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CAMON: Aerial-Ground Cooperation System for Disaster Network Detection

Julian Zobel*
Multimedia Communications Lab (KOM)
Technical University of Darmstadt, Germany
julian.zobel@kom.tu-darmstadt.de

Ralf Kundel
Multimedia Communications Lab (KOM)
Technical University of Darmstadt, Germany
ralf.kundel@kom.tu-darmstadt.de

Ralf Steinmetz
Multimedia Communications Lab (KOM)
Technical University of Darmstadt, Germany
ralf.steinmetz@kom.tu-darmstadt.de

ABSTRACT

Information on large-scale disaster areas, like the location of affected civilians, is highly valuable for disaster relief efforts. This information can be collected by an Aerial Monitoring System, using UAVs to detect smart mobile devices carried by civilians. State-of-the-art systems typically rely on a purely passive detection approach. In this paper, we present a cooperative communication system between UAVs and ground-based devices to improve the detection performance of such an Aerial Monitoring System. We provide different approaches for the cooperative information collection and evaluate them in a simulated inner-city scenario. The results highlight the effectiveness of the cooperative system, being able to detect civilian devices in the disaster area faster and more comprehensively than a non-cooperative approach.

Keywords

Aerial Disaster Monitoring System, Delay-Tolerant Networks, Cooperative Network Protocols, Simulation

INTRODUCTION

The increasing occurrence and severity of small- and large-scale natural disasters caused, for example, by extreme weather conditions in recent years (Université catholique de Louvain (UCL) 2019; Toya and Skidmore 2018; Gallucci 2018; Ranghieri and Ishiwatari 2014), led to an increase of scientific contributions to the fields of disaster preparedness and disaster relief. Especially due to the frequent and extensive destruction of infrastructure for information and communication technologies (ICT) like landlines or cellular networks, there is a necessity for innovative approaches to restore the desperately required communication for the affected civilian population (Toya and Skidmore 2018). Within this specific field, the use of Delay- and Disruption-Tolerant Networks (DTNs) in combination with Unmanned Aerial Vehicles (UAVs) have already proven their justification for existence.

On the one hand, DTNs provide basic communication capabilities for the affected civilians and are capable of supporting disaster relief services (Álvarez et al. 2018; Lieser, Alvarez, et al. 2017). They work independently of destroyed ICT infrastructure, by spanning short-ranged multi-hop networks, for example, by the use of WiFi Ad Hoc communication between mobile smart devices of civilians (Álvarez et al. 2018; Lieser, Alvarez, et al. 2017; Mori et al. 2015; Toya and Skidmore 2018; Baumgärtner, Lieser, et al. 2020; Hollick et al. 2019). On the other hand, however, disaster DTNs are usually fractured over large distances and exhibit a highly intermittent network topology, with dense clusters around points-of-interests like shelters and sparsely populated areas in-between (Álvarez et al. 2018). Despite employing robust *store-carry-forward* communication protocols that are able to cope with highly mobile and fractured network topologies, the exchange of information between distinct network clusters is solely dependent on the opportunistic mobility of the network nodes between these clusters. In other words, civilians that carry messages inside their smart device like in a digital backpack are required to move between disconnected

*corresponding author

network partitions to enable communication between these clusters. But as debris or flooding may inhibit the mobility on the ground, especially in a disaster scenario, inter-cluster communication is, as a result, at least scarce and tedious, if possible at all (Álvarez et al. 2018; Zobel, Lieser, Meuser, et al. 2021).

For that problem, a communication assistance system of one or multiple UAVs can be installed within the disaster area. The UAVs either can be used as aerial access points to a relay network mimicking a cellular network (Li et al. 2019), or as quick and efficient mobile data carries between network clusters (Qin et al. 2019). The first approach could provide a comprehensive network coverage that replaces the destroyed ICT infrastructure with small communication delays between senders and receivers. However, this may require an enormous number of UAVs and supporting infrastructure like chargers to maintain the relay network in large-scale disasters. In contrast, the latter approach can be applied with only a single UAV acting as a data carrier moving from cluster to cluster to collect and disseminate messages. Nevertheless, the performance may further increase with more data carriers available. The disadvantage of this approach is that message exchange is still delayed in direct correlation with the flight time of data carriers and distances between clusters (Lieser, Zobel, et al. 2019). Still, both approaches are good alternatives to fixed installments like long-range communication links over directional antennas, due to their flexibility to accommodate shifting disaster scenarios without requiring specialized hardware within each network cluster. Similarly, satellite-based communication is usually not available due to a widespread lack of satellite phones or comparable devices in the civilian population[1].

The biggest drawback of applying UAVs to support communication in a disaster scenario is the necessity to have information on the network topology, i.e., the location of civilians and DTN devices. Similar to almost all disaster relief efforts, rescue teams, or emergency services, such information is usually not available despite being paramount for efficient disaster relief (Mozaffari et al. 2017). UAVs are, however, also capable of collecting information on civilians and the disaster area, for example, by visual observation with on-board cameras or by tracking wireless communication signals, such as DTN beacons (Li et al. 2019; Zeng et al. 2019; Rubina et al. 2019). As part of an *Aerial Monitoring System* (AMS), UAVs can be deployed efficiently to monitor the disaster area, initially gathering important information on the location of civilians and keeping it up-to-date throughout the deployment. In previous work, we have presented the basic properties and requirements of an AMS. A large negative impact on system performance was detected to be the *passive device monitoring* approach, which requires an overlap of the area a UAV is currently able to monitor and the area that some action of a device is perceivable, both in space and time. Thus, we proposed a highly simplistic approach to split the monitoring effort between UAVs in the air and the ground-based DTN (Zobel, Meuser, et al. 2021).

In this paper, we present *CAMON* (Cooperative Aerial MONitoring), a system for cooperative aerial-ground network monitoring between the *Aerial Monitoring System* and the civilian *Disaster DTN*. The goal is to improve the efficiency of the aerial disaster network detection by overcoming the purely passive monitoring approach of state-of-the-art systems, while simultaneously being a lightweight solution that can be integrated into typical DTN communication protocols or used for standalone network detection. Specifically, we present three different approaches to collect the network information in *CAMON* and share it with the UAVs: (1) distributed proactive collection, (2) centralized proactive collection, and (3) reactive collection. The simulative evaluation of these protocols highlights different advantages and drawbacks depending on the aspired system requirements. Despite a particularly large impact on communication overhead, cooperation can provide a significant benefit to disaster network detection.

The rest of the paper is structured as follows. In the next section, related work on network detection and Aerial Monitoring Systems is discussed. Afterwards, we provide an overview of our Aerial Monitoring System and the Delay-Tolerant Network, before specifying the cooperative aerial monitoring system *CAMON*. The evaluation of *CAMON* and its different cooperation protocols is presented in the subsequent section. Finally, we conclude the paper and discuss further approaches for future work.

