Simulation Platform for Unmanned Aerial Systems in Emergency Ad Hoc Networks

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ABSTRACT

Natural disasters regularly impede communication infrastructure, leaving civilians without reliable means of communication. In such cases, ad hoc networks enable basic communication inside the affected areas. However, low human mobility and group formation limit their performance, as messages are confined to distinct communication islands. Autonomous Unmanned Aerial Vehicles can help in spreading messages across multiple such islands, as proposed in the literature. Evaluating the resulting Unmanned Aerial System (UAS) under real-world conditions requires significant resources, e.g., field tests and prototypes. For a systematic assessment of a UAS and its support strategies under controlled conditions, simulations are the preferred method. To this end, we propose the first simulation platform that combines ad hoc communication on the ground and the corresponding human mobility models with an extensible model for a networked UAS and their respective support strategies. We implement and evaluate two representative strategies, showcasing the capabilities of the proposed platform.

Keywords

Simulation Platform, Unmanned Aerial Vehicles, Delay Tolerant Networks, Emergency Ad Hoc Networks

INTRODUCTION AND MOTIVATION

Recent disasters such as Hurricane Harvey in 2017 or Hurricane Florence in 2018 demonstrated the highly destructive force of natural disaster, and they revealed the strong dependencies of the civilian population on critical infrastructures such as energy supply or information and communication technologies (ICT). Particularly in the aftermath of a disaster the communication volume increases and the communication infrastructure can no longer cope with the high communication demand (Klinsompus and Nupairoj 2015). In such resource-constrained situations, however, where communication is key for successful emergency response operations, there is a need for civilian-centric emergency communication networks.

In 2017, we conducted a large field test throughout one day to show the capabilities of smartphone-based communication networks for emergency response (Álvarez et al. 2018). The field test took place at the military training area *Senne* near Paderborn in Germany in conjunction with experts from the German Federal Office of Civil Protection and Disaster Assistance (BBK), the German Federal Agency for Technical Relief (THW), local fire departments, and other NGOs. A large set of emergency services (Lieser, Alvarez, et al. 2017), such as SOS Messages, Person-Finder, or a Resource Market were available for 125 participants to cope with various scripted

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Figure 1. The layout of the field test area (Álvarez et al. 2018).

disaster events in a realistic environment consisting of three different villages (Figure 1). The smartphones of the participants were used to build a large communication network which was based on the store-carry-forward principle known from delay-tolerant mobile ad hoc networks (DTN-MANETs) (Uchida et al. 2013). Message propagation was achieved in a flooding-based manner, where duplicates of all stored messages are forwarded every time a node discovers a new node in communication range. The field test demonstrated, on the one hand, that smartphone-based ad hoc networks can successfully be utilized to support emergency response efforts. On the other hand, the field test revealed the limited communication capabilities of DTN-MANETs which are highly dependent on the users' mobility to distribute messages.

Due to the high distance of Village B and C to Village A ($\approx 3.5\,km$ beeline, $\approx 5\,km$ by foot) and the natural human behavior of forming groups, the network was highly intermittent with large communication islands in and around the villages. Within these islands, communication performed well. Messages were distributed within a few seconds throughout an entire island. However, to achieve communication between distinct islands mobility is required for message transport. Participants, thus, would have to act as communication bridges between islands, but only a few of them actually moved between the villages, especially between the distant ones. Furthermore, if participants moved between the distant villages, it took them more than 60 minutes in most cases. Thus, lifetimes of most of the carried messages were already expired on arrival. Figure 2 displays the best and a median number of reached participants (out of 125) and the corresponding delivery delay within the message lifetime of 60 minutes. Instantaneous jumps indicate the distribution of a message when a new communication island is encountered, but the distances between those jumps show that it takes a long time for an encounter to happen.

During the field test, the interaction with the provided emergency services resulted in a total number of 1,835 unique messages which were duplicated and forwarded 18,418 times in the network. With a higher message lifetime, the number of reached participants would have further increased. However, this would also increase the amount of duplicates and therefore the network load resulting in more needed message storage space on the nodes. Furthermore, the relevance of a message or the relevance of the contained context information can decrease over time (Lieser, N. Richerzhagen, Luser, et al. 2019; Lieser, Alhamoud, et al. 2018).

Moreover, especially for high priority messages like SOS calls and warnings in emergency response services a timely delivery is crucial. Another example of the need to provide fast communication are tsunami warnings. For example after the Great East Japan Earthquake in March 2011, the affected population could not be warned sufficiently quickly of the upcoming tsunami because the effects of the earthquake had disrupted the communication in various regions (Ranghieri and Ishiwatari 2014). Thus, improving the performance of DTN-MANET emergency communication with regard to fast, reliable and thorough message propagation can significantly improve the efficiency of disaster relief and emergency response services and eventually saves lives.

In recent years, the increasing availability and popularity of small, commercially available Unmanned Aerial Vehicles (UAVs) has attracted remarkable attention from researches and practitioners. Besides their use for leisure activities, they proposed UAV application for example in search and rescue missions (Rémy et al. 2013; Scherer et al. 2015) or to relay communication of rescue team members on incident sites (Morgenthaler et al. 2012; Baumgärtner et al. 2017). Regarding the field test results, it became clear that inter-island communication cannot be efficient relying only on uncontrollable node movement. An Unmanned Aerial System (UAS), where multiple autonomous UAVs collaborate to efficiently support physical message transport between intermittent communication islands,

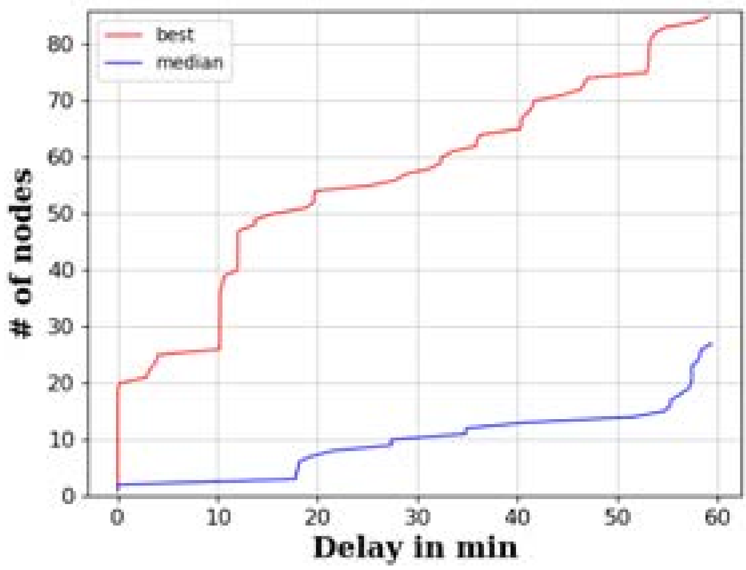

Figure 2. Number of reached nodes and the corresponding propagation delay during the field test. Messages had a lifetime of 60 minutes (Álvarez et al. 2018).

could provide a much more performant emergency communication. As drafted in Figure 3, a UAV could act as a communication bridge between otherwise intermittent communication islands and thereby, eliminate the necessity for ground nodes to move between islands for message dissemination.

