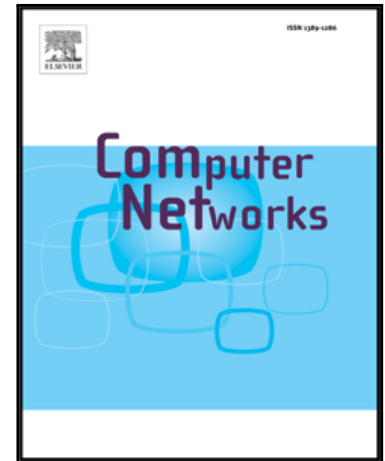


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# Wireless Sensor Networks and Multi-UAV Systems for Natural Disaster Management

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## Abstract

This work identifies the role of Wireless Sensor Networks (WSN) and Unmanned Aerial Vehicles (UAV) in the context of natural disaster management. Main applications of systems involving WSN and UAV are classified according to the disaster management phase, and a review of relevant research activities is provided along with the research and development challenges that still remain unsolved. The main objectives of this work are to present technical results useful to improve the wellbeing of people, and push the state of the art one step forward in the definition of a complete disaster management system.

*Keywords:* Wireless Sensor Networks, Unmanned Aerial Vehicles, Natural Disasters

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## 1. Introduction

The occurrence of natural disasters is a recurrent important problem in all the areas of the world (Table 1). The physical extent of the disaster makes it very hard and in some cases completely impossible for humans to timely react to and face the problem. Currently, efforts have been made in

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Table 1: Overview of the major events in Europe 1998-2009 [1].

Hazard type	Recorded events	Number of fatalities	Overall Losses (EUR Billion)
Storm	155	728	44.338
Extreme temperature	101	77 551	9.962
Forest fires	35	191	6.917
Drought	8	0	4.94
Flood	213	1 126	52.173
Snow avalanche	8	130	0.724
Landslide	9	212	0.551
Earthquake	46	18 864	29.205
Volcano	1	0	0.004
Oil spills	9	n/a	n/a
Industrial accidents	339	169	n/a
Toxic spills	4	n/a	n/a
<b>Total</b>	<b>928</b>	<b>98 972</b>	<b>148.831</b>

order to: recognize and forecast the possibility that a disaster will happen, react in an efficient manner to the disaster in course of happening, quickly assess the damage, fix and restore normal state. It is expected that, due to the climate change effects, natural disasters will occur with increasing frequency [68]. Consequently, significant research and development efforts are devoted to create systems to predict, prevent, and efficiently respond to natural disasters.

Recent developments in wireless communication technologies, energy storage, computing power and Unmanned Aerial Vehicles<sup>1</sup> (UAV) make a system composed of Wireless Sensor Networks (WSN) and multi-UAV the

<sup>1</sup>UAVs will be also referred to as *drones* in the rest of the paper

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perfect candidate to play an important role in the disaster management. The response time of search and rescue personnel in a natural disaster is the key for saving the lives of those in the affected areas. The most efficient and fastest situational awareness is achieved through aerial assessment, because of the possibility to quickly get to the affected areas and easily take images and videos of the current situation. Hence, UAV systems have been receiving increasing attention from the disaster management research and development community over the last few years.

In this paper we focus on the joint role that WSN and multi-UAV systems can play in this context, and, as first contribution, present a detailed overview of recent research efforts for using the two technologies to improve the efficiency of disaster management systems. The second main contribution of the paper is the presentation of a number of challenges that still remain unsolved. We believe that is important to analyze and focus on these challenges, whose solution will significantly improve the efficiency of disaster management systems.

In the remainder of this work, natural disasters in general terms are described and main phases of a disaster management cycle are identified in Section 2, different applications of WSN and UAVs in disaster management are analyzed in Sections 3 and 4. Discussion regarding some major open issues is presented in Section 5. The summary of related works surveying UAVs, WSN and networking issues in post-disaster management is presented in Section 6.

## **2. Disaster management phases**

Natural disasters happen daily worldwide and represent an important factor that affects human life and development. In order to respond to different types of natural disasters and develop feasible disaster management techniques and methods, it is important to understand the nature of a disaster and its phases. The concept of disaster phase has been used since several decades to describe and examine disasters and to organize emergency management processes.