RELATED WORK

The exploration and monitoring of areas is one of the many applications for Unmanned Aerial Vehicles (UAVs). Typically for search-and-rescue missions, this includes visual observation to identify victims in a disaster (Rémy et al. 2013; Mezghani and Mitton 2019; Scherer et al. 2015) or localize forest fires (Belbachir et al. 2015). Furthermore, UAVs can be used to support ground vehicles by providing additional information from an aerial viewpoint (Guérin et al. 2015). Another, more recently emerged application for UAVs is the support or complete provision of communication capabilities to devices on the ground. This can include acting as a relay network or as specific access points, for example, for WiFi, LTE, or 5G (Li et al. 2019; Lieser, Zobel, et al. 2019).

[1]E.g., the Iridium satellite network had only about 1.5 million users worldwide in 2020. (2020 Annual Report, Iridium Communications Inc.)

However, these approaches usually require knowledge on the location of devices, which can also be provided via identification approaches. Since visual identification has the drawback of requiring line-of-sight, which can easily be obstructed, other approaches use radio transmission for identification and localization. By listening for WiFi packets such as DTN beacons, the object can be located either by triangulation or the message itself contains the location information (Rémy et al. 2013; Rubina et al. 2019). Nevertheless, this identification requires a spatio-temporal overlap of the device and the UAV, i.e., an overlap of the device's transmission range and the UAV's reception range at the time of a transmission from the device.

In case a UAV-based service must be provided to a large area, multi-UAV systems are used, which split the workload among multiple UAVs usually over multiple smaller sub-areas (Sánchez-Garcia et al. 2019; Khan et al. 2014). For both single- or multi-UAV systems, areas must be traversed to identify devices or provide their service. Trajectories are determined based on the overall objective or service criteria. For that, several approaches, such as moving between grid cells (Khan et al. 2014), moving randomly through the area (Sánchez-Garcia et al. 2019), using bio-inspired algorithms like *Particle Swarm Optimization* (PSO) (Eberhart and Kennedy 1995; Arafat and Moh 2021), or a lawnmower or Boustrophedon pattern (Peralta et al. 2020; Hayat et al. 2020), have been discussed in literature before. For the initial assessment of the disaster area, when no knowledge of the situation is available, full area coverage is desirable. Calculating such a trajectory is also known as coverage path planning and is possible with an exhaustive lawnmower path for an Aerial Monitoring System. Even though this requires a long time to traverse the whole area, it provides a complete snapshot of it (Hayat et al. 2020).

Ad hoc networks and specifically Delay- and Disruption-Tolerant Networks (DTNs) are a large field of research due to the diverse applications in areas without working telecommunication infrastructure, such as disaster areas (Lieser, Alvarez, et al. 2017). Depending on the used DTN protocol, all nodes, for example, remember already encountered nodes, know their local 1-hop neighborhood, or know all other nodes within their local network cluster (Khelil et al. 2007; Lindgren et al. 2012). More sophisticated protocols could also proactively maintain communication routes to all nodes within their cluster (Battat et al. 2014) or determine nodes as special cluster heads or data sinks (N. Richerzhagen et al. 2015)

CAMON: COOPERATIVE SYSTEM FOR DISASTER NETWORK DETECTION

The collection of valuable information on a disaster area is one of the paramount first steps for efficient disaster relief. This could be, for example, an overview of the disaster area itself or specific information on infrastructure, roads, or the affected population. As already highlighted in the introduction, we assume that a *Delay- and Disruption-Tolerant Network* (DTN) is used to provide basic means of communication to the civilians within that area and that, in the end, we aim to support that disaster DTN with a UAV-based aerial communication assistance system (Lieser, Zobel, et al. 2019). However, this requires knowledge on the whereabouts of DTN devices, and therefore, we specifically target at the localization of smart devices worn or carried by the affected civilians within this paper. Note that although we focus only on the application of an aerial communication assistance system, this information is nevertheless similarly important for other disaster relief efforts. Within this section, we discuss the *Aerial Monitoring System* (AMS) that is used for disaster network detection, the disaster DTN itself, and the different approaches for cooperation between AMS and DTN.

Aerial Monitoring System

The deployment of an *Aerial Monitoring System* (AMS) within a disaster scenario allows quickly asserting the situation by gathering essential information, such as the location of affected civilians. UAVs are generally independent of destroyed or blocked roads and can move quickly over the disaster area, making them a great tool for reconnaissance and monitoring. The gathered information can be used to immediately navigate emergency service teams to where they are needed, but also to determine the optimal location or routes for UAVs of an aerial communication assistance system.

In our case, we rely on the detection of wireless signals from smart mobile devices, such as DTN beacons from smartphones of affected civilians. To sense a beacon message with a UAV of the AMS, an overlap of the transmission range of a DTN device and the reception range of a UAV is required in both space and time; i.e., the UAV must be able to receive the beacon at the time the DTN device is sending and, thus, the beacon can easily be missed. The performance of the AMS, such as the number of detected nodes or the age of that information, is directly related to several factors and requirements of the deployed AMS. For example, depending on the size of the operation area and the number of available UAVs and their properties like flight range or speed, it may be necessary to split the operation area into smaller monitoring areas. However, allocating monitoring areas is also influenced by the used coverage path planning approach, for example, a simple random traversal, a lawnmower (back-and-forth)

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path, or a distributed PSO-based approach (Eberhart and Kennedy 1995), the (assumed) communication range of DTN devices and UAVs, and so on. Requirements on the AMS' performance, like a maximum age-of-information, can bring further restrictions on the application of the monitoring UAVs. Many factors influence each other; for example, increasing a UAV's flight speed can lead to quicker results, but also increases the power consumption, which in turn may require either adapting the size or decreasing the coverage of the monitoring area. Covering all these factors and requirements, for example, as an optimization problem to get the best monitoring area allocation is not within the scope of this paper and is left open for future work. Instead, we rely on manually splitting the monitoring areas, similar to a human system operator.

For the AMS in this work, we use a system design comprised of a single base station and multiple quadrotor multicoper UAVs, as described in previous work (Lieser, Zobel, et al. 2019). The base station acts as a central system controller and provides infrastructure for starting, landing, and recharging UAV batteries. UAVs are capable of starting and landing at the base station, but can also autonomously monitor a certain monitoring area that is given by the base station. Communication between the base station and UAVs is possible over a low-throughput connection such as a satellite link or an LPWAN link like LoRa. Therefore, this communication link is not capable of transmitting larger data sets, such as the monitored data, but can be used as a control channel. UAVs are also able to communicate via WiFi with ground-based DTN nodes within a limited range around them. Specifications on the UAV-DTN communication and the UAV flight paths are given in the following sections.