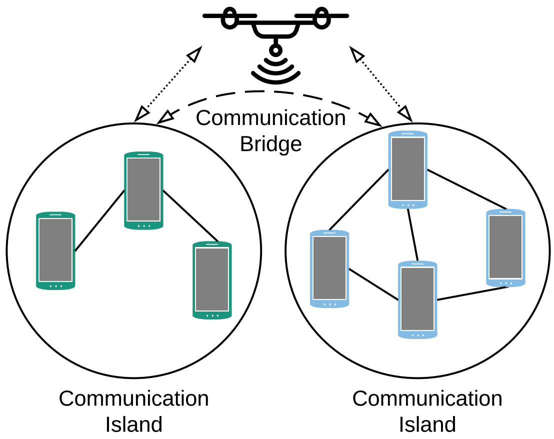

Figure 3. Communication amongst intermittent communication islands in a DTN-MANET requires nodes to act as communication bridges. UAVs are either acting as message relays by positioning themselves in communication range between two near islands, or by providing more efficient means of physical message transport between remote islands due to their mobility.

To design and to evaluate the applicability of such a system, field trials with prototypes or small testbeds are often conducted, and are indispensable to test the applicability of UAVs under realistic environmental conditions such as extreme weather conditions. However, this process has several drawbacks. On the one hand, an elaborate field test cannot be repeated on a regular basis due to the high costs and organizational complexity. Moreover, on the other hand, it would require already existing working prototypes to test them in the field, or at least in an experimental testbed.

Due to poor scalability, reproducibility, and possible law-restrictions, as well as the requirement of expensive hardware prototypes for experimental evaluations, performing simulations, is the preferred method for the development of complex systems. There exists no simulation platform that combines the possibility to simulate and evaluate Mobile Ad Hoc Networks on the ground in combination with Unmanned Aerial Systems, as discussed in the following section. This paper, therefore, introduces a simulation platform for Unmanned Aerial Systems as an extension of the discrete-event open-source simulation and prototyping platform Simonstrator.KOM (B. Richerzhagen et al. 2015) for mobile networks. It can be used for the implementation, simulation, and evaluation of a large-scale UAS in combination with mobile communication networks on the ground. The modular system design allows the simulation of various behavioral strategies and a multitude of different UAV parameter settings.

As a proof of concept, we implemented and evaluated an Unmanned Aerial Communication Support System for civilian-centric post-disaster emergency communication networks based on our field test (Álvarez et al. 2018). Two simple, yet diverse behavioral strategies are provided in the prototype implementation, to show the potential extensive scope of systems our simulation platform allows to develop. The results show that we can significantly improve the communication characteristics of the DTN-MANET on the ground, by improving the message propagation while also decreasing the delivery delay. Our simulation platform can further be used to determine optimal UAS settings, such as the minimal amount of UAVs required to reach an intended message delivery rate or delay.

The remainder of this paper is structured as follows. In the next section, related work is described, followed by the concept and design presentation of our UAS simulation platform. Afterward, we present two possible behavioral strategies and their proof-of-concept evaluation in two different scenarios. Eventually, we conclude the paper and discuss future work approaches.

RELATED WORK

The possible destruction of ICT infrastructures in the aftermath of disasters led to the development of many infrastructure-independent post-disaster communication systems based on DTN-MANETs and a variety of different applications. George et al. 2010 propose the use of wireless sensor nodes for the provision of real-time situational awareness on site for search and rescue mission teams. The system combines on-demand and delay-tolerant routing for heterogeneous nodes with good performance results shown in simulations.

Serval Mesh (P. Gardner-Stephen, Challans, Lakeman, Bettison, D. Gardner-Stephen, et al. 2013), *Twimight* (Hossmann et al. 2011), and *TRIAGE* (Luqman et al. 2011) are also multi-purpose infrastructure independent communication system that can be used in the case of a disaster. These systems also support different prioritization mechanisms to handle the limited bandwidth in DTN-MANETs. As already proven in the field test (Álvarez et al. 2018) and other prototypical hardware demonstrations (Meurisch et al. 2017), decentralized civilian communication systems for post-disaster scenarios are possible by utilizing the ubiquity of civil smartphones. The Simonstrator.KOM platform (B. Richerzhagen et al. 2015) allows to simulate large-scale civilian ad hoc networks as shown, e.g., for decentralized resource allocation in disaster scenarios (Lieser, N. Richerzhagen, Feuerbach, Meuser, et al. 2018).

Dedicated communication modules such as the Serval Mesh Extender (Lieser, Alvarez, et al. 2017; P. Gardner-Stephen, Challans, Lakeman, Bettison, Lieser, et al. 2017) make it possible to communicate over long distances (tested with 4 km distance) independent of any fixed infrastructure. In principle, such devices would be ideal to connect communication islands, but they need a line of sight to reach the specified communication distances which are often not possible. Furthermore, experts need to have access to strategic places, such as the edge of a communication island for a meaningful deployment of the communication modules. The locations of the islands are also strongly dependent on the course of a disaster and are therefore difficult to predict.

Besides these system examples for post-disaster communication there exist a variety of different applications, specifically designed for DTN-MANETs. With the goal to help the affected population to cope with the aftermath of a disaster, such services allow civilians to send out distress signals (Al-Akkad et al. 2014; Mokryn et al. 2012), have text-based conversations, make it possible to find friends and family, or to share resources at a digital market-place (Lieser, Alvarez, et al. 2017; Lieser, N. Richerzhagen, Feuerbach, Nobach, et al. 2017). To boost message delivery rate in a wide-spread, sparsely populated DTN-MANET environment, Uchida et al. 2013 insert cars with WiFi capabilities as additional nodes into the network, similar to Zhao et al. 2004. The simulation was conducted in the ONE simulator[1] with the cars moving on the streets with up to 50 $\frac{km}{h}$. Results indicate that even with 100 cars it took more than 30 minutes on average for messages to travel 4 km between two rescue shelters. Furthermore, only 80% of the messages are delivered at all.

