 60 minutes, combined visualization for all coverage scenarios.

Figure A.3d visualizes the node detection performance for C_{35}. Only Hierarchy and Reactive are able to achieve an average detection rate of 65% within three consecutive monitoring flights. As discussed before, this highlights the large gaps in the coverage paths, and that many clusters are not encountered at all. Nevertheless, the cooperative approaches always perform superior to Beacon. The large deviation of the confidences reinforces the high susceptibility of node coverage to the actual distribution of nodes and areas of interest in the disaster area. Especially in the best case, shown by the 97.5th percentile, however, Reactive is able to discover all nodes, performing significantly better than all other protocols. Therefore, the Reactive protocol shows to be the best choice when using *Cooperative Aerial-Ground Monitoring* in a dynamic disaster environment with reduced area coverage.

The dynamicity of the scenario is showcased by Figure A.4. Although the monitoring paths are fixed and do not change their covered area over time, the node detections still increase. This is only possible because devices move within the covered area, indicating mobility and changes in the network topology. However, the low performance despite a slow gradual increase over time for C_{35} highlights the importance to provide a sufficient area coverage, even when using our cooperative monitoring approach. On the other hand, the significant difference between cooperative and non-cooperative protocols for C_{60} especially demonstrates the large benefit that *Cooperative Aerial-Ground Monitoring* can provide for the efficient monitoring in disaster scenarios.

A.3 Civilian Disaster Mobility (CDM): Evaluation

Section 5.4 introduces our *Civilian Disaster Mobility* (CDM) model [313] and its integration into the PeerfactSim.KOM simulator. In this section, we compare CDM to other mobility models: An unrestricted Random Waypoint model (*RWP*), a Random Waypoint model with map-based movement restrictions (*RWP-MAP*), and an adapted version of the *SLAW* (self-similar least action walk) [159, 271] mobility model. The latter model was changed to allow the utilization of areas of interests from the PeerfactSim.KOM simulator, similar to their usage with CDM. The field test's trace files are used as baseline comparison (*Trace*).

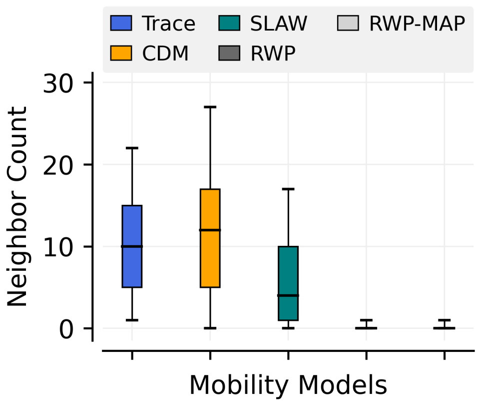
Therefore, all simulations are performed in the same environment as the field test and the analysis presented in Section 5.4. Thus, the simulation area is the map of the military training area used in the field test, 4500 m x 4500 m in size. Map data is provided by OpenStreetMap. The DTN utilizes a gossip-based communication protocol [149] with a message size of 300 Byte, a Time-to-Live (TTL) of 60 minutes, and a message generation rate of six per minute, in accordance to the real field test communication [15].

Node Mobility

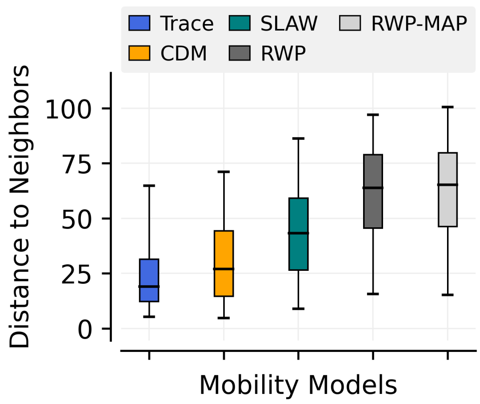
The differences of node mobility for the respective models are clearly visible in Figure A.6. Despite differences in the distribution of nodes and their mobility within the area, the RWP model (Figure A.6a) depicts a highly unrealistic behavior, considering the intended utilization for modeling human mobility in a disaster. Since mobility and communication in a DTN are intertwined, the RWP model does also not provide realistic DTN communication properties, as we highlight later on. With RWP-MAP, however, nodes are restricted in using the provided paths. The larger central roads are most used, but smaller bypaths are also traversed a few times.