Disaster DTN

The disaster network is comprised of several devices, which are capable of wireless communication via WiFi within a limited range around them. Each DTN device has a unique identifier and access to its location, e.g., using GPS. With the use of a DTN protocol (cf. Penning et al. 2019; Khelil et al. 2007), nodes within transmission range span a device-to-device multi-hop network between each other.

A vital part of each DTN protocol is the broadcast of beacons, making devices visible to each other and allowing recognition as a neighbor in the local DTN network. Thus, each device holds a list of known nodes in their direct 1-hop neighborhood. Beacons are regularly broadcasted by each device, either statically within a fixed or within an adaptive announcement interval, for example, based on the number of neighbors. In case a neighbor's beacon was not received within a certain time frame, we assume it moved outside of the communication range, and therefore, the neighbor is removed from the respective list. The interested reader is referred to (Baumgärtner, Graubner, et al. 2017) for more information on DTN announcement intervals.

Beacons may also include additional information like stored messages, the location of the sender, or other known neighbors, and can be used to identify the local cluster that DTN devices belong to, i.e., through a cluster hash ID. This information then can be used to detect changes in the local network topology, e.g., new devices merging into the local cluster or a fragmentation of the network (Khelil et al. 2007). For that, devices may also hold an additional list containing all known nodes in their local cluster. Which content is included in the beacons and how they are exchanged is presented in detail for the respective protocols in the following section.

CAMON: Cooperative Aerial-Ground Network Monitoring

One of the largest restrictions on the AMS' performance is the approach for detecting and monitoring DTN devices. Typically, UAVs traverse the monitoring area and passively sense for DTN beacons. As already discussed, this can lead to missed beacons in the AMS, as both UAV and DTN device must be in each other's reception and transmission range, respectively. Splitting the effort for node detection between the UAVs in the air and the DTN devices on the ground, however, has shown to be a possible improvement to the detection process (Zobel, Meuser, et al. 2021).

In this paper, we present the *Cooperative Aerial-ground Monitoring System* (*CAMON*), a system for communication between an AMS and a DTN for the cooperative detection and monitoring of a disaster network. With *CAMON*, we shift the workload of information collection on the network from a purely passive approach on the UAVs towards a shared approach between the nodes in the ground network and the UAVs in the air. The goal of our system is to provide a lightweight solution for cooperative network detection that can be integrated into typical DTN communication protocols on the one hand, but is also capable of standalone network detection on the other hand. For that, we defined three different protocols within *CAMON* which primarily determine the content of beacon messages and the message exchange in the DTN. In all protocols, beacons are sent within a fixed time interval.

The UAV is still required to listen for DTN beacons, as this is the only possibility to detect the presence of a DTN device. However, on the reception of a beacon, the UAV may actively send a Cluster Information Request (REQ) message to the beacon's origin. In turn, that DTN device may answer with a Cluster Information Reply (REP)

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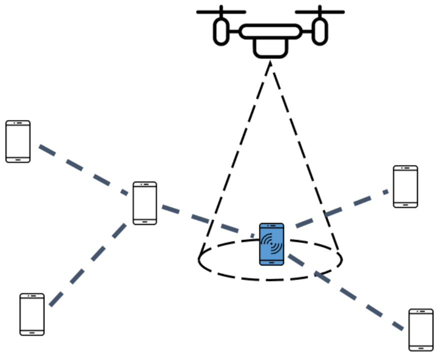
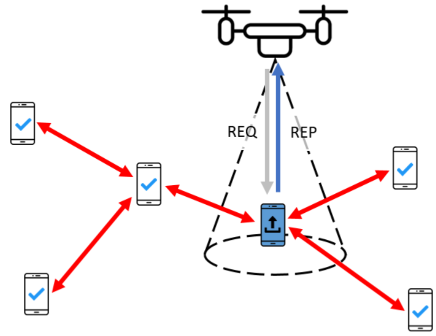
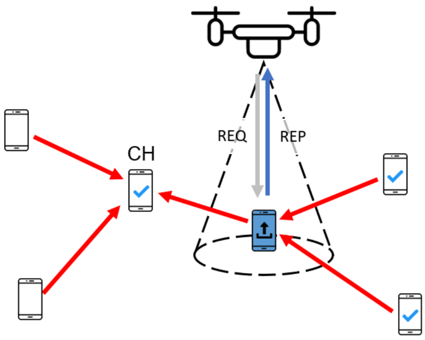


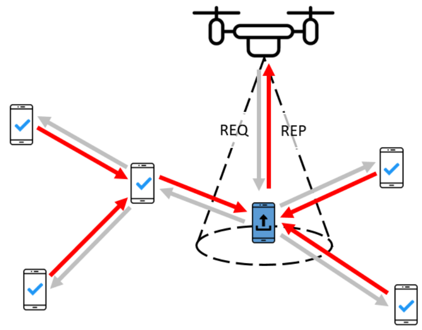
(a) Beacon: UAVs can only detect nodes within their communication range by listening to beacons.



(b) Proactive: Nodes recurrently flood information in the network (red). When receiving a REQ message, the contact node (blue) immediately transmits its current state of information (ticks) to the UAV.



(c) Hierarchy: Nodes construct and maintain a hierarchical structure (red) with a central Cluster Head (CH). When receiving a REQ message, the contact node (blue) transmits its information on their hierarchical layer (ticks) to the UAV.



(d) Reactive: When receiving a REQ message, the contact node triggers the information collection in the cluster (grey). Up-to-date information is shared in the network (red) and transmitted to the UAV via the contact node (blue).

Figure 1. Sketches for the presented *CAMON* protocols. Information flow in the DTN is denoted by red arrows. The contact node receiving the Cluster Information Request (REQ) message is marked in blue. Cooperatively detected nodes received as part of a Cluster Information Reply (REP) message are marked by ticks.

message that contains the known information of the local cluster. To prevent broadcast storms—overloading the network with excessive message flooding—, devices are addressed individually by UAVs. Furthermore, UAVs will not contact other devices within a certain response wait time and also not contact devices from the same cluster for a certain cluster re-request time after receiving cluster information. In case the cluster topology changes, however, the hash ID of the cluster will also chance and, therefore, the UAV sends an additional REQ outside of that pause interval. The exact procedure depends on the applied protocol, which are discussed in the following. Sketches of the respective protocols are shown in Figure 1.

Non-Cooperative Protocol (Beacon)

The non-cooperative protocol (cf. Figure 1a) is used as a baseline comparison for the cooperative *CAMON* protocols. All REQ messages from UAVs are dropped and no cooperative communication between DTN nodes is conducted. In this protocol, devices send minimalistic beacons only including their ID and location. Therefore, each device must be detected individually by the UAVs, which is the standard case without a cooperative network detection approach.