Proposed applications for Unmanned Aerial Systems include Search and Rescue missions (Rémy et al. 2013; Scherer et al. 2015), forest fire localization (Belbachir et al. 2015), inspection of infrastructure like power lines (Erdelj et al. 2017), aerial contamination measurement (Daniel et al. 2009), LTE coverage provision (Rohde et al. 2013; Li et al.

[1]http://akeranen.github.io/the-one/

2015), and message relaying for rescue team members on incident sites (Morgenthaler et al. 2012; Baumgärtner et al. 2017).

However, most of these applications used unique hardware prototypes to show their feasibility, or build mathematical models to provide insight into possible advantages and drawbacks, very few use simulations. A very basic simulation for UAV trajectories is used by Belbachir et al. 2015 and Erdelj et al. 2017 but neither the simulation tool nor the capabilities for realistic UAV simulations are stated. A discrete event simulation for UAVs is presented in Dietrich et al. 2017a including a 3D visualization. However, the tool is specifically designed to evaluate maintenance processes for long-term UAV deployments. Communication happens without limitations and with perfect reception only between a mission controller and the UAVs. In Mori et al. 2015 a large-scale simulation of very different nodes such as balloons, cars, and UAVs is shown. Entities build up a mesh network to provide communication between users. The simulator and its details, however, is not specified and nodes are either static or only use a random waypoint movement model, which insufficiently represents real-world behavior.

In conclusion, there are some approaches for the simulation of Unmanned Aerial Vehicles or comprising systems. However, they are limited in their applicability to general system development or lack certain features like realistic node movement or communication models. Most often, simulations are implemented specifically for the tested approaches and do not allow for the implementation of other systems.

Thus, a simulation tool which provides broad access to different movement and communication models allows the realistic simulation of different kinds of nodes like UAVs or smartphone users, and in particular is fit for the implementation and evaluation of diverse UAS as required for quick and large-scale development of such systems. There exists no simulation platform fulfilling these requirements.

SIMULATION PLATFORM FOR UNMANNED AERIAL SYSTEMS

The open-source Simonstrator.KOM (B. Richerzhagen et al. 2015) simulation platform provides several models for wireless communication, message transport, node mobility, and energy consumption relying on the network simulator PeerfactSim.KOM (Stingl, Gross, et al. 2011; Stingl, B. Richerzhagen, et al. 2013). Furthermore, Simonstrator.KOM allows simulating a large number of heterogeneous nodes with different properties at the same time. It can also use map data from OpenStreetMap[2] (OSM) to simulate, e.g., urban environments where node movement can be restricted to walkways, bike lanes, or roads, respectively.

This simulation environment constitutes a well-suited basis which we extended towards a fully fledged simulation platform for Unmanned Aerial Systems[3]. The added extensions and their interactions are shown in Figure 4. The PeerfactSim.KOM simulator is extended by required UAV components such as batteries, actuators, and controllable movement models, which eventually form the entire simulated vehicle. Besides the possibility to simulate UAVs, we also added a base station that provides necessary infrastructure like battery recharging and landing pads for the UAVs. On the application layer at the Simonstrator.KOM platform, mission planning, and coordination were added to the base stations and controlling strategy execution to the UAVs. In the following, we discuss the extensions in detail.

Energy Consumption and Battery Recharging

PeerfactSim.KOM already provides a battery model including the power consumption of device components such as displays, communication interfaces like WiFi, or miscellaneous equipment like GNSS sensors. Power consumption is adjustable for each device, respectively, using voltage and power draw in different states, for example, *TRANSMIT* or *RECEIVE* in case of a WiFi chip. Batteries are defined by their capacity in Joule. We added a new component modeling the actuators required for the UAV propulsion, where the power consumption is regulated continuously between a minimum and a maximum parameter. This is necessary to abstract situations such as constant flight speed and altitude, where only friction has to be compensated, or ascent, where actuators require more power to accelerate the UAV. Parameter settings for power consumption depend on the actual UAVs—or more specifically the used actuators—that are modeled, as mentioned by Dietrich et al. 2017b.

Due to the limited battery capacity, a long-term UAV deployment requires the possibility to recharge or to entirely replace a drained battery. We include a charger model to the simulator, which continuously recharges a UAV's battery by a fixed amount of Joule per second, modeling, for example, a contactless induction charger as proposed by Hu et al. 2008. However, continuous recharging is not the most efficient solution regarding vehicle utilization due to the long downtimes during the recharge process (Erdelj et al. 2017). We, therefore, added another model that

[2]www.openstreetmap.org
[3]The source code and simulation environment is available online: https://dev.kom.e-technik.tu-darmstadt.de