The ongoing process of planning the countermeasures before a disaster happens, responding to it during the disaster, and recovering after the disaster, is usually illustrated by the disaster management cycle. Its earliest

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example can be found in [7], while the most common four-phase disaster management cycle (Figure 1), presented by [4], can be summed up in the following:

- *Prevention/mitigation.* Where the goal is to minimize the effects of disaster (building warning codes and risk zones, risk analysis, public education).
- *Preparedness.* The main focus of this phase is on planning how to respond to a disaster. It includes preparedness plans, emergency exercises and training, but also the Early Warning System (EWS) development and implementation.
- *Response.* In this phase the goal is to minimize the hazards created by a disaster. It includes Search and Rescue (SAR) missions and emergency relief.
- *Recovery.* The damage has been assessed in this phase, and the knowledge acquired during the disaster will be used to evaluate the prediction models for the disaster.

When a disaster occurs, the most important issue that needs to be solved is to preserve human lives. In this context, the first 72 hours after the disaster are the most critical. Ochoa and Santos state that the major problem is the lack of communication and situational awareness during a disaster, where the first responder teams need to improvise, thus degrading the efficiency of the disaster response mission [53]. Fischer and Gellersen survey the location and navigation support for emergency responders, where the importance of real-time knowledge is among the critical issues [26]. We introduce the Search and Rescue (SAR) mission protocol and methodology, proposed by the International Search and Rescue Advisory Group (INSARAG) as an illustrative example to introduce the concept of disaster management system. The INSARAG's set of guidelines<sup>2</sup> state that the SAR process must be conducted by teams. Activity assignment and local decisions are brought by a team leader, while all the team activities

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<sup>2</sup><http://www.insarag.org/en/methodology/guidelines.html>

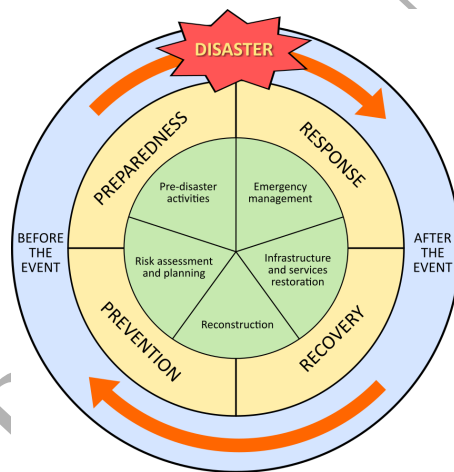


Figure 1: Disaster management cycle [4].

are coordinated by an incident commander. A common SAR mission is conducted in four major steps: 1) the commander establishes the search area (a smaller search area minimize the problems of communication among the rescuers), 2) a command post is established in the search area, 3) first responders are divided into scouts and rescuers and 4) scout teams report their findings to the command post and rescuers gather the information from the command post in order to know where to act.

In order to increase the efficiency of people involved in SAR missions as well as in the disaster management system as a whole, different technologies can be used at the same time: sensor networks, social networks, autonomous robots, satellite observations, etc. Li and Goodchild discuss the role that social networks could play in the emergency management. They point out the primary challenges in emergency response that are basically information related: the knowledge about the disaster, and the information sharing and communication in order to facilitate coordination of the disaster management teams. However, existing communication channels are neither sufficient nor adequately used in response to major disasters [42]. In this work, the accent is put on the usage of WSN and UAVs for emergency and disaster management.

### **3. Applications of WSN and multi-UAV Systems in Disaster Management**

The issues and approaches in disaster management are presented by Chen et al [17], where the applications of WSN and multi-UAV systems are classified in different application domains that fall into 3 main groups: *monitoring*, *response* and *forecast*. This classification is done roughly following the disaster management phases, where the *forecast* group of applications refers to the prevention and preparedness, the *response* group refers to the disaster response and recovery, while the *monitoring* covers the whole disaster cycle, as these applications provide disaster information during all the phases.

In this work, the classification of the WSN and multi-UAV applications in disaster management is based on their main objective. For instance, structural monitoring, disaster forecast, environmental monitoring and early warning system design are grouped together since their common

