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Calling Ground Support: Cooperative DTNs for Improved Aerial Monitoring Systems

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***Abstract*—Unmanned Aerial Vehicles (UAV) are very well suited to support long-range communication between intermittent local clusters of Delay- and Disruption-Tolerant Networks (DTN) in a disaster. However, knowledge on the disaster scenario must be gathered initially to be able to install such a system in the first place. For that, UAVs as part of an Aerial Monitoring System are deployed to assess the situation and collect information on the location of devices and the topology of the DTN itself. A comprehensive overview requires a significant effort for detailed monitoring, since each device in the DTN must be detected by the UAVs. In this paper, we introduce cooperative behavior in the DTN to collect information on the ground and sharing it with UAVs in the air. Evaluation results indicate that by calling ground support, the Aerial Monitoring System can reduce the area coverage while simultaneously increase the overall monitoring efficiency.**

***Index Terms*—Delay-/Disruption-Tolerant Networks, Network Cooperation, UAVs**

I. Introduction

Due to the increase in the number and severity of natural disasters like extreme weather conditions over the last decades [1]–[4], researchers all over the world are dedicated to contribute to disaster preparedness and disaster relief with innovative approaches. Two of the prominent topics, especially with a focus on disaster relief for the civilian population, are Delay- and Disruption-Tolerant Networks (DTNs) and Unmanned Aerial Vehicles (UAVs). DTNs are mainly used to provide basic communication capabilities and disaster relief services to the affected civilians when critical infrastructures for information and communication technologies are unavailable. By spanning multi-hop device-to-device networks, e.g., using WiFi Ad Hoc, they are independent of destroyed communication infrastructure [2], [5]–[9]. Disaster DTNs are typically highly intermittent and fractured networks, and thus, employ communication protocols with robust *store-carry-forward* approaches to overcome gaps between clusters in the network. As presented in previous work [5], this makes DTNs highly dependent on opportunistic forwarding and mobility within the disaster area. Without movement of civilians carrying DTN devices between local clusters, communication is only possible within a local cluster due to the lack of communication links [5], [6].

To overcome this problem, UAVs can be used to establish communication links between distinct local clusters, by quickly and efficiently disseminate and relay messages within the disaster DTN [10]–[12]. In contrast to alternatives like long-range communication over directional antennas or satellite-based solutions, a UAV system can directly interact with the DTN, avoiding the need for specialized hardware that needs to be placed or be available in a local cluster first. The mobility of UAVs also allows to accommodate to mobility in the network much better than static antenna relays can, e.g., by adapting UAV flight routes [11]. As a clear disadvantage, however, UAVs cannot be applied in strong winds which makes them unsuitable for certain situations like hurricanes or at least significantly delays a possible application. Additionally, sending UAVs to form communication links requires knowledge on the location of DTN devices or DTN clusters in the first place, which is typically assumed to be available when needed [10], [13], [14]. But although this knowledge is similarly important for other disaster relief efforts, rescue teams, or emergency services, it is rarely possible to estimate or know it a priori, due to the uniqueness of each disaster and the mobility of affected civilians [11], [15].

However, UAVs are also very well suited to quickly collect information on the disaster area and keep it up-to-date through constant monitoring, due to their mobility and independence of destroyed or blocked roads [16]. Such *Aerial Monitoring Systems* (AMS) which deploy autonomous UAVs can provide detailed information of the disaster area with limited requirements on human personnel. Information can be gathered by UAVs for example by visual detection of civilians through onboard cameras, although this only works for civilians that are outside of buildings and when the line-of-sight from the UAV is not obstructed. The detection of carried civilian smartphones or other smart mobile devices also works inside of buildings and through obstacles, e.g., by tracking 5G [17], [18] or WiFi signals [19], such as DTN beacons.

The workload of detecting signals or beacons in such a system is usually handled completely by the monitoring UAVs, binding large amounts of resources for a profound monitoring result. Furthermore, the detection process is completely passive and does not incorporate any interaction between the ground DTN and the Aerial Monitoring System. In this paper, we propose to shift the workload of localization and detection of DTN devices from the monitoring UAVs to the ground DTN, where the knowledge of individual DTN devices and their location is typically already available. UAVs of the Aerial Monitoring System then actively call for ground support when encountering a local cluster. We present both our design for such a cooperative DTN protocol as well as the respective Aerial Monitoring System. Our simulation results highlight that the cooperative behavior of the DTN allows to significantly increase the efficiency and performance of the disaster area monitoring and DTN node detection.