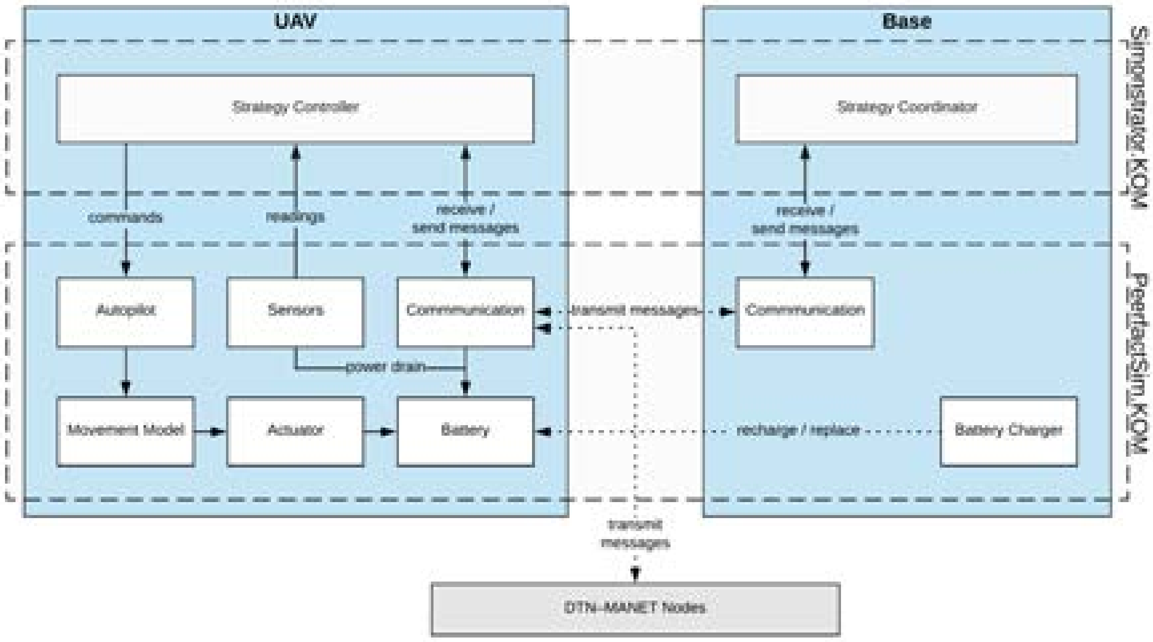

Figure 4. Overview of system components for UAVs and base stations comprising the UAS in the simulation platform, with their respective location in Simonstrator.KOM and PeerfactSim.KOM architecture. Dependencies between components are indicated by lines and arrows, dotted lines show non-permanent connections like message transfer over the network or during the battery recharging process.

is emulating manual or automated battery replacement. The default time to replace the entire battery is set to 60 seconds, based on the results in Fujii et al. 2013 and Ure et al. 2015, but can be customized if required. As in a real deployment, chargers are part of base stations.

UAV Autopilot and Movement Model

Available models for node movement included simple approaches like random walk or random waypoint, but also more sophisticated models like social movement between attraction points in an urban environment (N. Richerzhagen et al. 2017). Realistically, the application cannot directly control the movement of a user. Thus, the movement models in the simulator are fully separated from the application layer. However, this separation is not given in the case of a UAV, since vehicle movement is controllable by an autopilot. We therefore added a controllable UAV movement model.

In our platform, we premise all UAVs to be capable of fully autonomous flight, performed by an autopilot. All autopilots offer a generic interface to the application layer, through which commands like *'move to coordinate x'* or *'change altitude'* can be issued. The autopilot then autonomously executes the commands within the capabilities of the UAV. These capabilities are specified by a UAV movement model. We first implemented a model for multicopter UAVs due to their straightforward and precise maneuverability, their ability to hover, and because they constitute the majority of commercially available UAVs (Namuduri et al. 2018). The models define basic procedures like take-off, touch-down, ascent, and descent, but also flight maneuvers such as hovering, circling a position, or route traversal. Furthermore, variables like minimum and maximum speed, reachable flight altitudes, and movement limitations, in general, are defined therein.

Communication

Devices for wireless communication such as Bluetooth and WiFi are already implemented in PeerfactSim.KOM. Available communication devices can be used for various purposes, such as for control and coordination messages between UAVs and the Base Station, for communication between multiple UAVs, and the communication between UAVs and the DTN-MANET nodes on the ground. The modular setup of communication devices in PeerfactSim.KOM allows using multiple, possibly different devices in parallel, which enables the full separation of channels, if necessary. For example, we can use a WiFi device on the UAVs to exchange messages with the nodes on the ground in accordance with the employed DTN-MANET protocol. Another WiFi device then is used for UAV-to-UAV communication allowing decentralized coordination of the UAVs or to build up a distinct relay network (Morgenthaler et al. 2012). A long-range control channel may also be deployed by a third device, e.g., using LoRa[4].

System Application

These extensions on the simulator layer now provide the capabilities which are necessary to develop and evaluate a mobile aerial system in SIMONSTRATOR.KOM. We utilize the interfaces given by the simulator to define a modular system design that is independent of the simulated UAV and thus of its hardware. On each UAV, a Strategy Controller is responsible to execute a given strategy and fulfill the states mission objectives. Controlling the autopilot and using communication devices is available through provided interfaces. Sensor readings like the vehicle's location or battery levels can also be obtained and may be included in the strategy execution.

Base stations, in contrast, run a Strategy Coordinator in the application layer. It is responsible for managing all strategies currently in execution. Several strategies can run in parallel, each of them with its distinct set of UAVs. Executed strategies on the base station are responsible for the coordination and control of their respective UAVs. Hence, each strategy used in the application requires a definition for UAVs and another for the base station.

SUPPORT STRATEGIES FOR POST-DISASTER COMMUNICATION NETWORKS

As shown in our previous work Álvarez et al. 2018, the typical human behavior of forming groups and loitering around important locations, in the field test three different villages, leads to heavily intermittent communication islands in the DTN-MANET. Conventional dissemination methods that rely on occasional and uncontrollable encounters of nodes, therefore, cannot provide sufficient communication performance. Especially for high priority messages such as emergency calls, long propagation delays are unacceptable (Álvarez et al. 2018; Baumgärtner et al. 2017).

Small, commercially available UAVs could be used as controllable communication bridges between separated islands. The simulation platform for Unmanned Aerial Systems presented in this paper empowers the assessment of the feasibility and the impact of such a deployment. System behavior is defined by strategies which can be customized and exchanged, allowing to evaluate the advantages and disadvantages of different strategies. Furthermore, adapting parameter settings in the simulation enables the assessment of each strategy with different UAVs or under varying environmental influences. Thus, this platform provides an extensive scope of potential systems that can be developed and evaluated.

As a proof-of-concept, we designed a UAS for the support of civilian-centric post-disaster emergency communication networks. Two basic strategies with distinct features and requirements were implemented to show the wide range of possible UAV deployments (c.f. Figure 5), namely a full-coverage relay mesh requiring large numbers of UAVs (Morgenthaler et al. 2012) and a message ferry approach with only a few UAVs moving between fixed locations (Zhao et al. 2004). Both strategies use multicopter UAVs and are evaluated for their impact on a ground-based network using the DTN-MANET protocol HyperGossip (Khelil et al. 2007).