Distributed Proactive Protocol (Proactive)

In the distributed proactive protocol (cf. Figure 1b), devices actively share all available information, i.e., their own location, the knowledge of their direct 1-hop neighborhood, as well as the knowledge of all devices in the local network cluster within their beacons. Each datum for a known device is stored and exchanged as a Triple *(ID, Timestamp, Location)*. Whenever a beacon is received, the information on the sender is directly updated. Additionally, beacons can include information on the local cluster as seen from the beacon sender. Each datum of the received beacon is inserted into the device's knowledge base after checking that the received datum is more recent than an already stored datum. The device sends its updated information with its next beacon to also inform the rest of the neighborhood.

However, not every beacon must contain information on the neighborhood and the local cluster, as this would require significant bandwidth and could overload the wireless medium. Especially when the transmitted information contains no new information, it is redundant and should not be sent. Thus, network information is only appended to a beacon if there was a perceivable change, either that (i) a beacon of a currently unknown node was received, (ii) a beacon of a known neighbor was not received for a certain time, or (iii) a neighbor sent a beacon with a different cluster hash ID. While the former two cases are directly indicating a topology change locally, the latter shows a change in the local cluster outside the 1-hop neighborhood. As an additional precaution to limit broadcast storms and redundancy, all devices only append their information to their next beacon if no other beacon with the same information is received until then.

With that, the proactive protocol is a simple flooding-based approach for information exchange amongst the DTN devices. Information is available on all nodes and updates are propagated whenever reasonable changes occur. Therefore, on the reception of a REQ message from a UAV, a device directly replies with the available information; no further communication within the DTN is required. However, data may be inaccurate or outdated at the time of uploading the data to the UAV with very recent changes. Additionally, the frequent flooding of information and updates imposes a significant load on the network despite efforts to reduce it in general.

Centralized Proactive Protocol (Hierarchy)

In contrast to the distributed proactive protocol, the centralized proactive protocol does not share all information on all nodes in the network. Instead, a hierarchical structure is built and maintained throughout each network cluster, as shown in Figure 1c, which only requires the exhaustive exchange of location and neighborhood information for the setup of the hierarchy. Based on exchanged information and a given metric, one DTN device is collectively chosen to be the central cluster entity. In our case, the metric chooses the node closest to the geometric center, but there are other possibilities for such metrics (cf. N. Richerzhagen et al. 2015).

Once established, maintaining the network hierarchy requires regular beacons to detect topology changes, and thus, performs similar to the distributed protocols. Location information is sent only towards the central cluster entity using the constructed hierarchy instead of flooding the whole cluster, which could reduce the network load. Nevertheless, adapting the hierarchy accordingly when changes occur requires additional messages. Especially in crowded but highly mobile scenarios, this may lead to an increase in the overall network load instead of a reduction, as the maintenance overhead will similarly increase with the necessity to adapt the hierarchy more often.

This hierarchical protocol is a more complex approach to centrally collect cluster information at a single DTN device. Each device has only the information of its local neighborhood and the nodes in the hierarchy below itself. Therefore, the workload to collect and push cluster information to the central cluster entity is decreasing with a lower hierarchy level. Whenever a UAV sends a REQ message, the device can still send its constrained set of information. Nevertheless, UAVs will predominantly contact the central cluster entity, if available, and will not contact any nodes from the local cluster after receiving information from the central cluster entity until a change in the network is announced. For cooperative communication with the UAV, no further information exchange is required within the DTN.

Reactive Collection Protocol (Reactive)

One of the most severe issues with proactive protocols, in general, is the large number of overhead messages, which is constantly required for updating the overall information state. Especially in cases when, e.g., no UAV comes in contact with the cluster, the information is collected or maintained unnecessarily. The reactive collection protocol uses the same behavior as the non-cooperative approach as default behavior, so only sending small beacons on a regular basis. The collection is only triggered when a UAV is present.

Whenever a beacon is received by a UAV, it can transmit a REQ message to the beacon's sender, as shown in Figure 1d. The receiving node then triggers the collection process of the local cluster information by broadcasting a beacon with the information of its 1-hop neighborhood to all neighbors, similar to the distributed proactive protocol. Receivers update their local cluster information with the content of this message and re-broadcast their own information as part of their next beacon. With that, the information is flooded throughout the local cluster and updated on every node until a steady state of information is reached. However, when a broadcast with the same information is recognized, the node will not transmit its beacon; only beacons with more recent and different information to the known state of information are sent to prevent redundant transmissions. The initializing node of the trigger sends the REP message with the information on the local cluster to the UAV after a certain time

Table 1. Simonstrator Environmental Settings

Scenario	Map	Inner City, Post-Disaster
	Size	2000 m x 2000 m; 100 Nodes
	Node Movement	Civilian Disaster Mobility [a]
	Points of Interest	5, random distribution
	Duration	1 h, 10 random seeds each
Comm.	PHY	WiFi, IEEE 802.11g
	Range	approx. 75 m
	Data Rate	5 Mbit/s
CAMON	Approach	[Beacon, Proactive, Hierarchy, Reactive]
	Beacon Interval	[0.5 s, 1 s, 2 s]
	Information Validity Interval	[5 s, 10 s, 20 s]
AMS	UAVs	4 quadrotor UAVs [b]
	Flight Time	max. 24 min at 10 $\frac{m}{s}$
	Monitoring Areas	4, 1000 m x 1000 m each
	Coverage Path Planning	Lawnmower
	CPP Strip Width	[100 m, 333 m, 500 m]

[a] cf. Zobel, Lieser, Meuser, et al. 2021, [b] cf. Zobel, Lieser, Drescher, et al. 2019

without receiving beacons with updated information. Since all nodes send their beacons within a fixed interval in our specific case, we defined this time limit to be two times the set interval.

The reactive collection protocol tends to overcome the problematic overhead of proactive approaches by exchanging local cluster information only when requested. As a drawback, this also requires sending a large number of messages in a short time, which could negatively influence other applications within the DTN. Reliable information is only available on all nodes directly after the collection process and is not updated afterwards. Thus, another UAV contact requires triggering a new collection process.

EVALUATION

Both the *Aerial Monitoring System* (AMS) and the *Disaster DTN* were implemented as part of the Simonstrator (B. Richerzhagen et al. 2015) framework within the simulation environment for Unmanned Aerial Systems and ground-based DTNs (Lieser, Zobel, et al. 2019). *CAMON* is implemented based on the given descriptions in the previous section. The mobility of 100 DTN devices represents disaster mobility of civilians (Álvarez et al. 2018) within an inner-city disaster area of 2x2 km^2 based on previous work (Zobel, Lieser, Meuser, et al. 2021). Five points of interest, for example, representing shelters and first aid stations, are randomly chosen for each simulation run, with the restriction that they cannot overlap and have a distance of at least 200 m to each other. Devices gather in the area of these locations or form groups and move to other locations. Mobility itself uses available Open Street Map[2] (OSM) data, thus, devices move only on streets and pedestrian walkways.