The remainder of the paper is structured as follows. Section II discusses related work. Section III presents the design for DTN ground support and the Aerial Monitoring System, followed by the evaluation of the cooperative approach in Section IV. Finally, Section V concludes the paper and provides an outlook on future work.

II. Related Work

Aerial object identification as well as aerial reconnaissance and monitoring of areas are typical applications for Unmanned Aerial Vehicles (UAVs). Visual observations include search-and-rescue missions for victim identification [20]–[22] or the localization of forest fires [23]. However, visual or other camera-based approaches that require line-of-sight can easily be obstructed by any object. They are also not suitable for localization of persons or objects inside of buildings, and have the additional drawback of a limited coverage due to a small angle of view and usually also a considerable weight of cameras [19], [20]. Device identification or localization using radio waves or radio transmissions is, therefore, also of great interest for the research community. This could, for example, be performed by listening for WiFi packets such as DTN beacons that are either triangulated or contain the information on the device location within [19], [20]. For larger areas, multi-UAV systems of UAV swarms were successfully used to detect devices by their WiFi signal. These systems have the advantage of splitting the workload on multiple UAVs and covering large areas in a comparably short time [24], [25].

Regardless of whether a single- or multi-UAV system is used, the monitoring area must be traversed by a UAV, either moving between grid cells [25], randomly through the area [24], by using bio-inspired algorithms like PSO [26], [27], or a lawnmower or Boustrophedon pattern [28], [29]. Also known as coverage path planning, calculating or determining the best paths for UAVs for an optimal monitoring process is a large field of research also highly dependent on the overall objective. For the application of Aerial Monitoring Systems, especially for an initial assessment without any knowledge on the disaster situation or the network topology, a full coverage lawnmower path is a typical exhaustive but also expensive choice. Although it will bind UAVs for a long time to traverse every point within a monitored area, it will also provide a full view and information on the whole area [29].

Cooperative networking and monitoring is also a comprehensive field of research. Within ad hoc networks in general, information like operational states can be reported to all nodes or special monitoring nodes for the maintenance and updating of communication routes [30], or for the determination of cluster heads and data sinks within local clusters for cellular data offloading [31]. Although maintenance for communication routes is typically not needed within DTNs, nodes usually keep track of encountered nodes such as their local neighborhood or their local cluster. By exchanging for example hashes of known messages or nodes, nodes in a cluster can determine their affiliation to that cluster, or detect new peers, network partitions, and communication failures [32]. Cooperative behavior within aerial networks or between UAVs is commonly used for the application of UAV swarms [24].

The cooperative support of ground vehicles by UAVs is also possible, for example, in search-and-rescue missions of Unmanned Ground Vehicles (UGVs) to search a target [33] or for the efficient transportation of industrial goods [34]. Other work uses UAVs to support communication within DTNs [10] or as aerial access points for 4G or 5G networks [17]. However, little research was conducted to assess the possibilities and capabilities of ground DTNs to support aerial networks or aerial systems.

III. Design

Disaster DTNs use ad hoc communication between smart mobile devices like smartphones to restore communication capabilities for civilians within disaster scenarios where communication infrastructure is unavailable [5], [6]. In contrast to typical Mobile Ad Hoc Networks (MANETs) with fixed end-to-end connections, DTNs are specifically designed for highly mobile and highly fractured intermittent networks, with the application of robust, usually flooding-based communication protocols [32], [35] following the *store-carry-forward* principle. All active DTN devices participate in the dissemination of messages while being carried around by civilians, by opportunistically forwarding messages to other encountered devices. A vital part of each DTN protocol are regularly broadcasted beacon messages, that allow devices to recognize each other. Depending on the implementation, beacons may include additional information besides a device's unique identifier, such as known messages or a hash of known messages [32] or the exact location of the device. In the following, we present how such additional information can be leveraged by Aerial Monitoring Systems and other devices in the DTN.

A. Aerial Monitoring System

Gathering knowledge on the location of civilians within a disaster area is essential for disaster relief. This includes immediate measures like directing emergency service teams in the right direction, but also long-term measures like supporting civilian communication networks by aerial data ferries [10], [36]. In general, UAVs are unaffected by destroyed or blocked roads and can traverse large areas in a relatively short time. As part of a larger Aerial Monitoring System (AMS), this makes UAVs a great tool for gathering this essential information, i.e., in this case by detecting DTN devices via beacon messages.