Nevertheless, RWP-MAP still considerably differs from the field test traces (Figure A.6d), where only the major roads between the villages were used. Such a behavior can be approximated by our CDM model, as shown in Figure A.6c, as well as the SLAW model. The node distribution visualization for SLAW is not shown, due to its closeness to CDM in the aggregated spatial node distribution. The largest difference between *Trace* and CDM is the node distribution within the villages. As shown in the magnified areas, participants in the field test clustered at different locations within the villages more heavily. With CDM, however, nodes are distributed more evenly around the center of the village, since our model does not include additional points-of-interest within each area.

To gain a more profound understanding of the models' differences, we further evaluate the network mobility, such as the direct network neighborhood around nodes and their mobility behavior. Figure A.7 summarizes the most important aspects. The number of network neighbors within the 1-hop distance is shown by Figure A.5a. Clearly, RWP and RWP-MAP provide a highly distributed mobility, and thus, nodes are entirely disconnected from each other for most of the time. In comparison to *Trace*, nodes with SLAW have a generally lower number of neighbors, while the opposite is the case for CDM. On the other hand, as indicated by Figure A.5b, the

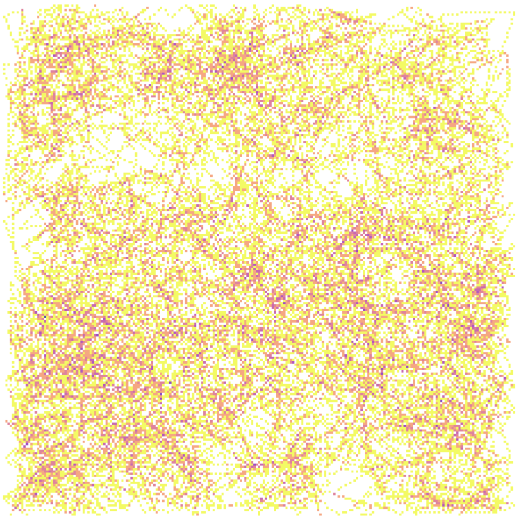


(a) Number of 1-hop neighbors.

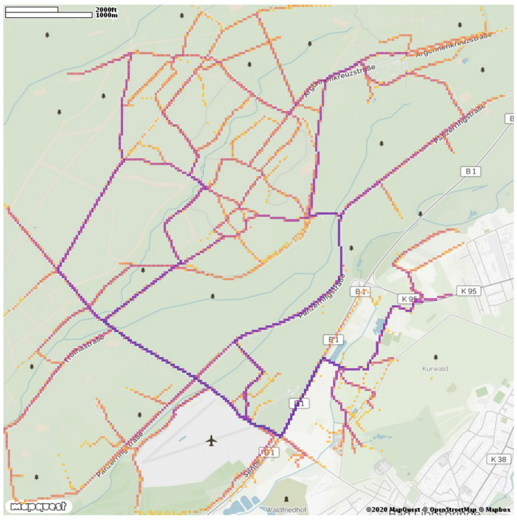


(b) Distance between 1-hop neighbors.

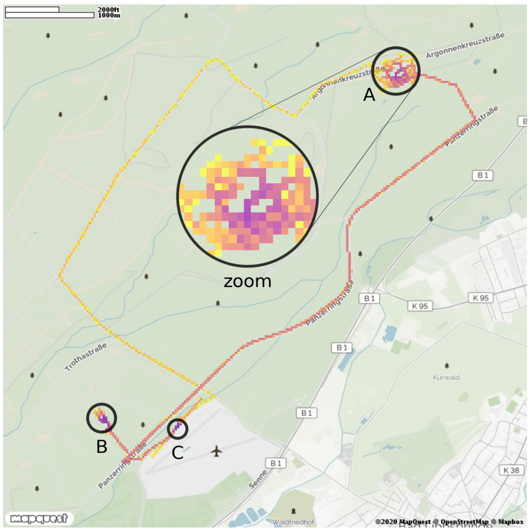
Figure A.5: Network neighborhood metrics [313].