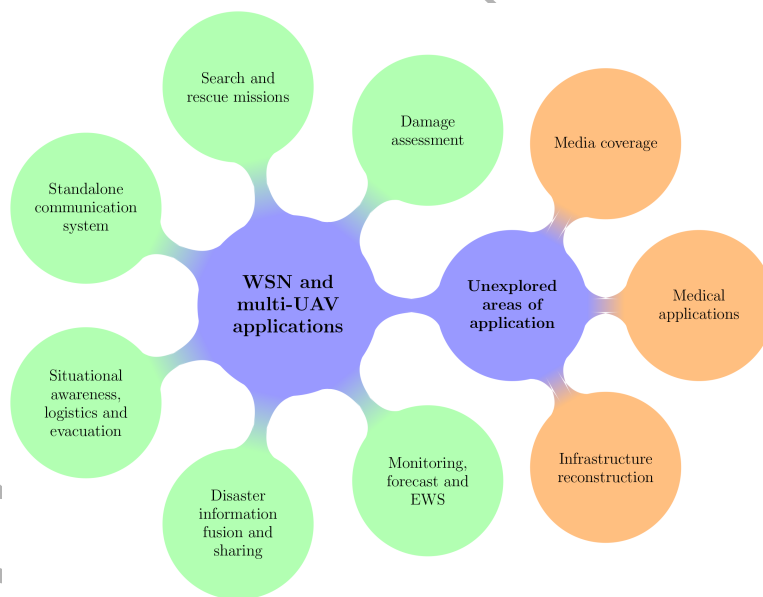


Figure 2: Applications of WSN and multi-UAVs in disaster management.



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goal is to predict and forecast the occurrence of a disaster. The groups of WSN and multi-UAV applications in disaster management considered in this work are the following (Figure 2):

- Monitoring, forecast and early warning systems,
- Disaster information fusion and sharing,
- Situational awareness, logistics and evacuation,
- Standalone communication system,
- Search and rescue missions,
- Damage assessment.

A review of the related works that deal with the WSN and Multi-UAV applications in disaster management is presented in Tables 2 and 3, while the detailed analysis is provided in the following sections.

### *3.1. Monitoring, Forecast, and Early Warning Systems*

This section covers the applications of WSN and multi-UAV systems whose goal is to predict the disaster by structural and environmental monitoring, information analysis for forecasting and early warning systems. The algorithms and methods of predicting and forecasting the natural disaster are executed during the prevention and preparedness phases of the disaster management cycle.

Early Warning Systems (EWS) represent the essential part of the preparedness towards natural disasters, therefore a lot of effort is put into the development of an efficient EWS. The UrbanFlood<sup>3</sup> is a European project whose aim is to investigate the use of sensors within flood embankments to support an online early warning system, real time emergency management and routine asset management. The goal of the project is to create an internet based EWS service platform that can be used to link sensors via the Internet to predictive models and emergency warning systems. Balis et al. identify a set of key challenges that the project UrbanFlood has to

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<sup>3</sup><http://www.urbanflood.eu/>

Table 2: WSN-related work applied to various natural disaster management scenarios. Here, a full circle represents the application of higher importance in the appropriate disaster phase, while a hollow circle represents the application of lower importance.

Application domains	Prev	Prep	Resp	Recov	References
Monitoring, forecast, EWS	●	●	○		[12, 17, 28, 67]
Disaster information fusion and sharing	○	○	●	○	[9, 39, 49]
Situational awareness, logistics, evacuation			●	○	[21, 22, 30, 32, 50, 64, 66]
Standalone communication systems			●	○	[6, 15, 27, 29, 36, 46, 69]
Search and rescue missions			●	○	[18, 40, 52, 53, 55, 70]
Damage assessment			○	●	[23, 38, 59]

Table 3: WSN and UAV solutions for disaster management scenarios.

Pre-event	Post-event	WSN	UAV	Monitoring, forecast and EWS	Disaster information fusion and sharing	Situational awareness, logistics and evacuation	Standalone comm. system	Search and rescue missions	Damage assessment	Year	Ref
•		•		•						2014	[28]
•		•		•	•					2013	[17]
•	•	•	•	•		•				2008	[22]
	•	•	•	•			•			2014	[73]
•	•		•	•		•				2015	[25]
•	•		•	•		•				2015	[56]
	•		•	•	•	•				2015	[74]
•	•		•	•	•	•				2015	[24]
•	•	•	•	•	•	•				2015	[41]
	•	•	•		•					2014	[49]
•	•	•			•					2015	[9]
	•	•			•			•		2010	[64]
	•	•	•		•				•	2004	[39]
	•		•		•	•				2015	[13]
	•		•		•	•				2016	[60]
	•		•		•	•				2015	[57]
	•		•		•	•				2015	[43]
	•		•			•				2006	[32]
	•	•				•				2010	[30]
	•	•				•		•		2007	[55]
	•		•			•		•		2008	[50]
	•		•			•				2015	[11]
	•		•			•		•		2015	[34]
	•		•			•		•		2016	[76]
	•		•			•		•		2015	[65]
	•	•	•			•	•	•		2015	[48]
	•	•					•			2005	[29]
	•	•					•			2010	[6]
	•	•					•			2011	[27]
	•		•				•			2011	[51]
	•		•				•			2012	[19]
	•		•				•			2012	[47]
	•	•	•				•			2012	[69]
	•		•				•			2013	[44]
	•	•					•			2014	[15]
	•		•				•			2014	[20]
	•	•					•			2014	[46]
	•		•				•			2015	[14]
	•		•				•	•		2013	[59]
	•		•				•	•		2016	[63]
	•	•						•		2005	[52]
	•	•	•					•		2014	[70]
	•		•					•	•	2012	[38]
	•		•						•	2013	[3]
	•		•						•	2014	[23]
	•		•						•	2015	[45]