Table 1 gives a detailed list of the simulation settings for the Simonstrator framework. Specifically, the presented *CAMON* protocols are compared against each other: (i) the non-cooperative protocol (beacon) as a baseline vs. (ii) the distributed proactive protocol (proactive), (iii) the centralized proactive protocol (hierarchy), and (iv) the reactive collection protocol (reactive). To investigate the influence of different beacon intervals on the performance of *CAMON*, we also simulate each protocol with a beacon interval of 0.5 s, 1 s, and 2 s, respectively. The information validity intervals—the time after which old information is removed from both neighborhood and local cluster knowledge on each node—is set to ten times the beacon interval according to (Baumgärtner, Graubner, et al. 2017). Four quadrotor multicopter UAVs with a maximum flight time of 25 minutes are available for the AMS. The lawnmower algorithm is used for coverage path planning of monitoring areas. To evaluate differences in area coverage, the strip width for the algorithm is adapted as 100 m (10 strips), 333 m (3 strips), and 500 m (2 strips), respectively. With the used WiFi model, UAVs are able to observe an area of approximately 50 meters around them while in flight. DTN devices can communicate within a distance of up to 75 m (Álvarez et al. 2018).

This evaluation uses the following metrics:

[2] www.openstreetmap.org

Messages per Second The number of messages that are either sent or received by a DTN device per second. Values are aggregated averages over all devices.

Bytes per Second The amount of data that is either sent or received by a DTN device per second. Values are aggregated averages over all devices.

Direct Contacts The accumulated number of identifying beacon messages a UAV receives from any DTN devices.

Direct Node Detections The number of nodes detected on a UAV by receiving an identifying beacon message of the respective node.

Node Detections The number of nodes detected on a UAV either by a direct detection or by receiving a *CAMON* REP message containing additional node information.

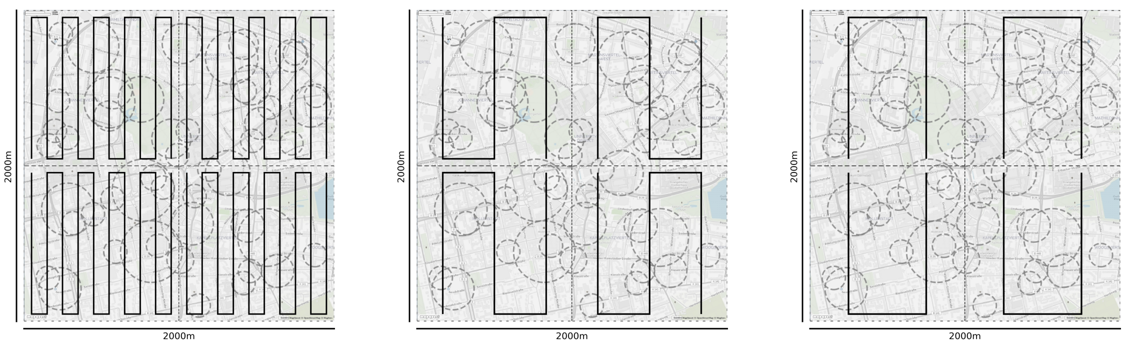
Cooperative Detection Ratio The share of cooperatively detected nodes within the set of all node detections. A node only counts as cooperatively detected if it is never directly detected.

Note that both the direct contacts and the node detections metrics are counted per each monitoring area and aggregated afterwards. As a result, one node can be detected by multiple UAVs and, therefore, counted multiple times, e.g., when located at the border between adjacent monitoring areas.

Monitoring Areas

The operation area of the AMS is divided into four smaller, square-shaped monitoring areas of 1x1 km^2 each and every of the four UAVs is assigned to one monitoring area. We use the simple but efficient lawnmower algorithm—also known as back-and-forth or Boustrophedon algorithm—for the coverage path planning of UAVs within the monitoring areas. UAVs start from the base station, approach the first waypoint of their monitoring path, traverse the area following the given trajectory, and finally move back to land at the base after reaching the last waypoint. The distance between single strips of the lawnmower routing is directly correlated to the distance and time to cover the whole trajectory but also influences the coverage of the monitoring area as UAVs can only observe a limited area around them. Therefore, we have a tradeoff between a long flight time and an exhaustive coverage or a shorter flight time with a decreased coverage. On the one hand, an exhaustive coverage will result in a detailed observation of the area but also results in an increased age of information at the return of the UAV. Furthermore, the required distance for an exhaustive coverage may exceed the maximum flight distance of the UAV. On the other hand, important information could be missed with a less exhaustive coverage, although the collected information will arrive more timely and we can also use UAVs with only short-range flight capabilities.

In our evaluation, we define the strip width w for the coverage path planning as shown in Figure 2, to alter UAV area coverage and flight time. With $w = 100\,m$, thus 10 lawnmower strips covering each monitoring area, UAVs are able to cover 100% of the area within a 20-minute flight, including approaching to and returning from the monitoring area, traveling a distance of 11 km in total. This setting utilizes the full capacities of the used UAVs, and thus, is used as the upper bound for the monitoring area size. By increasing w to 333 m, the area coverage is reduced to



(a) **100 m** (b) **300 m** (c) **500 m**

Figure 2. UAVs traverse the four monitoring areas in a lawnmower pattern, shown in black. The strip width for the lawnmower route is used as 100 m (100% coverage), 333 m (52% coverage), and 500 m (33% coverage), respectively. Areas of interest of all simulation runs are outlined in the background.

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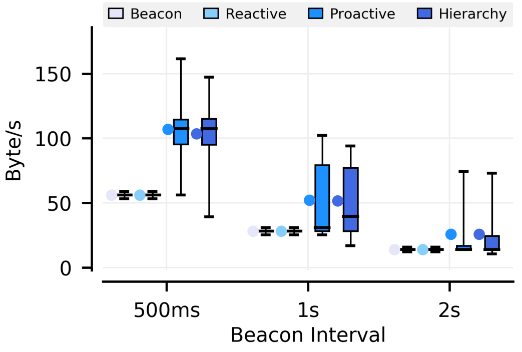
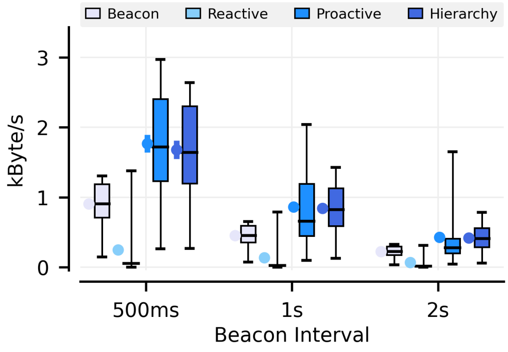


(a) Average data sent per node per second. DTN without UAV interaction.