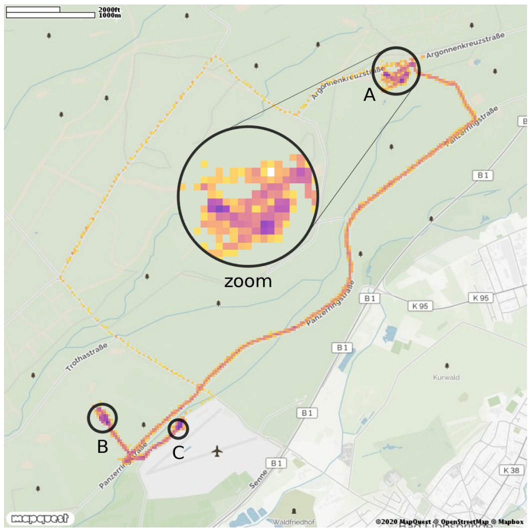
(a) RWP.



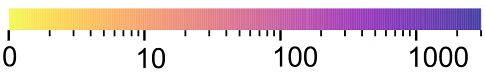
(b) RWP-MAP.



(c) CDM.



(d) Field test traces [15].

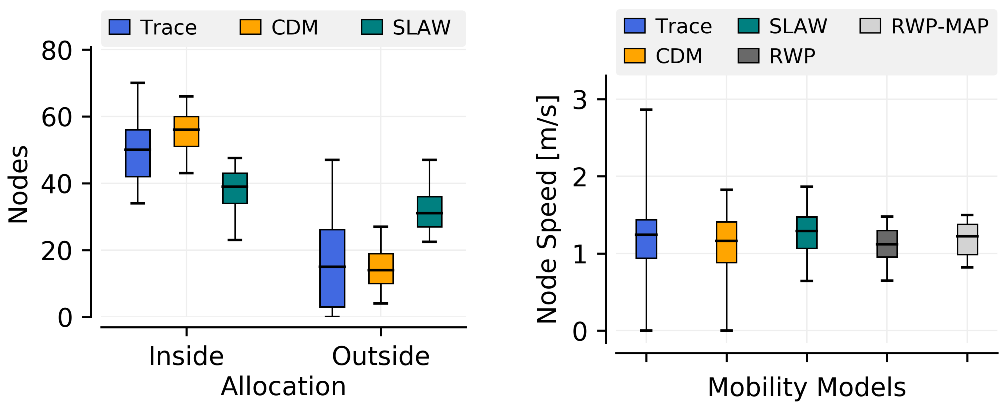


(e) Logarithmic color code, node measurements per cell.

Figure A.6: Spatial node distribution aggregated over the entire simulation time. Positions are sampled in 20x20 m^2 cells every 30 seconds. Colors, as shown in the legend, denote the number of nodes measured within a cell [313].

distances between neighbors is higher than in the trace files for CDM and especially SLAW. In both cases, CDM is closer to *Trace*, although not accurately approximating it. We presume that this difference can be attributed to the different mobility within the villages. In *Trace*, nodes cluster close at specific locations inside villages, which may reduce the number of neighbors in reach, on the one hand, and decrease the general distance between reachable neighbors, on the other hand. For CDM, this is much more evenly distributed, hence more neighbors and larger distances between neighbors are more probable. Despite a similar behavior within villages, SLAW does not have group movement but single nodes moving much more frequently between the villages. This reduces the overall number of nodes in villages and also increases the distance between neighbors, compared to CDM.