Note that AMS application comes with similar ethical issues like, for example, aerial video reconnaissance in disaster scenarios or the application of DTNs in general. Gathered data must be secured against unauthorized access and not used for any other purpose than disaster relief. Furthermore, the network must be resilient against malicious behavior, which is especially challenging due to the decentralized nature of DTNs. Similarly, the UAV system itself must be safe to use, to prevent further injuries or damages within the disaster area. As this work focuses on DTN cooperation and possible impacts on Aerial Monitoring Systems, however, data security, as well as network and hardware safety, are not within the scope of this paper.

The exact requirements for the deployment of an Aerial Monitoring System depend on a large number of different factors, like the size of the operation area, the number of available UAVs, and the specific properties of these UAVs like type, flight range, and flight speed. Further factors are the localization range on monitoring UAVs, i.e., the communication range for DTN-based systems, the used coverage path planning approach, such as random traversal, lawnmower paths, or a PSO-based traversal [26], and specific requirements on the Aerial Monitoring System, like a maximum age of information. Most of these factors are interdependent, for example, a higher flight speed results in a shorter traversal of the operation area, but also in an increased power consumption [36]. This results in a shorter flight range, which may not be sufficient to traverse the whole area, such that the area must be divided into smaller parts that are monitored by multiple UAVs in parallel.

Within this work, we focus on the communication aspect of the AMS, and thus, make the following assumptions. First, the base station of the deployed Aerial Monitoring System is located within a limited and defined operation area. The AMS has several autonomous multicopter UAVs of the same type at its disposal. Monitoring UAVs are able of autonomous flight, including takeoff and landing at the base station, as well as autonomously initiating, executing, and concluding their assigned monitoring missions. The base station is able to supply and replace depleted UAV batteries. Each UAV possesses communication capabilities to receive and transmit messages from and to the ground DTN.

Secondly, we assume that the operation area is split into several rectangular, equally-sized monitoring areas, that are individually assigned to a UAV. The optimization of the area division is not in the scope of this paper; therefore, the division is pre-defined by a human operator. Each UAV traverses its area using a lawnmower pattern (also known as back-and-forth or Boustrophedon pattern). The strips of these paths are aligned to the longest edge to minimize turns and are separated by a path clearance distance on each side. UAVs will autonomously start from the base, traverse the full path (if possible), and return to the base station to recharge and drop the monitored information, before repeating this process.

B. Cooperative DTNs: Ground Support for Aerial Monitoring

UAVs listen for incoming beacon messages of DTN devices during their flight over the monitoring areas. Received information is stored and can be used later-on, e.g., to assess the topology of the network. However, this monitoring process is usually passive with the full workload resting on the UAV. A detection is, therefore, only possible when the communication range of UAVs and DTN devices and a beacon transmission overlap both in space and time. Thus, essential information can easily be missed, especially when the area cannot be monitored in high detail. However, a detailed overflight of the monitoring area requires a significant amount of time, increasing the age of already gathered information and, by that, lowering the validity of the information when returning back to the base station. Our goal is to decrease the age of data and increase its level of detail. For that purpose, we utilize the knowledge of devices in the DTN, as information on devices is usually available within the DTN, or at least within a local cluster. This knowledge can be used to identify clusters within the DTN, and we propose to use and cooperatively share the available knowledge within the DTN with UAVs. Further, it helps to reduce the required overhead within the communication protocol and to detect changes in the local network topology, e.g., new devices merging into the cluster or a fragmentation of the cluster [32]. By shifting parts of the workload for detecting and locating DTN devices from the UAVs to the ground, a less fine-granular monitoring of the area can be sufficient to reach the same goal. With the ground support of a cooperative DTN, basically, a UAV requires contact to only one device of a local network cluster that shares the information of that cluster, instead of passively tracking each one of the devices.

Within this work, our cooperative DTN is based on a simple and robust flooding approach. Each device holds a list of nodes in their direct 1-hop neighborhood and an additional list of all nodes in their local cluster; the latter includes the device itself. Devices broadcast a beacon with their unique ID, their current location, and a hash of all IDs in their local cluster list at a fixed announcement interval. Regarding related work on static and adaptive announcement intervals in DTNs, the interested reader is referred to [37].