The idea of the relay mesh strategy is to provide a provisional communication infrastructure to an affected area. Ground devices communicate with the UAVs which act as relay nodes within the dedicated aerial relay network (Morgenthaler et al. 2012). UAVs collect messages and further disseminate them through the relay network, other UAVs then distribute the messages down to the DTN-MANET nodes. The advantage of this strategy is the complete coverage of the affected area, with short delivery delays and also exhaustive message distribution. However, the large amount of required UAVs is a considerable drawback. To provide full-coverage service in a 4 km^2 area with an approximated 75 meters transmission range for the WiFi communication given by the simulator, the distance between UAVs should not exceed 150 meters. Thus, at least 178 UAVs are required to staff each location in a quadratic equidistant relay mesh. For continuous service, however, additional UAVs are required as replacements, otherwise vacancies in the mesh will have a negative impact on the performance. By executing simulations with the graphical representation, as shown in Figure 6, we figured out that 200 UAVs are sufficient to provide continuous service in the complete area without vacancies in the mesh.

The message ferry approach (Zhao et al. 2004) utilizes UAVs as controllable and highly mobile nodes to amplify the communication performance amongst intermittent communication islands forming around important locations. On each of the islands, UAVs hover for some time—in our simulation set to 30 seconds—while collecting and distributing DTN-MANET messages. After that, they move to the next island in the sequence, where the procedure is repeated. UAVs are therefore simple data carriers, but due to their high velocity and independence of roads they

[4]https://lora-alliance.org/

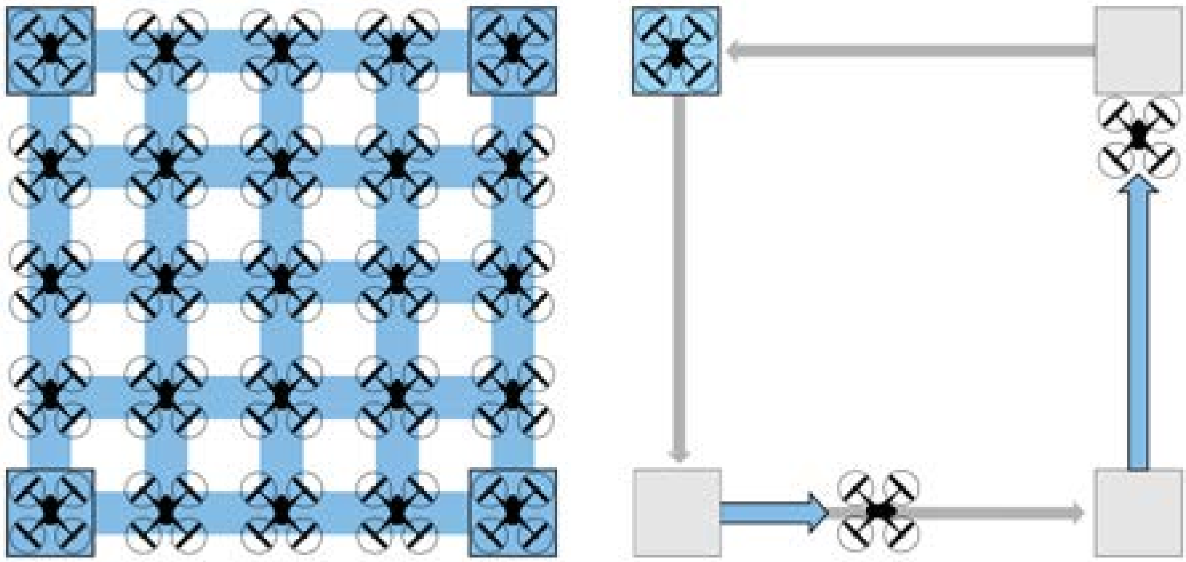

Figure 5. Visualization of two basic, but very different support strategies. Left: Full coverage mesh with equidistant relay node positioning, high requirements on the number of available UAVs. Right: Message ferry strategy, few UAVs can carry data between communication islands but it requires physical transport of each message.

can distribute their messages significantly better than achievable by foot or by car. The advantage of this strategy is a faster message dissemination compared to the conventional DTN-MANET store-carry-forward principle. Furthermore, the strategy can also be executed with only a single UAV, but we expect performance to increase with more UAVs. The drawbacks are a longer and less thorough message dissemination in comparison to the relaying mesh, and most significantly the necessity to know the location of communication islands in advance. In this implementation, a single shortest route connecting all islands and the base station is calculated. Locations are approached sequentially in the same order by each UAV. Performance increases by using multiple or different routes are open for further research.

Both strategies are evaluated with the parameters summarized in Table 1. A 2 km x 2 km inner-city area is simulated for 5 hours with 100 ground nodes moving as pedestrians on walkways. Nodes choose their targets from important locations such as market places, parks, or hospitals. On arrival, nodes stay at the location for a certain pause time between 5 minutes and 5 hours. These pause times model human behavior like social grouping and tasks that have to be executed at these locations, as shown in the field test (Álvarez et al. 2018). A workload generator creates a broadcast message to all nodes every 10 seconds on a randomly chosen node. After a defined message lifetime (time-to-live, TTL) of 30 minutes, messages are discarded and removed from all nodes. As evaluation metrics, we measure the recall, as the percentage of nodes that have received a message within the TTL, and delivery delay, representing the time it took to reach all nodes. Evaluation results are shown in Figure 8 for recall and delivery delay, comparing the DTN-MANET without support against the mesh and the ferry strategy, respectively. Simulations were repeated ten times with varying random seeds. Boxes indicate the 25th and 75th percentile with the median value as bold dash and whiskers indicate the 2.5th and 97.5th percentile. The horizontal axis shows the different pause time, ranging from 5 to 60 minutes minimum pause time, and also without movement between islands.

It can be observed that the unsupported DTN-MANET is behaving as expected. With less inter-island movement, recall drops due to fewer encounters with other nodes, to a point when messages are only distributed within an island when there is no node movement. However, even with 30 minutes TTL and node movement, messages are distributed to 4 of 5 islands at best. Furthermore, more than 50 percent of delivered messages require more than 9 minutes, and 25 percent need more than 20 minutes for their dissemination. As seen in the setting without movement, message dissemination within a communication island is very fast. Measured values show a delivery delay of a few milliseconds on average.

The mesh strategy achieves a perfect recall and very short delivery delays. In some cases, nevertheless, dissemination can take a few minutes to reach every single node on the ground. This results due to packet collisions during the message propagation to or within the DTN-MANET, since relay nodes only push new messages down to the ground nodes once. In accordance with the HyperGossip protocol (Khelil et al. 2007), messages are stored and only forwarded if a previously unknown node is met. Thus, the forwarding is only triggered by nodes moving to a new communication island.