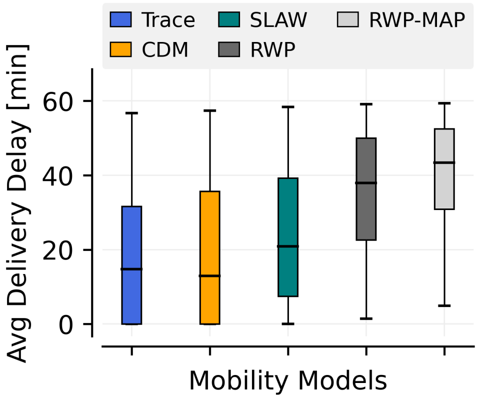
This is additionally supported by the distribution of node locations shown in Figure A.7a. Less nodes are generally inside of villages compared to *Trace* and CDM, and vice versa. CDM, in general, achieves a similar median number of nodes outside of villages like the traces, but with a much more narrow distribution. CDM lacks to depict the higher variation in mobility between villages. Additionally, the number of nodes inside of villages is also higher on average than that of *Trace* and provides a smaller distribution. The larger spread must be attributed to the natural behavior or the participants, which we did not depict accurately with our approximated number of moving groups. Nevertheless, the median number of nodes outside of villages was approached closely by that. Integrating bursts or pauses in the group formation process in our model could be possible to depict a higher spread. However, this would require a more elaborate analysis of group formation behavior than possible with the available trace data. In another disaster scenario, furthermore, group formation could also behave completely differently, raising the question how accurately models must depict single scenarios. Similarly, Figure A.7b shows that some nodes in the trace files moves significantly faster than $2\frac{m}{s}$. This could, however, also be attributed to inaccurate location readings or some participants did run at some points.



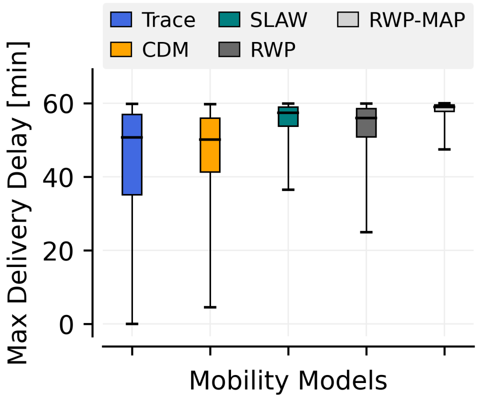
(a) Node location inside and outside of villages.

(b) Node speed outside of villages.

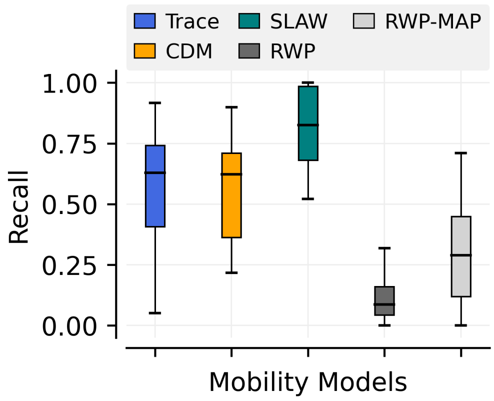
Figure A.7: Network mobility metrics [313].



(a) Average delivery delay.



(b) Maximum delivery delay.



(c) Recall.

Figure A.8: Recall and delivery delay comparison for different mobility models [313].

Although this is also not depicted by neither mobility models, CDM achieves a closer resemblance by incorporating the group encounter behavior that results also in static behavior outside of villages. SLAW does not have social interactions modeled, and thus, provides a generally higher node speed, despite using the same node speed distribution as CDM.

Communication Performance

Due to the reliance on the *store-carry-forward* principle (cf. Section 2.2), communication in intermittent DTNs is highly dependent on node mobility. This renders, for example, random movement models unsuitable for the evaluation of disaster DTNs since they diverge too much from reality, as shown in the following. Utilized mobility models must closely depict the appropriate mobility in terms of the communication performance to obtain expressive simulation results. Therefore, we further compare the different mobility models with the field test traces based on message delivery delay and recall.

Figure A.8 visualizes the comparison of delivery delays and recall for the different mobility models. Similar to the results of node mobility, CDM provides more similar results to *Trace* compared to SLAW, RWP-MAP, and RWP. Especially the random models demonstrate a considerably decreased communication performance than with real human mobility. SLAW, on the other hand, achieves a much better recall than *Trace* as a result of the more frequent and more constant transit mobility of single nodes between villages.