(b) Average data received per node per second. DTN with UAV interaction.

Figure 3. Overhead measured by the amount of data sent and received on average per node. Proactive and Hierarchy generate larger traffic due to information exchange and maintenance messages, indicating a dynamic network topology. The overhead quickly decreases with increasing beacon interval, as cluster information updates are sent less often. The Reactive protocol generates less traffic in the presence of a UAV per device, illustrating a tightly connected local cluster with fast information collection.

52% and the time and the distance is reduced to 9 minutes and around 5 km, respectively. An additional increase of w to 500 m further decreases the area coverage to 33%, the time to approximately 6 minutes, and the distance to 3.5 km. Note that the relation between w, area coverage, and flight time is not linear, as only the distance between the vertically running lawnmower strips is scaled but the length of the strips is not changed. Furthermore, the UAV's approach and return of the monitoring area is dependent on the location of the start and end locations of the path.

Communication Overhead and Beacon Interval

One drawback of the *CAMON* protocols is the increased communication overhead required for exchanging information. This overhead is directly related to the size of the beacon interval, as a smaller interval results in more beacons sent and eventually a larger overhead in total. Furthermore, it is also related to the used protocol due to the differences when beacons are sent and which information they contain. In addition, the HIERARCHY protocol requires extra messages for maintaining the network structure. Figure 3a depicts the amount of sent data per node for the standalone DTN without UAV interaction. In contrast, Figure 3b shows the amount of received data per node, when interacting with UAVs.

First of all, a clear difference between BEACON and REACTIVE in comparison to PROACTIVE and HIERARCHY is visible. The former two protocols only send a small beacon with the static interval, and as intended, the REACTIVE protocol shows no distinction to the simple protocol without the presence of a UAV. The latter two, however, show an increased average overhead, but also a high deviation in its distribution. Especially for the 500 ms beacon interval, the average overhead for sending data is increased by approximately a factor of two. However, the overhead is also dependent on the mobility of devices: a more dynamic environment leads to more message exchanges for both the PROACTIVE and HIERARCHY protocol. Therefore, we see the possible range of the overhead vary between more than three times that of the other protocols in dynamic environments down to a similar overhead more static environments, indicating a highly mobile and dynamic network topology.

As expected, increasing the beacon interval reduces the amount of data both sent and received on all nodes. More interestingly, however, the overhead introduced by the extra maintenance messages for HIERARCHY exceed the overhead by the PROACTIVE protocol with a larger interval, probably due to a high mobility in the network the amount of maintenance messages is generally high. This can also explain why the PROACTIVE protocol drops more significantly with a higher beacon interval, since the number of beacons and exchanged local cluster information is decreasing faster than the amount of required maintenance messages (cf. Fig. 3b).

Most notably, Figure 3b highlights the different behavior of the REACTIVE protocol w.r.t. UAV presence. While normally functioning similar to BEACON, shown in Figure 3a, a UAV topology request triggers the one-time flooding of information within the local cluster but also nodes skipping regular beacons while waiting for the information to circulate. This generally reduces the average overhead during the interaction, in contrast to the other protocols functioning as normal. However, this—visually—significant drop also must be taken with care. On the one side,

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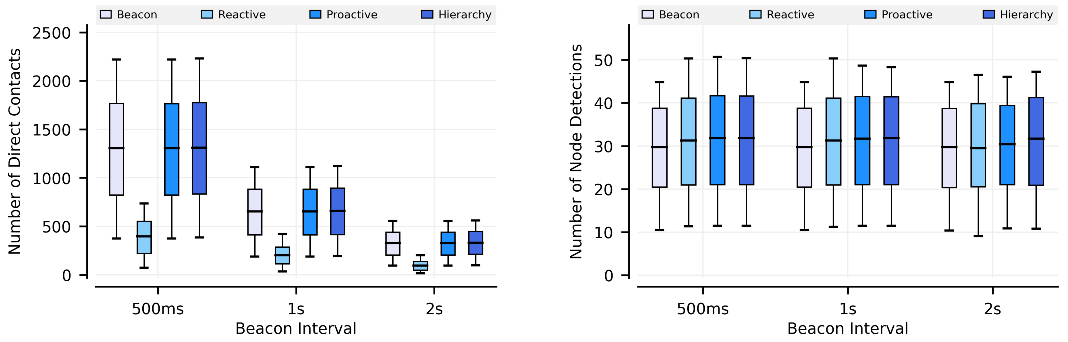


(a) Number of directly received beacon messages on UAVs. **(b) Number of unique node detections based on beacon messages on UAVs.**

Figure 4. Received beacon messages and detected nodes on UAVs ($w = 100\,m$) for different beacon intervals. The number of received beacons is reduced with a larger beacon interval, but not the number of detected nodes; demonstrating the low impact of the beacon interval on the performance of *CAMON*.

the aggregation of measurements for all nodes, allowing the visualization in the first place, obscures the existing sharp increase in information exchange when reactively collecting the local cluster data for the UAV. And on the other hand, this also highlights that local clusters are tightly connected, resulting in a large number of nodes staying silent throughout the collection process as only a few nodes need to exchange information, further reducing the averaged received data amount. More widespread clusters and networks may require far more messages, and thus, more overhead to collect the information than a tight cluster.

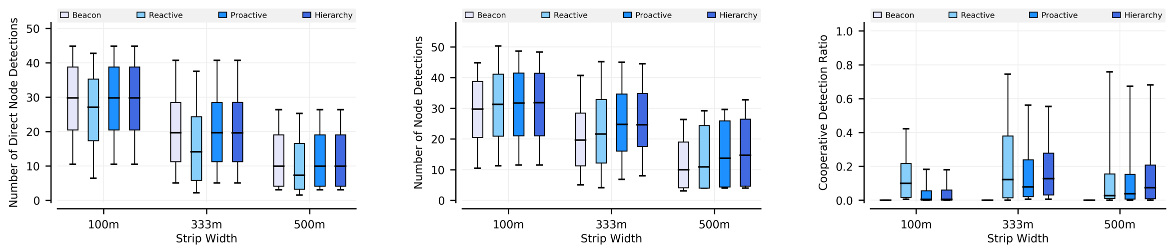
Finally, we look at the influence of the beacon interval on the node detection performance of the AMS. Figure 4a depicts the number of seen DTN beacon messages at monitoring UAVs on a tight monitoring path ($w = 100\,m$). Again, we clearly see the difference of the REACTIVE protocol as it significantly reduces the number of beacon messages when a UAV is present, while the other protocols proceed in their normal beacon sending behavior. Furthermore, the overall number of received beacons diminishes drastically with a larger beacon interval, as expected. When comparing to the number of individually detected nodes shown in Figure 4b, however, it becomes obvious that the beacon interval does only have minimal influence on the number of detected nodes, despite a significant influence on the overall number of received messages. Thus, the size of the beacon interval is not crucial for the performance of the AMS or *CAMON*, but has a large impact on the occupation of the wireless medium and redundancy in node contacts. For the remainder of this evaluation, we refrain to a beacon interval of 1 s for comparability.