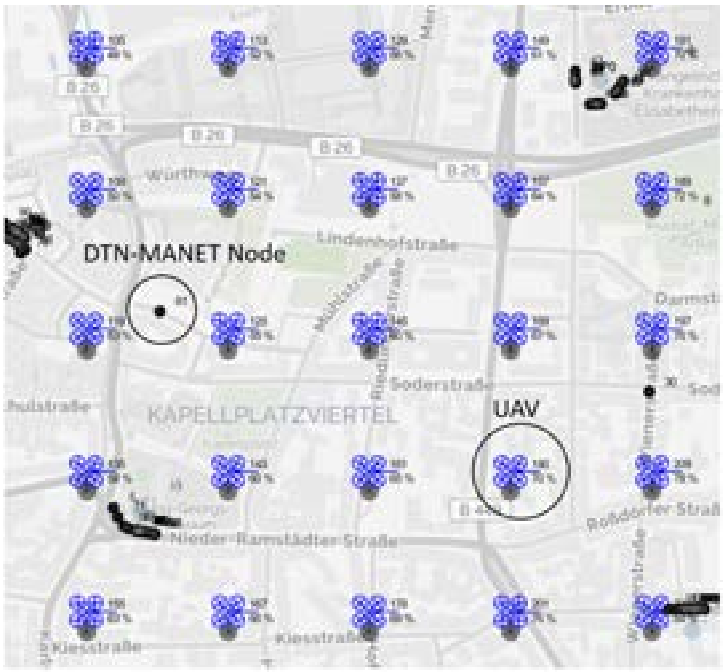

Figure 6. UAVs form a relay mesh in an urban environment. The graphical representation of SIMONSTRATOR.KOM shows UAVs hovering above the map and DTN-MANET nodes on the ground. Nodes use pedestrian walkways when moving or gather around important locations. UAVs are visualized with their current battery levels.

As shown in Figure 7, message ferries follow a predefined path. Since the physical movement of the messages is required for the dissemination, there are significant delivery delays in comparison to the mesh strategy. However, delays are much smaller than for the pure unsupported DTN-MANET environment, most of them in the range of 5 to 10 minutes. With node movement, delays are considerably higher due to the lack of node encounters while they move between islands. This also has a small negative influence on recall, if the message lifetime is exceeded while a node moves. As a consequence, the message ferry approach performs best when the ground network topology is not changing and every node is part of a communication island.

In conclusion, the relay mesh strategy outperforms the ferry strategy in both recall and delivery delay. However, the mesh strategy is highly inefficient in environments with communication islands, due to the large sparsely frequented areas in between where no UAVs are needed for communication support. As the number of UAVs influences both the complete system costs in acquisition and maintenance, the amount of required infrastructure such as landing pads and battery chargers, as well as the size of necessary power sources, an efficient utilization of the available UAVs is key. The message ferry strategy on the other hand requires significantly less UAVs and specifically targets

Parameter	Setting
Simulated Time	5 hours
Simulated Area	2 km x 2 km
Number of Islands	5
Number of Nodes	100
Node Movement	1 – 2 $\frac{m}{s}$
Pause Time	5 – 300 minutes
Message Lifetime (TTL)	30 minutes
Message Generation	1 broadcast every 10 seconds
Mesh Strategy	200 UAVs, 150 meters mesh distance
Ferry Strategy	10 UAVs, 15 $\frac{m}{s}$ speed
UAV Flight Time	20 – 25 minutes
UAV Flight Altitude	30 meters
UAV Battery Replacement	60 seconds

Table 1. Simulation parameter settings for the urban scenario.

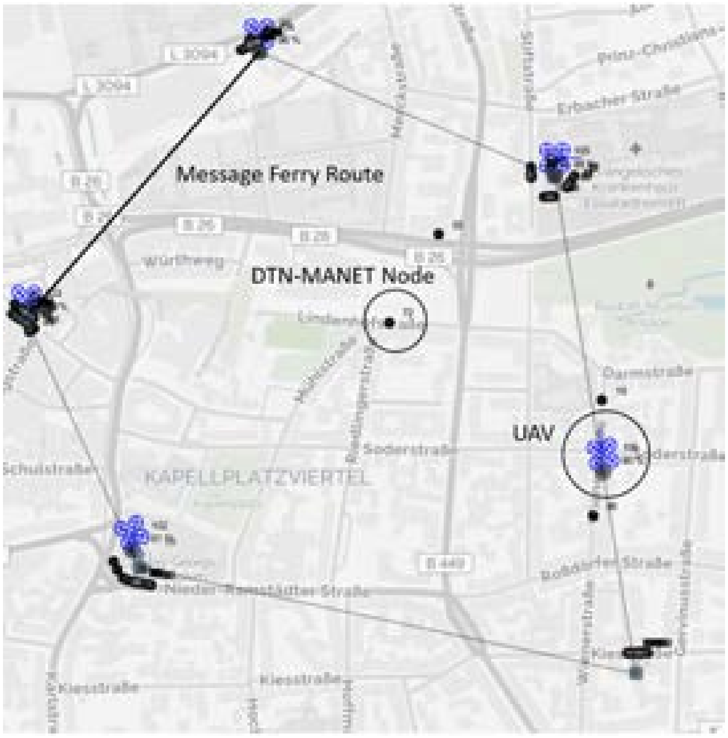

Figure 7. Message ferry UAVs move between five communication islands. They hover above each location while exchanging messages with the DTN-MANET nodes on the ground, before moving to the next. UAVs only visit statically defined islands, thus, nodes out of transmission range cannot be reached.

the dissemination between communication islands. However, for a practical real-world application, the system must be configured such that it performs well in the considered scenario by using the available resources in a meaningful way. We therefore analyze the impact of the number of available UAVs on the ferry strategy. Therefore, we map the environmental characteristics of the field test (Álvarez et al. 2018) into the simulation platform as displayed in the visualization in Figure 9. This contains the underlying map of the area, the number of participants and the movement patterns between the three different villages.

With normal movement speed, it takes a node approximately 12 minutes to walk from Village B to Village C and approximately 50 to 70 minutes to walk from Village C to Village A. In the field test area, there was no direct walking path connection between Village B and Village A. We use 10 different seeds for the simulation to alternate the movement and the workload generator. Available UAVs were varied between 0 and 20 and a TTL of 10, 30, and 60 minutes was considered, respectively. Although a 10 minutes TTL is too short for common DTN-MANETs, results give insight into the possibilities of quick dissemination regarding emergency calls enabled by UAV support.