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face [8], which gives a broader picture on a set of challenges that need to be addressed in most of the systems coping with flood-related disastrous events:

In order to meet the need of sensors that could detect structural collapses, slope failures and other natural disasters, different sensing systems are being developed. Bond et al. describe the development of a fully automated, continuous, real-time monitoring system that employs GPS sensors and pseudolite technology to be used for displacement monitoring [12]. Authors show that their GPS based system is capable of measuring displacements in sub-centimeter precision, which makes it suitable for different structural monitoring applications. Sudheer shows the efforts done in creating a system for landslide monitoring, which is composed of dedicated Deep Earth Probes that are wirelessly connected and that integrate a set of geophysical sensors such as rain gauge, soil moisture sensors, pore pressure transducers, strain gauges, tiltmeters, and geophones [67].

Chen et al. describe an early warning system for natural disasters, which relies on existing and available WSN technologies and that focuses on providing reliable data transmission, important amounts of data from heterogeneous sensors and minimizing energy consumption [17]. Besides methods for dynamic routing, network recovery and managing mobility for reliable transmission, the system incorporates data fusion approach to integrate all the obtained data into a unified geohazard overview. Frigerio et al. tackle the methodology, techniques and integrated services adopted for the design and the realization of a web-based platform for automatic and continuous monitoring of the Rotolon landslide (Eastern Italian Alps) [28]. The described monitoring system integrates different sensors with dual purposes: monitoring displacement of landslides and triggering alarm in the case of a debris flow.

Feng et al. propose a flood monitoring system, using data obtained by a fleet of UAVs [25]. The high-resolution images obtained from crafts, need to be processed in order to detect inundated areas. The system performs several phases to achieve this goal: (i) UAV data acquisition and pre-processing; (ii) feature selection and texture analysis; (iii) image classification; and (iv) accuracy assessment. Authors use Random Forest Classifier to classify regions and achieve high accuracy rate (87.3%).

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A similar approach is presented by Popescu et al. [56]. Authors propose a methodology for detection, localization, segmentation and size evaluation of flooded areas from aerial images taken with UAVs. The approach is based on sliding box method and texture features analyses. The process of feature selection takes into account a performance degree obtained from false positive and false negative cases. The evaluation of the system proves a rate of accuracy of 98.87%.

Farfaglia et al. [24] introduce Advanced System to Monitor the Territory (SMAT), a research project that aims to develop a system of system exploiting multiple Unmanned Aerial Systems (UAS) in civilian monitoring operations. The project assumes the usage of different types of UAVs from micro multi-rotor helicopter, to light fixed-wing crafts. All drones can be equipped with different sets of sensors required to monitor floods, earthquakes and volcanoes. Gathered data will be then processed by modules developed in the next stages of the project.

Kureshi et al. propose a framework for an info-symbiotic modeling system using cyber-physical sensors to assist in decision-making [41]. Simulations can be useful in all phases of disaster risk management. However, the complexity of the environment, human behaviors and the unpredictable nature of natural disaster, makes it difficult to model. The system utilizes advanced simulations, Agent Based Models, cyber-physical sensors and systems, and a dynamic data-driven approach to attempt fully encompassing all facets of disaster management. The framework adaptively manages the heterogeneous collection of data resources and uses agent-based models to create *what-if* scenarios in order to determine the best course of action.

### 3.2. Information Fusion and Information Sharing

Although the information fusion is necessary and helpful in all the disaster management phases, its most relevant impact can be appreciated during the disaster response phase. The goal of the information fusion and sharing is to combine different sources of information available and to make a bridge between different information technologies that can be of use in other applications for disaster management.