When receiving a beacon of an unknown device, its ID and location are extracted and stored in both lists as a Triple *(ID, Timestamp, Location)*, otherwise updated if the devices are already known. In case that the local cluster hash is different, the receiver responds by transmitting its local cluster list to the sender of the beacon, instead of the regular beacon message. This transmission may trigger a similar response of the second device if its updated local cluster list differs from the received list. Furthermore, other devices in range may receive the exchanged messages, update their local cluster list and also provide their updated list to others, such that the information is eventually propagated throughout the whole local cluster. To prevent broadcast storms, devices use a random back-off timer and only propagate information further when no other neighbor did broadcast it before. After the lists are stable, each device holds the same information on the local cluster and only the regular beacons are transmitted within their 1-hop neighborhood. Nevertheless, this neighborhood may change regularly due to the high mobility of devices. If no beacon of a known neighbor was received within a time frame of ten times the beacon announcement interval (cf. [37]), the neighbor is deleted from the neighborhood list. Additionally, if no information on this device is received within that window through local cluster updates, the node is also deleted from the local cluster list, the hash is updated, and devices will again exchange their information until it has stabilized. Without updating the information of the cluster, it will soon get outdated, and be of less value or simply be wrong information. However, if the missing node is seen by another device within the cluster, this device propagates the information that it is still part of the cluster. On reception, the device which missed the node will update its lists and will also not propagate the loss of the neighbor to prevent the circulation of contradicting information. In case that is was already propagated, the information of the new detection is clearly indicated by the newer timestamp and will overwrite the information of the loss. With that, on the one hand, information is exchanged only when significant changes occur within the cluster to reduce the required overhead. On the other hand, information is kept up-to-date with a reasonably short cluster information interval.

When a monitoring UAV receives a beacon message from one of the DTN devices, it requests ground support. The device responds with its full information on the local cluster, and the UAV updates the position of the devices according to the received local cluster list. In case that the same cluster is encountered again within the cluster information update interval, no further request is sent. If devices in the cluster currently exchange updates or other beacons are received, the UAV can also integrate the more recent information into its storage. Overall, the interaction between UAVs and the DTN is kept to a minimum and information only flows from ground to air, according to the main objective of gathering information on the DTN topology via the Aerial Monitoring System. Nevertheless, information on the global topology or additional data like messages from outside of a local cluster could be transferred from the UAV to the DTN cluster, if needed.

IV. Evaluation

We evaluated our approach of a cooperative DTN acting as ground support for an Aerial Monitoring System (AMS) within the SIMONSTRATOR [39] simulation platform. The implementation of the AMS is based on the simulation platform for Unmanned Aerial Systems as described in previous work [10]. The evaluation scenario is a 2x2 km^2 inner-city disaster area. Movement of mobile devices is restricted to streets and walkways accessible for pedestrians based on Open Street Map[1] (OSM) data. Device mobility is attracted by five points of interest within the disaster area, which are randomly chosen for each simulation run, representing for example shelters or first aid stations [5]. Devices gather around the points of interests within a radius of up to 200 m, or otherwise move between these locations using a Civilian

[1] www.openstreetmap.org

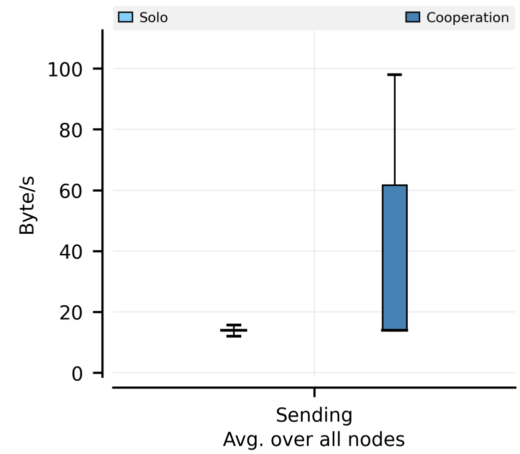


Fig. 1: Depending on the number of DTN nodes in each network cluster and the occurring topology changes, cooperation increases the required overhead by a factor of 2.5 on average to more than 7 at max.

Disaster Mobility model [38]. A detailed list of environmental settings for the simulation framework is given in Table I.