Integrating group mobility — comparable to that seen in the field test — as predominant transit behavior between villages facilitates CDM to achieve much more realistic results than the other mobility models. Nevertheless, the results indicate on the one hand that CDM generally underestimates mobility between villages, as seen by the lower recall and increased delivery delay, but on the other hand does not incorporate stray nodes or slower transit nodes that reduce the recall, as shown in the higher 2.5th percentile for CDM. Further adaptation and parametrization of the model could increase the resemblance to the real-world traces, but is not within the scope of this thesis. Overall, however, the proposed Civilian Disaster Mobility (CDM) model already approximates the mobility in the field test more closely than other mobility models.

A.4 Dynamic Monitoring Area Allocation (DMAA)

In the context of this thesis, we utilize a basic aerial monitoring strategy with static rectangular monitoring areas and a lawnmower coverage path. Furthermore, we utilize a single UAV type, resulting in equal flight ranges and speeds for every UAV. However, monitoring areas can be more complex and the available UAV types more diverse. Additionally, the number of available UAVs can change over time, for example, increase due to other terminated strategies or decrease due to technical failures.

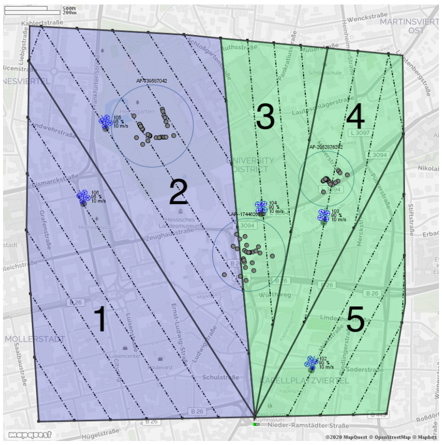
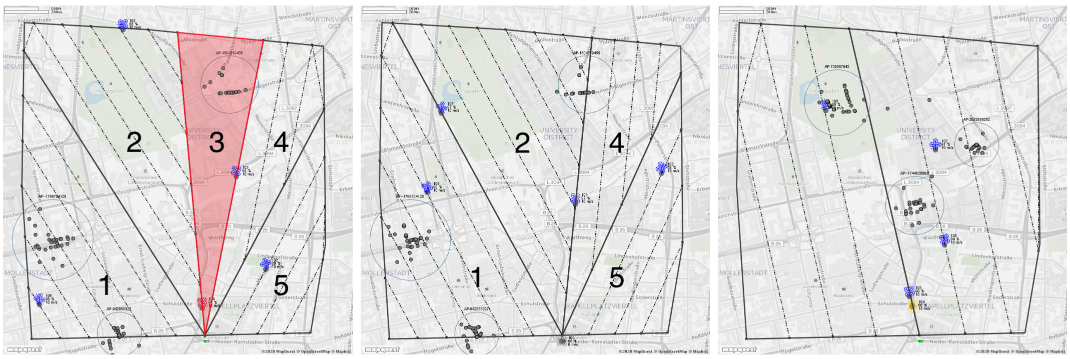


Figure A.9: LR-UAVs #1 and #2 are assigned larger areas than SR-UAVs #3 to #5 [316].

We addressed such possibilities in a preliminary study [316], introducing the concepts and a working prototype for *dynamic monitoring area allocation* (DMAA). The operation area of the aerial system is an arbitrary convex polygon, with the base station on its edge instead of in the center. UAVs are separated into two long-range UAVs (LR-UAV; #1 and #2) and three short-range UAVs (SR-UAV; #3, #4, #5) based on their battery capacity; SR-UAVs have half of the usable capacity of LR-UAVs. In our case, UAVs are deployed with their optimal speed with respect to the achievable range (cf. Section 5.3); thus, this also halves their flight range.