As indicated by the straight lines in Figure 9, UAVs fly directly between villages. The flight duration between Village B and Village C is 45 seconds, between B and A 4.4 minutes, and 4.1 minutes between A and C, respectively. UAVs need 18 seconds between the UAS Base Station and Village C, and furthermore, will hover over each village for a dissemination time of 30 seconds. Because the combination of flight and hover time will consume more than 53% of the full battery capacity, a UAV will not be able to complete more than one iteration. Thus, it will return to the base station after visiting Village C, B, and A consecutively, for a 60-second battery exchange phase. The total time it will take a UAV to complete one full iteration including dissemination and battery exchange, therefore, is around 12 minutes.

Figure 10 depicts the results for recall and delivery delay, starting with no UAV support up to 10 message ferry UAVs. Boxes indicate the 25th and 75th percentile with the median value as bold dash and whiskers indicate the 2.5th and 97.5th percentile. The results for 11 up to 20 UAVs are not displayed in the figure, because only minor changes in the delivery delay are perceived.

With no UAV support and a TTL of 10 minutes, messages only spread in the village where the message is generated, resulting in approximately a third of the nodes receiving the message with a very low delivery delay. With a TTL of 30 and 60 minutes, the movement of the nodes is sufficient to deliver messages between the different villages, resulting in a median recall value of 0.7 and 0.8, respectively. However, Figure 10 shows that one or two UAVs

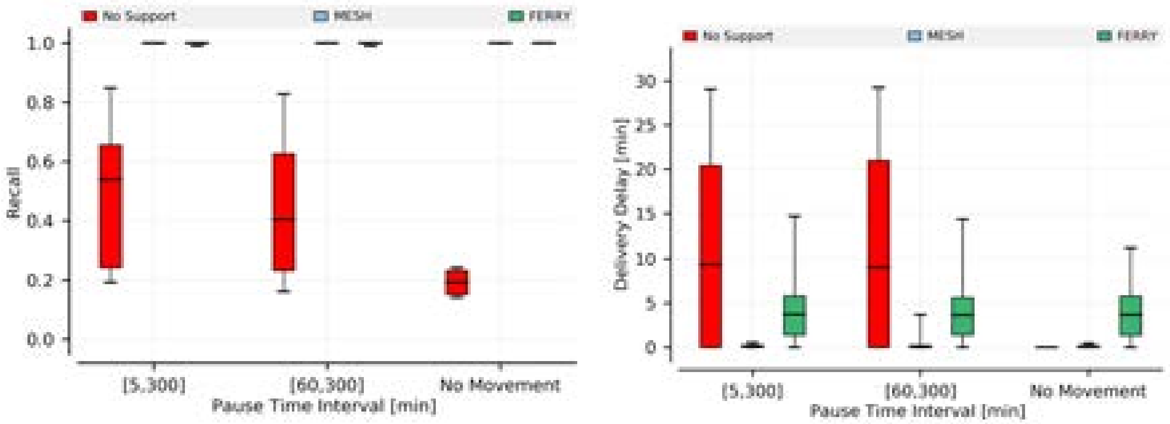

Figure 8. Recall (left) and delivery delay (right), comparing the DTN-MANET without support to the relay mesh strategy and the message ferry strategy, respectively.

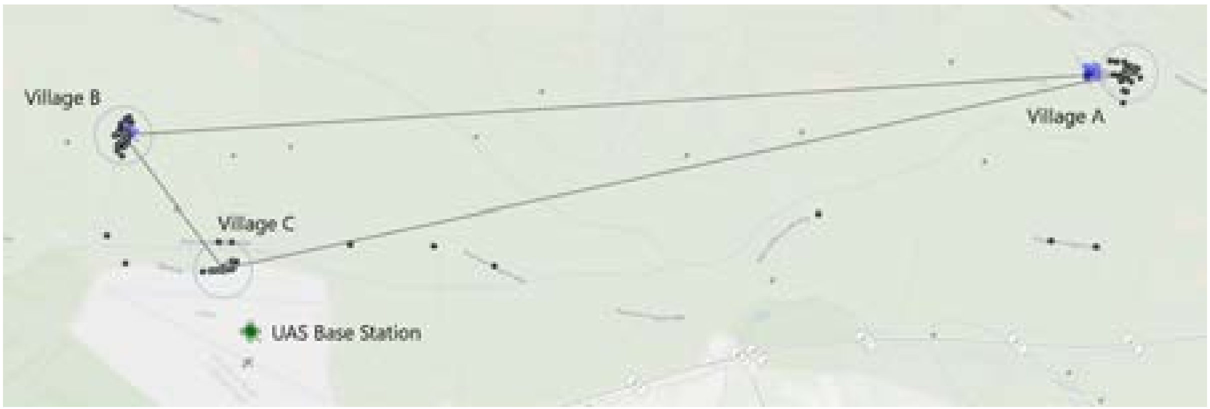

Figure 9. Simulation of the field test environment in Simonstrator.KOM. Similar to the behavior perceived in (Álvarez et al. 2018), most nodes group within the three villages. Only a few nodes move between the villages using the roads connecting Village A and C (approximately 5 km) and Village B and C (approximately 1 km). The UAV Base Station is located near Village C. Straight lines indicate the route UAVs take, reducing the distance between Village B and C to around 660 meters as well as the distance between Village A and C to under 3.7 km. The full route including the distance to the UAS Base Station is around 8.6 km long, one UAV takes around 12 minutes to complete one full iteration, including the time for dissemination and battery exchange.

increases the recall significantly, regardless of the applied TTL. As this requires the physical transport of messages transmitted to other communication islands, the perceived delivery delay also increases, best seen in the results for 10 minute TTL. The utilization of additional UAVs further increases the recall while reducing the delivery delay. However, due to the fixed route between villages and the base station, which the UAVs traverse, more UAVs will only result in decreased intervals between visits of UAVs in the villages. The route traversal time stays the same, nevertheless, which leads to a saturation of the system. Thus, no more significant changes in both recall and delivery delay are perceived. Furthermore, the optimal recall of 1.0 cannot be reached for a TTL of 10 or 30 minutes due to nodes moving in between communication islands. Messages that are generated during the transit can expire before the node reaches an island, with increasing negative influence for smaller TTL settings. This problem cannot be solved by the used message ferry strategy, e.g., by increasing the used UAVs, but requires more complex strategies that are left open for further research.