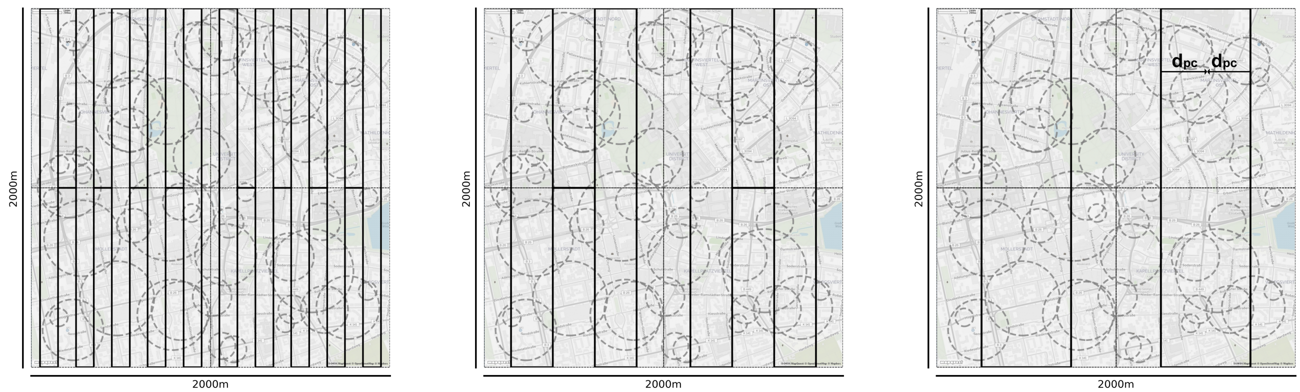
We compare our approach of cooperative DTN devices (Cooperation) against a non-cooperative approach (Solo), in which UAVs detect DTN devices without ground support. The base station to reload UAVs of the AMS is located in the center of the operation area. Four small multicopter UAVs with a flight time of around 22 minutes at a speed of 10$\frac{m}{s}$ [36] are available. The performance of the AMS is defined by the number of devices that are found by each UAV and the time it takes to detect them.

A. Communication Overhead

A direct comparison of the required communication bandwidth is provided by Figure 1. Each network node in the non-

TABLE I: Simonstrator Environmental Settings

Scenario	Map	Inner City, Post-Disaster
	Size	2000 m x 2000 m; 100 Nodes
	Node Speed	0.8 – 1.5 $\frac{m}{s}$
	Node Movement	Civilian Disaster Mobility [38]
	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
DTN	Approach	[Solo UAV, Cooperative DTN]
	Beacon Interval	2 s
	Cluster Info Interval	20 s
AMS	UAV	4 multicopter (cf. [36])
	Flight Time	approx. 22 min at 10 $\frac{m}{s}$
	Monitoring Areas	4, 1000 m x 1000 m each
	Coverage Path Planning	Lawnmower
	Path Clearance d_{pc}	[50 m, 150 m, 250 m]



(a) d_{pc} = 50 m (b) d_{pc} = 150 m (c) d_{pc} = 250 m

Fig. 2: The operation area is divided into four square-shaped monitoring areas. The lawnmower pattern is used to calculate flight paths of monitoring UAVs, shown in black. The strips of the flight paths are separated by a path clearance distance d_{pc} on each side. The distribution and extent of points of interest of the used mobility model for all simulation runs is shown in the background as grey circles.

cooperative approach requires around 14 Bytes per second on average to broadcast beacons. In contrast, the cooperative approach has a significantly higher overhead. While the median is similar to the non-cooperative approach due to nodes simply sending similar beacon messages, the required bandwidth to spread cluster information increases to an average of around 60 Bytes per second in 25% of the cases, and up to 100 Bytes per second for another 25%. With that, the average overhead is increased by a factor of 2.5 for the cooperative approach. But depending on cluster sizes and the number of topology changes, this overhead can increase to more than seven times that of the non-cooperative approach. Clearly, this significant increase in the overhead for cooperatively collecting topology information in the DTN must be considered when using the approach. The high demand should not interfere with or prevent the functionality of essential services within the disaster DTN, like emergency calls.

B. Monitoring Areas

The operation area is divided into four equally-sized squares of $1\,\mathrm{km}^2$, and each of these monitoring areas is assigned to one monitoring UAV. As depicted in Figure 2, we use the lawnmower-pattern coverage path planning approach to calculate paths for the UAVs, with a path clearance d_{pc} of $50\,\mathrm{m}$, $150\,\mathrm{m}$, and $250\,\mathrm{m}$, respectively. The distribution of the different points of interest and their attraction areas are shown by grey circles, aggregated for all simulation runs.