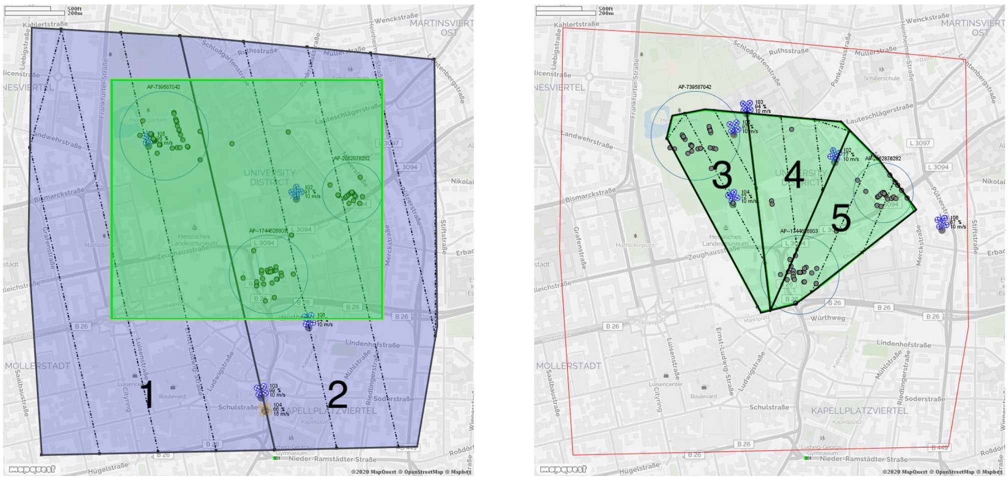
DMAA compares the capabilities of UAVs — mainly speed and range — and calculates a suitable allocation of monitoring areas based on the comparison of range capabilities. However, other criteria, like maximum speed or a minimal number of turns, could be used to determine monitoring areas. Furthermore, our prototype only approximates allocation based on the allocated area and not on the resulting lawnmower coverage path. The optimization of area allocation, especially considering a possible variety of optimization goals, is not within the scope of our preliminary study. Nevertheless, as shown in Figure A.9, the prototype of DMAA already allocates considerably larger areas to the LR-UAVs using a simple heuristic.

Most importantly, however, DMAA constantly re-evaluates the current allocation for available UAVs. We demonstrate this at the example of a UAV malfunction, visualized in Figure A.11. Initially, a problem with SR-UAV #3 forces it to return to the base station, it is unusable for the remaining deployment, and its monitoring area is not covered (Figure A.10a). However, the flight ranges of the remaining UAVs are not exhaustively used, and, therefore, the failure can be compensated by calculating a new area allocation with only four UAVs (Figure A.10b). Due to the different capabilities, UAVs #1 and #2 are also compensating more than #4 and #5. After some time, all SR-UAVs also fail, and DMAA tries to compensate for these losses as well. Nevertheless, the available flight range of the UAVs is not enough to provide full



(a) Failure of UAV #3. (b) Compensation for UAV #3. (c) Two LR-UAVs compensate further failures.

Figure A.10: Example of *Dynamic Monitoring Area Allocation* (DMAA) with a reducing number of available UAVs. Failures are compensated by adapting the area allocation, which consequentially may require adapting the used lawnmower path planning [316].



(a) LR-UAVs monitor the entire area. The populated area is approximated by the green bounding box.

(b) SR-UAVs closely monitor the populated area, defined by a convex hull around all found node locations.

Figure A.11: DMAA enables separate monitoring approaches for populated and empty areas [316].

area coverage of the two remaining monitoring areas. Thus, the lawnmower path is reduced by increasing the clearance between lawnmower strips until a monitoring traversal can be guaranteed (Figure A.10c).

Another approach we pursued in our study was the adaptation of monitoring areas based on the encountered network topology. Specifically, an initial detection flight is performed to acquire necessary information in the first place. This information is then used to identify network clusters and differentiate populated and empty areas, as shown in Figure A.11a with a bounding box denoting the populated area. Populated areas are monitored closely to provide up-to-date information. Empty areas, on the other hand, cannot be entirely neglected since new nodes or clusters could, e.g., move into the area. Thus, we utilize the LR-UAVs to monitor the entire operation area as best as possible. In its current form, this does not exclude already monitored areas, but the optimization of area allocation is planned in the future. For the monitoring of populated areas, we can decide for monitoring the entire area, for example, as defined by the bounding box or a convex hull around all found nodes, or monitor individual clusters. Furthermore, different Coverage Path Planning (CPP) approaches are applicable, such as a lawnmower path or a spiral paths when using circles to define cluster borders [54]. Figure A.11b provides an example for a convex hull around all found nodes. It is separated into three monitoring areas that are assigned to the SR-UAVs and monitored using a lawnmower path. The separate monitoring approaches enable to monitor the found clusters more closely and with a higher frequency than with a topology-agnostic approach. Future work will encompass the detailed evaluation of different monitoring approaches as well as the optimization of monitoring area calculation and allocation.