Lawnmower Strip Width and Coverage

As presented, the coverage of monitoring areas is directly related to the strip width of the lawnmower route calculation for UAVs. A large strip width results in a faster traversal but also a lower coverage than a smaller one. The coverage, however, influences the performance of our disaster network detection as this can result in missed devices or whole clusters. By introducing cooperative behavior between DTN and AMS through the use of *CAMON*, we want to overcome these gaps, that are occurring from larger strip widths, by using the knowledge in the DTN to detect nodes outside of the reach of a monitoring UAV.

Figure 5 depicts the performance for node detection per UAV for the four *CAMON* protocols with different lawnmower strip widths. As we can see for the number of direct contacts in Figure 5a and the number of overall detections in Figure 5b, there is a general trend of reduction for both metrics with increasing strip widths. This behavior is to be expected, as less area is covered, and therefore DTN nodes are also missed. However, it becomes clear that while the number of direct node detections is decreasing with all protocols, the number of overall detected nodes is only decreasing in a similar fashion for the non-cooperative BEACON protocol. The REACTIVE protocol, in contrast to the HIERARCHY and PROACTIVE protocols, is more influenced by a larger strip width with a few less node detections than the others.

Nevertheless, the overall number of node detections using *CAMON* does not reveal the influence of the introduced cooperative behavior. For that, Figure 5c depicts the share of cooperatively detected nodes from the set of all detected nodes shown in Figure 5b. This share for BEACON is naturally 0, as no cooperation is happening. Interestingly, the REACTIVE protocol shows a significantly larger share of cooperative detections even for the full coverage monitoring



(a) Number of direct node detections based on received beacons on UAVs. **(b) Number of uniquely detected nodes on UAVs, direct and cooperative detection.** **(c) Share of cooperatively detected nodes on all uniquely detected nodes.**

Figure 5. Node detection performance per UAV for different *CAMON* protocols and lawnmower strip widths. The influence of cooperative behavior increases with lower area coverage, as less nodes are detected directly and the node detection per UAV similarly decreases.

($w = 100\,m$) and also the largest share of up to 75% for both $w = 333\,m$ and $w = 500\,m$. Since the HIERARCHY and PROACTIVE protocols send more beacons in the presence of a UAV than the REACTIVE, more nodes can be detected directly and the share of cooperatively detected nodes is generally smaller. For all protocols, however, cooperative detections are most present at $w = 333\,m$, ranging from approximately 20% to 40% share in the upper quartile up to a maximum around 60% to 75%, highlighting the large impact of cooperation on the network detection. But with $w = 500\,m$, the share is reducing again in the upper quartiles while the maximum is increasing, indicating that a few larger clusters are detected solely through cooperation, but the overall detection is reducing to a few direct detections only.

Through the wide distribution, we can deduct that *CAMON* can have a large influence on the detection of nodes in some cases, but may also provide only a minor influence in other cases. This is highly dependent on the distribution of nodes and if they are covered by UAV monitoring paths: if a large portion of the cluster is covered, more nodes will be detected directly in general, but if only one or a few nodes are covered instead, more nodes will only be detected through cooperation. Furthermore, a more even—but probably also more unrealistic—distribution of nodes among the monitoring areas would yield a narrower distribution over all UAV metrics. As a result, these metrics provide a good view on each UAVs detection performance and the influence of strip width and node distribution on that, but lack a clear representation of the overall AMS performance, at which we take a closer look in the following section.

Aerial Monitoring System Performance

We track the network detection performance of the AMS by evaluating the number of DTN nodes, which were detected by the entire system, over time. The results are depicted in Figure 6. For better readability, Figures 6a, 6b, and 6c visualize the average performance of the *CAMON* protocols for the different strip widths separately for only the first 20 minutes, thus, the duration of one full coverage flight. Dashed vertical lines denote the time when the UAVs have returned to the base station and start a new monitoring area traversal, for example, 20 minutes for $w = 100\,m$. Figure 6d shows a combination of all protocols and strip widths for the entire simulation time for comparison.

For full coverage (cf. Fig. 6a), all nodes are detected within the first area traversal of 20 minutes independent of the used *CAMON* protocol. Cooperative behavior brings only a slight increase of 1 or 2 minutes in the initial detection time of nodes, as they are first detected over cooperative measures before being detected directly by the UAVs. Furthermore, the cooperative protocols do not show very different behavior. The only clear difference is seen between minutes 12 and 14, when the PROACTIVE protocol finds the last 20 nodes faster than the other two protocols. The results, however, are similar with all protocols.

The system performance for the lowest coverage with $w = 500\,m$ is shown in Figure 6b. After 3 consecutive monitoring flights—18 minutes—, the non-cooperative BEACON approach found 40 nodes, while PROACTIVE and HIERARCHY found around 54 and REACTIVE found 63 nodes, respectively. As seen in Figure 6d, more nodes are only found much later after more than 45 minutes by the cooperative protocols, although the spike highlights that a whole cluster was found at once. Without cooperation, node detections increase only slightly when detecting one single node or a few nodes that are moving. Interestingly, the REACTIVE protocol is able to detect more nodes much faster than the other two cooperative protocols, which require more than 35 minutes to catch up. In the end, HIERARCHY and REACTIVE reach around 70 nodes while PROACTIVE detects 65. This slightly lower average detection

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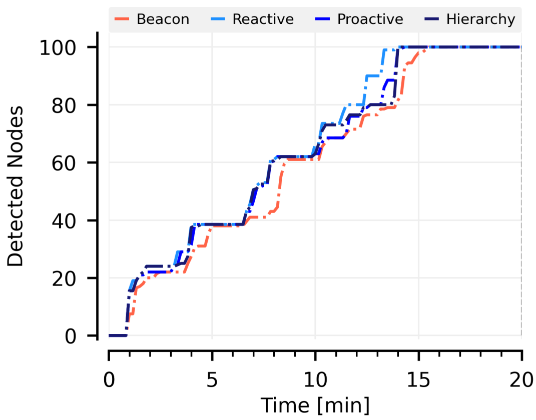
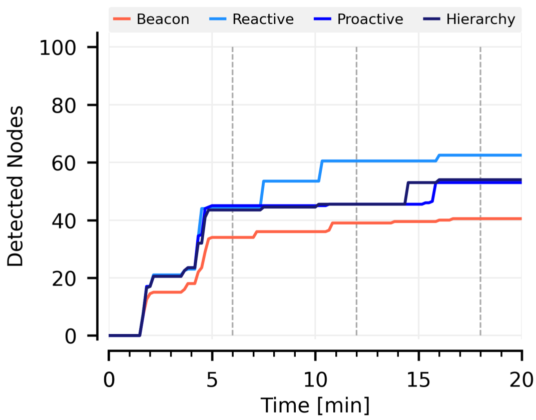
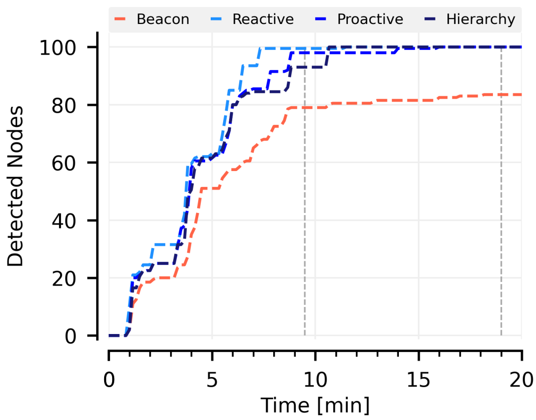