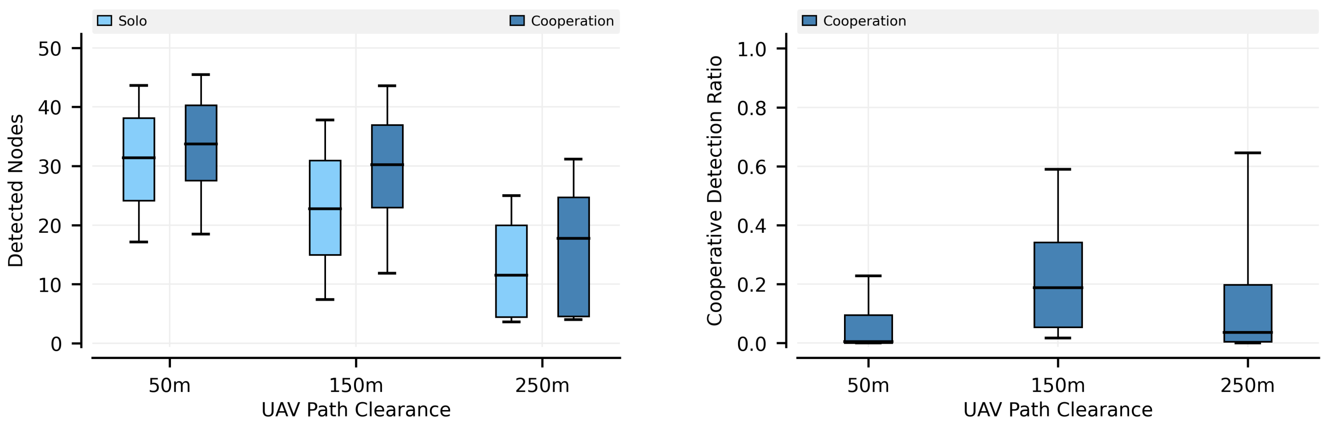
The most influential factor on spatial and temporal AMS performance is the used path clearance distance. It determines the time in which a monitoring UAV traverses the full path, and therefore, also the frequency a UAV can monitor the same area, but similarly also the coverage of the monitoring area. In this case, a path clearance of $50\,\mathrm{m}$ allows complete coverage of the whole monitoring area, but it also takes 20 minutes for the full traversal including takeoff and landing. However, increasing the path clearance to $150\,\mathrm{m}$ reduces the traversal time to less than 10 minutes on the one hand, and thus, doubles the traversal frequency of the area. But on the other hand, the area coverage also reduces to only 50% and leading to large gaps in the path that are not monitored at all. Moreover, further increasing the path clearance to $250\,\mathrm{m}$ reduces the area coverage to 30% and the traversal time to around 6 minutes.

Clearly, there is a tradeoff between temporal and spatial coverage of monitoring areas. As seen especially in Figure 2c, a large path clearance leads to large gaps in the monitoring coverage. Comparing this with the actual distribution of attraction areas, large gaps may lead to significant losses in the node detection performance.

C. Number of Detected Devices

Figure 3a shows the number of detected DTN devices for different path clearance distances with and without a cooperative DTN, respectively. The bold dash denotes the median, boxes indicate the 25^{th} and 75^{th} percentiles (quartiles) and whiskers the 2.5^{th} and 97.2^{th} percentiles, respectively. The plot aggregates the result for each of the four monitoring UAVs on each path traversal. Therefore, we see a relatively large spread in the box plot due to an unequal distribution of points of interests within the individual monitoring areas, but also because a portion of devices are tracked multiple times by different monitoring UAVs, when clusters overlap two or more monitoring paths. The latter issue becomes clear for a $50\,\mathrm{m}$ path clearance. More than three quarters of measurements for the solo approach indicate more than the expected 25 detections of an equal split. And the number even increases further for the cooperative approach, since more nodes were detected although they are within other monitoring areas.

Overall, we see that the cooperative approach significantly increases the number of detections for all distances. For $50\,\mathrm{m}$, however, this increase is less than for $150\,\mathrm{m}$ and $250\,\mathrm{m}$,



(a) Aggregated number of detected nodes for each monitoring UAV.

(b) Ratio of cooperatively detected nodes out of all detected nodes.