In conclusion, *Dynamic Monitoring Area Allocation* (DMAA) enables aerial monitoring systems to autonomously allocate and adapt monitoring areas based on the available UAVs and available topology information. This also enables the appropriate appliance of heterogeneous UAVs and resilience against failures. Therefore, the concept of DMAA constitutes a valuable addition to any aerial monitoring system that permanently monitors dynamic disaster areas, providing adaptivity and resilience for an autonomous long-term deployment.

LIST OF ACRONYMS

A2A	Air-to-Air
A2G	Air-to-Ground
AoI	Area of Interest
COTS	commercial off-the-shelf
CPP	Coverage Path Planning
DTN	Delay-Tolerant Network
ICT	Information and Communication Technology
LoRa	Long Range
LoS	line-of-sight
LPWAN	Low-Power Wide-Area Network
MANET	Mobile Ad Hoc Network
RAN	Radio Access Network
SAR	Search-and-Rescue
TTL	Time-to-Live
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
WiFi	Wireless Fidelity
WSN	Wireless Sensor Network

B

SUPERVISED STUDENT THESES

Master Theses

[1] Ivan Rubinskii. "Applying Autonomous Unmanned Aerial Systems with Uncertain and Deprecated Information." Master Thesis. Technische Universität Darmstadt, 2022.

[2] Patrick van Halem. "Implementation and Performance Evaluation of Asynchronous Traffic Shaping on Real-Time Processors." Master Thesis (co-supervison with Christoph Gärtner). Technische Universität Darmstadt, 2021.

[3] Simon Johannes Gütthoff. "Cooperative Network Topology Monitoring in UAV-Supported Post-Disaster Ad Hoc Networks." Master Thesis. Technische Universität Darmstadt, 2020.

[4] Benjamin Heinz. "Low-Power Long-Range Multi-Hop Relay Communication Protocols for Emergency Crisis Communication." Master Thesis. Technische Universität Darmstadt, 2019.

[5] Jakob Peter Karg. "A Recommendation System for Semi-Automated Scheduling of Ground Station Passes." Master Thesis, *awarded best master thesis 2019 at the Multimedia Communications Lab (KOM)*. Technische Universität Darmstadt in cooperation with the ESA/ESOC Darmstadt, 2019.

Bachelor Theses

[6] Tobias Faschingbauer. "Modelling UAV Flight Properties based on Real-world Flight Sensor Measurements." Bachelor Thesis. Technische Universität Darmstadt, 2022.

[7] Henry Kalff. "Processing and Transmission of Network Topology Data in Aerial Monitoring Systems for Disaster Situations." Bachelor Thesis. Planned submission: 13.2.2023. Technische Universität Darmstadt, 2022.

[8] Patrick Pascal Wagner. "Optimizing UAV Allocation for Non-Convex Disaster Monitoring Areas." Bachelor Thesis. Technische Universität Darmstadt, 2022.

[9] Lukas Wehrstein. "Modular Simulation Environment for Wireless Sensor Network Evaluation." Bachelor Thesis, *awarded best bachelor thesis 2022 at the Multimedia Communications Lab (KOM)*. Technische Universität Darmstadt, 2022.

[10] Inga Susanna Dischinger. "Prototype System for Adaptive Self-Regulating LoRa Networks." Bachelor Thesis. Technische Universität Darmstadt, 2021.

[11] Paul Frommelt. "Prototype System for Energy-Efficient Mobile Data Offloading in Hetereogeneous Wireless Sensor Networks." Bachelor Thesis. Technische Universität Darmstadt, 2021.