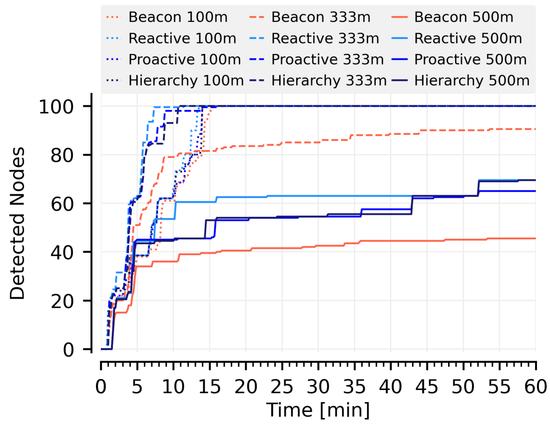
(a) $w = 100\,m$**: Cooperative detection provides only slightly faster initial detection of nodes with similar end result for all protocols.**



(b) $w = 500\,m$**: Cooperation outperforms non-cooperation by 10% to 20%. A large number of nodes is missed entirely.**



(c) $w = 333\,m$**: Cooperative protocols clearly outperform non-cooperative behavior with fast and comprehensive node detection.**



(d) Combined plot for protocols and strip widths.

Figure 6. Average system performance for different protocols and lawnmower strip widths over time.

rate after 60 minutes may be a result of incomplete cluster knowledge on the encountered node using this protocol, since HIERARCHY and REACTIVE were able to retrieve a more comprehensive cluster knowledge at the same time. Overall, the average detection rate for the cooperative protocols is—depending on the used protocol and evaluated time frame—between 10% and 25% higher than that of the non-cooperative approach. However, multiple clusters are still missed due to the significant strip width and the resulting gaps in the monitoring area coverage, which cannot be overcome by *CAMON*.

As depicted in Figures 6c and 6d, the area coverage for $w = 333\,m$ is sufficient enough to detect all nodes with cooperative protocols within 15 minutes. Furthermore, the cooperative approaches detect more than 90% with the HIERARCHY protocol, around 98% with the PROACTIVE protocol, and even full node detection with the REACTIVE protocol within the first monitoring flight of 10 minutes. The non-cooperative approach reaches around 80% in the same time and around 90% within one hour. As expected, the performance is significantly worse than with full coverage, although the initial detection is faster. With around 50% of the area covered, still more than 80% of nodes are found on average, highlighting the non-uniform node distribution in the disaster scenario. The quick and comprehensive detection of cooperative protocols also shows that all larger clusters are encountered, only smaller groups cannot be detected in the first monitoring flight.

Summarizing the results, the positive impact of *CAMON* on the AMS node detection performance becomes clear when reducing the area coverage of monitoring UAVs. Generally, cooperative behavior allows a faster and more comprehensive node detection while reducing coverage and with that also flight duration at the same time. In turn, this allows to increase the monitoring frequency, providing access to more up-to-date information on the monitoring areas. In the initial reconnaissance phase, the use of *CAMON* can reduce the network detection time by up to 53%

compared to the non-cooperative approach, depending on the used protocol. Although the overall differences in the performance between the cooperative protocols are not that large, the REACTIVE protocol shows the best performance of all. At first, initial node detections are slightly faster. Due to the cluster information being most recently collected when transmitted to the monitoring UAV, REACTIVE provides accurate and up-to-date information of the encountered cluster. Other protocols may provide more outdated information and, therefore, also seem to miss a few nodes that have very recently arrived. Secondly, the REACTIVE protocol has the lowest impact on the overall DTN overhead, as cluster information messages are only exchanged when the UAV triggers the data collection. In contrast, PROACTIVE and HIERARCHY exchange messages constantly, leading to a larger overhead. And thirdly, this minimal approach of the REACTIVE protocol still results in significantly less messages generated during the UAV encounter with the cluster and, by that, also less redundant node detections on the UAVs.

CONCLUSION

For any kind of disaster relief effort in a large-scale disaster, information on the disaster area, such as the location of affected civilians, is highly valuable. Within this work, we present *CAMON*, a system for cooperation between the UAVs of an Aerial Monitoring System (AMS) and the smart mobile devices within a civilian disaster DTN. In contrast to state-of-the-art AMS' that rely on pure passive observation with the full workload on UAVs, *CAMON* cooperatively collects and provides DTN topology information which significantly increases the overall efficiency of the aerial network detection. As a result, the age-of-information and with that the validity of relevant information is similarly improved, providing more accurate and up-to-date information for disaster relief.

For *CAMON*, we provide three different approaches for the information collection in the DTN and simulated them within an inner-city environment for differing UAV area coverage. The largest differences of these protocols are present in the requirements on the communication medium, while the performance in collecting and sharing topology information is much more similar. Thus, *CAMON* can be used as an extension to typical DTN implementations, using the protocol most suitable for the specific DTN appliance and used communication protocol. However, we evaluated the presented approach for cooperative network detection only in an inner-city post-disaster environment. For other scenarios—especially such with significantly different network topology or user mobility—, future work must assess the efficacy and general applicability of our system.

The presented evaluation results highlight a strong dependence of the performance between the—initially unknown—network topology and the chosen monitoring area coverage. On the one hand, if area coverage is too low and clusters are located outside that coverage, they will be missed entirely. On the other hand, a high area coverage may then detect these clusters but requires a large amount of time for the monitoring. Thus, finding an optimal solution for this tradeoff is essential for future work. Another approach could be to perform the initial monitoring in high detail but with lower performance and to adapt the monitoring routes depending on the gathered information to subsequently increase performance. This, however, is only feasible with a sufficient number of available UAVs. In general, the adaption of monitoring routes, monitoring areas, or system behavior based on available knowledge is a highly interesting area that will be approached in future work.

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