Fig. 3: Detected nodes and the amount of cooperatively detected nodes for different path clearance distances. For a distance of $150\,\mathrm{m}$, up to 60% of detected nodes are provided by DTN ground support. Thus, the number of detected nodes does not degrade significantly compared to the non-cooperative approach for the detailed monitoring with a distance of $50\,\mathrm{m}$.

respectively. With a distance of $250\,\mathrm{m}$, median and upper quartiles are significantly higher for the cooperative approach, but similar for the lower quartiles. This is due to the large path clearance which results in misses for communication opportunities, both for the solo and the cooperation approach. Neither beacon messages nor cooperative messages can be received if clusters are out of reach of the monitoring UAVs. The most significant improvement of AMS node detection is achieved with a path clearance of $150\,\mathrm{m}$. In conjunction with Figure 2b, we can conclude that with this distance the monitoring paths are close enough to at least provide contact to one node of most clusters for cooperative communication, in contrast to the solo approach. However, the overall number of detections is still reduced compared to $50\,\mathrm{m}$, because there are less opportunities to track nodes in clusters that are under the paths of multiple UAVs.

The direct impact of cooperation on the node detection is visualized in Figure 3b, depicting the ratio of cooperative detections from all detections. Note that the solo approach is not depicted because no cooperation is used. Similar to Figure 3a, the largest impact of cooperative behavior was achieved with $150\,\mathrm{m}$. In half of the monitoring traversals, between 10% and 35% of detected nodes were detected only due to cooperation with the DTN. And in around a quarter of traversals, the cooperative ratio was even higher with a maximum at approximately 60%. More interestingly, the maximum ratio reaches even higher with around 65% for $250\,\mathrm{m}$, although most cooperative detections only make up 20% of the detections. Thus, there are incidences when probably a single cooperative device from a cluster was reached, which added a significant number of cooperatively detected nodes to this traversal, but was not reached in other traversals. Again, we can conclude that a large number of clusters was not reached at all with this large path clearance or otherwise were already reached directly.

Overall, Figure 3b highlights the significant benefit of DTN ground support on the overall node detection. Although increasing the path clearance, the cooperative approach at $150\,\mathrm{m}$ performs similarly compared to the non-cooperative solo UAV approach with $50\,\mathrm{m}$ on average. As discussed before, this also means that the monitoring UAV can approximately double the frequency it is traversing the same area, thus, significantly decreasing the age of information from that area. Furthermore, there is still a noticeable positive effect of cooperation for a larger path clearance, despite the large drawbacks from missing entire clusters.

D. Aerial Monitoring System Performance

Ultimately, the question arises to which extend the overall Aerial Monitoring System performance is influenced by DTN cooperation. This performance is measured by the number of detected DTN nodes over the detection time. Figure 4 visualizes this performance for the solo UAV and the cooperative DTN approach for the three path clearance distances, respectively. Note that this metric describes the whole AMS performance with the total number of detectable nodes found. Shown values describe the means of the system performance. Due to better readability, the shown time frame covers only 30 minutes.

First of all, it becomes clear that the detailed monitoring with a distance of $50\,\mathrm{m}$ shows no significant performance gain from cooperative behavior. In between, cooperation leads to a faster initial detection of around 1–2 minutes, but the end result is the same. After around 16 minutes, all nodes within the DTN are found, despite requiring the longest time with 20 minutes for one traversal. In contrast, a tremendous portion of network clusters is clearly missed with a distance of $250\,\mathrm{m}$. Despite being able to traverse the areas approximately five

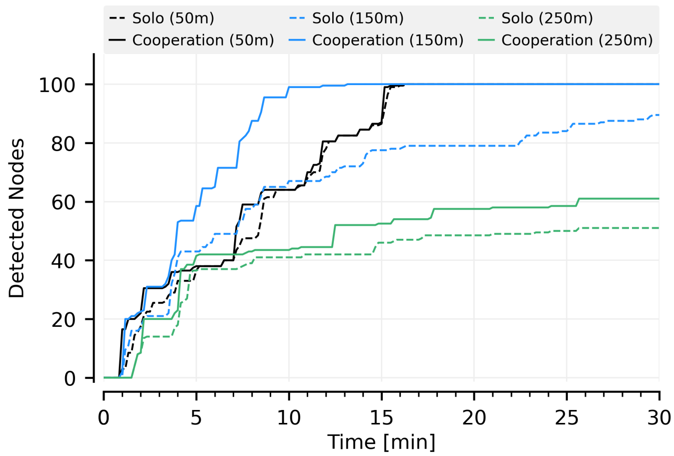


Fig. 4: Performance of the Aerial Monitoring System measured for the number of detected nodes over time for different path clearance distances. The benefits of cooperation are small for $50\,\mathrm{m}$ and $250\,\mathrm{m}$, but significantly larger for a $150\,\mathrm{m}$ clearance.

times during this 30-minute time frame, on average only half of the nodes are detected with the solo approach and slightly more than 60% with the cooperative approach.