Evaluation results like this can be used to design and optimize a Unmanned Aerial Communication Support System for specific scenarios. Regarding the characteristic of the supported DTN-MANET, required strategy properties can be determined. For example, when supporting a DTN-MANET with a TTL of 60 minutes 2 UAVs are sufficient to achieve optimal recall in our scenario. Utilizing additional UAVs result in lower delivery delay, however, more than 7 UAVs do not yield significant improvements, reaching a delivery delay of less than 10 minutes for approximately 75% of the messages.

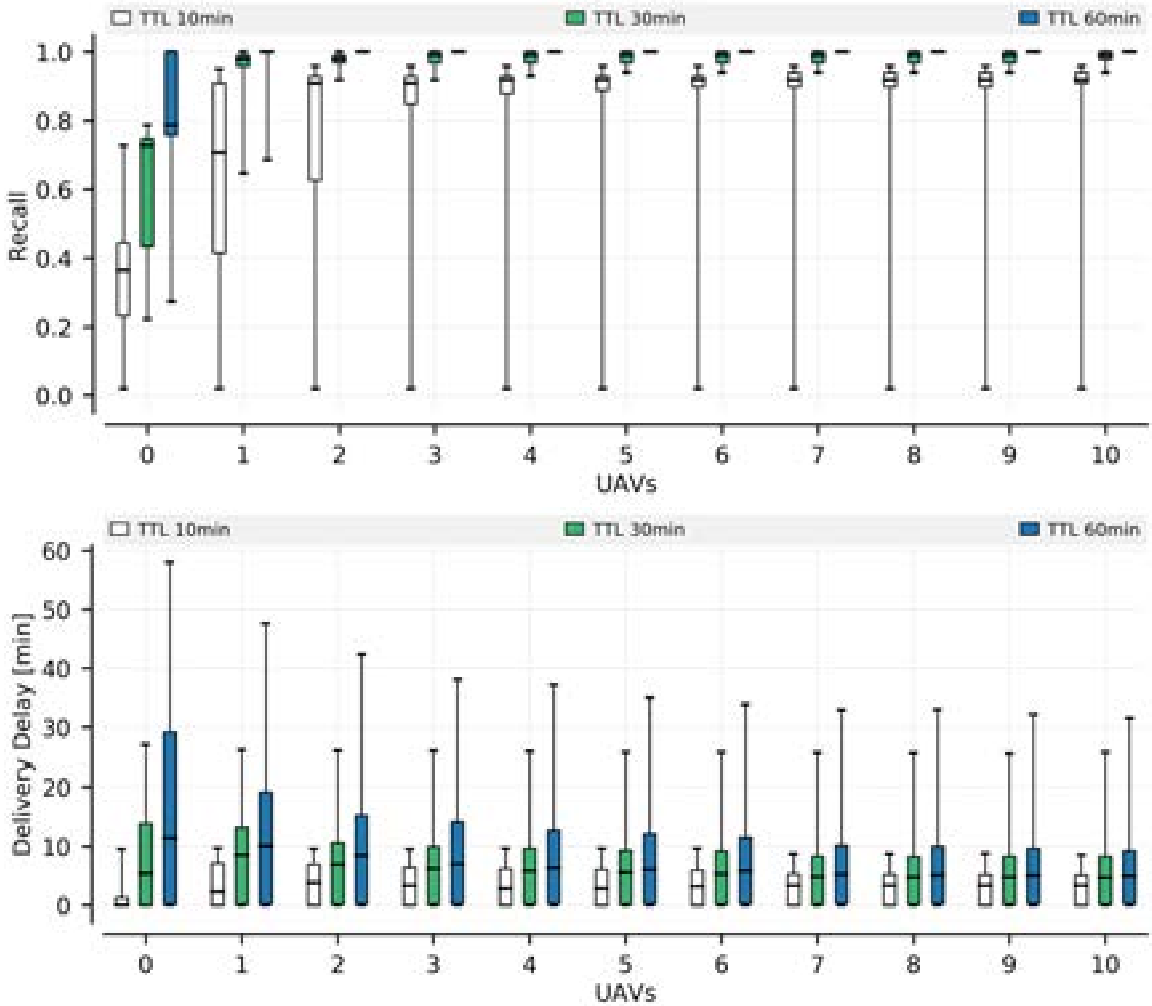

Figure 10. Recall and delivery delay variance shown for increasing numbers of UAVs. The TTL was set to 10, 30 and 60 minutes, respectively. As indicated, a few UAVs already significantly increase the communication performance, especially with longer TTL. The setting '0 UAVs' shows the unsupported DTN-MANET performance.

CONCLUSION, DISCUSSION & FUTURE WORK

In this paper, we motivated the need for efficient UAV-based communication bridges between DTN-MANET communication islands in post-disaster scenarios based on our findings from a large-scale field test (Álvarez et al. 2018) and other related work. However, to assess the performance of individual strategies for the deployment and coordination of UAVs, it is not feasible to repeat such tests on a regular basis. To address this issue, we proposed a discrete event-based simulation platform for Unmanned Aerial Systems (UASes) in this work, combining models for an individual UAV's behavior and its communication abilities with a fully-fledged network simulator for DTN-MANETs for the first time.

To showcase the capabilities of our platform, we discussed two representative strategies for large-scale UAV support of a DTN-MANET in post-disaster scenarios. We evaluated both strategies in an urban environment, highlighting their individual cost vs. performance profiles. Additionally, we provided an in-depth discussion w.r.t. the meaningful utilization of resources by modeling the conducted field test in our simulation platform and evaluating the message ferry strategy with different amounts of UAVs. Our evaluation successfully demonstrates the ability of our proposed platform to assess the performance of UASes and the determination of critical strategy properties in combination with various DTN-MANET scenarios.

For future work we plan to integrate additional models, such as channel models for long-range communication (e.g., LoRa) and other UAV types (e.g., fixed-winged UAVs) into our platform. Furthermore, we want to assess the ability of UAV support strategies to adapt to changes in the DTN-MANET caused by human behavior and changing communication demands (Klinsompus and Nupairoj 2015) and message type priorities (Lieser, N. Richerzhagen, Luser, et al. 2019) over the course of the disaster. Therefore, monitoring techniques in a resource-constrained environment are of great interest.

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