[12] Yashita Saxena. "Design and Assessment of UAV Movement Models for Simulative Evaluation." Bachelor Thesis. Technische Universität Darmstadt, 2021.

[13] Jan Uhlig. "Strategy Transitions in Autonomous Aerial Systems for Post–Disaster Communication Support." Bachelor Thesis. Technische Universität Darmstadt, 2020.

[14] Louis Neumann. "Strategies for MANET Monitoring with Unmanned Aerial Vehicles." Bachelor Thesis. Technische Universität Darmstadt, 2019.

Student Research Projects

[15] Niklas Stöhr. "Concepts for Territorial Allocation and Route Calculations for UAVs in Aerial Topology Monitoring Sytems." Studienarbeit. Technische Universität Darmstadt, 2020.

[16] Bastian Drescher. "Optimierung von Nachrichten- und Datentransport durch Unbemannte Luftfahrtsysteme." Studienarbeit. Technische Universität Darmstadt, 2019.

Student Labs

[17] Niklas Jüttner and Henry Kalff. "UAV Lawnmower Path Calculation for Non-Convex Disaster Areas." KOM Lab/Project. Technische Universität Darmstadt, 2022.

[18] Donghyuck Son, Maurus Taupadel, and Timur Levent Görgü. "UAV Coverage Path Planning for Polygonal Disaster Areas." KOM Lab/Project. Technische Universität Darmstadt, 2022.

[19] Miron Abraha and Lorenz Wagner. "Adaptive Path Coverage Planning for UAVs with ML." KOM Lab/Project. Technische Universität Darmstadt, 2021.

[20] Tobias Faschingbauer. "On-Board Sensor Logging for UAV Flight Parameter Evaluation." KOM Lab/Project. Technische Universität Darmstadt, 2021.

[21] Sayan Sikdar. "Simulation Model for Fixed-Wing UAV." KOM Lab/Project. Technische Universität Darmstadt, 2020.

[22] Marcel Mann and Philipp Skrinjar. "LPWAN Control Channel for UAV Systems." KOM Lab/Project. Technische Universität Darmstadt, 2019.

[23] Julian Kordisch. "3-D Movement Model for UAVs as Post-Disaster MANET Distributors." KOM Lab/Project. Technische Universität Darmstadt, 2018.

C

AUTHOR'S PUBLICATIONS

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[1] Julian Zobel, Ralf Kundel, and Ralf Steinmetz. "CAMON: Aerial-Ground Cooperation System for Disaster Network Detection." In: *Proceedings of the 19th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2022.

[2] Julian Zobel, Paul Frommelt, Patrick Lieser, Jonas Höchst, Patrick Lampe, Bernd Freisleben, and Ralf Steinmetz. "Energy-Efficient Mobile Sensor Data Offloading via WiFi using LoRa-Based Connectivity Estimations." In: *ComputerScience4BioDiversity, Lecture Notes in Informatics (LNI), INFORMATIK*. 2021.

[3] Julian Zobel, Patrick Lieser, Tobias Meuser, Lars Baumgärtner, Mira Mezini, and Ralf Steinmetz. "Modeling Civilian Mobility in Large-Scale Disasters." In: *Proceedings of the 18th International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. 2021.

[4] Julian Zobel, Tobias Meuser, and Ralf Steinmetz. "Calling Ground Support: Cooperative DTNs for Improved Aerial Monitoring Systems." In: *Proceedings of the 11th IEEE Global Humanitarian Technology Conference (GHTC)*. IEEE. 2021.

[5] Julian Zobel, Niklas Stöhr, Ralf Kundel, Patrick Lieser, and Ralf Steinmetz. "Dynamic Monitoring Area Allocation for Aerial Post-Disaster Situation Monitoring." In: *Proceedings of the International Conference on Networked Systems (NetSys)*. 2021.

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[7] Patrick Lieser, Julian Zobel, Björn Richerzhagen, and Ralf Steinmetz. "Simulation Platform for Unmanned Aerial Systems in Emergency Ad Hoc Networks." In: *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM), awarded with the Best Student Paper Award*. 2019.

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Darmstadt, 20. September 2022

Julian Zobel

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