For a distance of $150\,\mathrm{m}$, however, the positive impact of cooperative behavior becomes more imminent. The solo approach reaches an average detection of approximately 80% after 2 area traversals (20 minutes) and 90% after 3 traversals (30 minutes), respectively, but is not able to detect all DTN nodes on its own. In contrast, the cooperative approach shows a significantly faster and more comprehensive node detection performance, compared to all other results. Only a single traversal of $10\,$minutes is required to achieve an average node detection rate of 98%. Furthermore, missing nodes are detected quickly within the second flight, several minutes before full detection was achieved with a distance of $50\,\mathrm{m}$ for either approach. This clearly highlights a direct improvement in the efficiency of the monitoring by using cooperation while being able to decrease the required monitoring granularity.

Overall, this evaluation shows that by receiving ground support from the monitored DTN, an Aerial Monitoring System can greatly improve its spatial and temporal efficiency in node detection and continuous monitoring. Nevertheless, both approaches are similarly vulnerable to miss entire clusters, if the path clearance distance is too large. Clearly, more research must be conducted on how to efficiently adapt monitoring paths while also reducing the chance to miss entire clusters.

Due to the large increase in overhead which is introduced by shifting the monitoring load from the AMS to the ground DTN, the cooperative approach currently provides no direct incentives for DTN devices to participate and take the increased workload, at least from a communication viewpoint. However, as the information gathered by the AMS can be used to precisely guide help, disaster relief, or communication support, the civilians using the DTN devices will indirectly benefit from their expense.

The simulation results now provide the basis for a real-world implementation and evaluation, which is planned in the future, but currently decelerated due to new and tighter legal regulations within the EU and Germany for the application of UAVs outside of actual disasters. Practical results from a real-world DTN application without UAV support can be found in our previous work for a smartphone-based civilian disaster communication network [5].

V. Conclusion

This work presents the design of an Aerial Monitoring System (AMS) for detecting and monitoring devices in a civilian-used Disruption- and Delay-Tolerant Network (DTN) for disaster communication. Furthermore, we introduced cooperative behavior in the disaster DTN, such that the workload of gathering localization and monitoring information on DTN devices is shifted from the AMS to the ground. The provision of ground support allows the AMS to monitor individual areas in less detail, resulting in less area coverage but without a loss in node coverage. Therefore, areas can be monitored more often due to a reduction of traversal time, reducing the age of information, and thus, the information quality that is provided by the AMS to other disaster relief services. Nevertheless, the required overhead for cooperation also puts significant stress on the communication medium of the DTN, which must be considered before deployment. Similarly, area coverage of the Aerial Monitoring System must still be sufficient, or otherwise, the monitoring performance will reduce significantly.

Our evaluation results show that the average overhead increases by a factor of 2.5 for a cooperative approach compared to a non-cooperative approach. At the same time, the cooperative AMS can halve both area coverage and traversal time without a loss in DTN device detection, while simultaneously increasing its monitoring performance. By contributing up to 60% to the overall number of device detections, the collaborating DTN provides significant support to Aerial Monitoring, and thus, to disaster relief in general.

Besides a practical hardware implementation, future work should encompass both the collaboration within the DTN and an improvement in the Aerial Monitoring System. For the DTN, more sophisticated collaborative protocols could decrease the required overhead and relief the communication medium. Currently, devices only store up-to-date information on their neighbors and the local network cluster. However, historic data such as information on nodes that left the cluster or information on other clusters could be highly beneficial for the Aerial Monitoring System. This could be used to adapt the currently static monitoring approach, for example, by explicitly searching for unknown clusters or devices at the locations that are hinted at in the historic data sets. Furthermore, the dynamic adaptation of monitoring areas based on population, e.g., such that sparsely populated areas are monitored in less detail or areas are adapted in size and shape based on the gathered information, could further increase the efficiency of Aerial Monitoring Systems for disaster areas.

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