Kumar et al. propose a first responder system based on the use of mobile autonomous agents that are deployed in the emergency area [39].

Authors envision a system that should be deployed together with emergency personnel, where the role of the system is to acquire the information about the unknown environment and increase situational awareness. Robot agents would autonomously organize in order to optimize the deployment and communication, and they could possibly be tele-operated by a human operator. All the robots would be equipped with a set of different environmental and hazardous substance detection sensors, thus being able to create a map of hazardous areas. Mosterman et al. present an experimental system where multiple heterogeneous vehicles come together and are controlled and coordinated via cyberspace to accomplish complex logistical operations in automated humanitarian missions [49]. The physical world involves operating vehicles (such as cars or drones) with digital control on a time scale of milliseconds and is confined to the dimensions of an individual vehicle. The system responds to requests and information about the state of the infrastructure, and an open architecture allows adding vehicles to the fleet anytime during design or deployment.

Bartoli et al. propose an efficient architecture of a smart public safety platform that integrates heterogeneous components such as smart data gathering and analysis system, communication system, WSN and social networks [9]. The data gathering and analysis system is composed of five elements:

- adapters: interfaces for the interaction with social and sensor networks;
- data gathering subsystem: a software component that manages the information collection;
- data analysis subsystem: databases and algorithms for data processing;
- operative centre: core of the structure that collects the output of data analysis and elaborates them;
- data exposure system which shows the results in human-friendly format.

A surveillance system using a fleet of UAVs is introduced by Wada et al. [74]. Each UAV is provided with a mobile optical sensors and image

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transmission modules developed by the authors. After the launch, a craft executes auto flight along the way points by recognizing its positions. The system is able to get a video of the target area, transmits it to the server and shares it with users via the Internet. With additional equipment the UAVs can be used as communication relays, for radiation detection or non-disaster surveillance, such as environment monitoring.

Brown et al. introduce the Surveillance for Intelligent Emergency Response Robotic Aircraft (SIERRA) project focusing on forest fire applications for enhanced situational awareness [13]. A fleet of UAVs fly over a region, while gathering and transmitting information to the central server. The data is then analyzed and integrated into a fire-predictor software. Authors present some preliminary results proving the efficiency of the system.

ASIMUT project (Aid to Situation Management based on MULTimodal, MULTiUAVs, MULTilevel acquisition Techniques) project consists of handling several fleets of UAVs including communication, networking and positioning aspects for disaster relief scenarios [60]. The system has three main components: i) Ground Control Station (GCS) - the central component responsible for control, receiving and processing all the data; ii) High Level Coordination Swarm (HLCS) composed of fixed-wing UAVs; iii) Low Level Swarm (LLS) composed of multi-rotor UAVs. Each vehicle is equipped with a WiFi communication module for direct communication with its neighbors. GCS sends tasks to HLCS vehicles, which forward them to the most suitable vehicles in LLS to perform the measurements. The system includes algorithms allowing for autonomous swarm management in order to optimize the communication.

Ramchurn et al. propose Human-Agent Collectives for Emergency Response (HAC-ER) [57]. The project aims to improve situation awareness in disaster management scenarios by combining information from many different sources: rescue teams deployed on the field, a fleet of UAVs and crowdsensing. To limit the number of irrelevant and erroneous data the system includes Crowdsanner, a module using machine learning to create a Heatmap, with spots requiring intervention. A fleet of UAVs can be then deployed to further investigate the situation in these spots. UAV controller allows the assignment of tasks to the most suitable drone in the area. The whole design is complemented by communication interfaces

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allowing information flow between different components.

### 3.3. *Situational Awareness, Logistics, and Evacuation*

The goal of this set of applications in disaster management is to gather the information during the disaster phase, especially regarding the movement of the people endangered by the disaster, as well as concerning the rescue teams deployed on the disaster area. The use of WSN and multi-UAV systems for situational awareness, logistics and evacuation is being done during the disaster response and recovery phases.

In [21], authors analyze the overall structure of the WSN and multi-UAV system needed for assessing the different types of natural disasters, and outline the challenges that such a system should cope with. The project IMATISSE (*Inundation Monitoring and Alarm Technology In a System of SystEms*) presented in their work, aims at integrating the WSN and multi-UAV system with a novel crowdsensing paradigm, where smartphone users provide the captured smartphone data, thus complementing the WSN and increasing the amount of available information used for situational awareness.

Coordination among unmanned ground (UGV) and aerial vehicles and issues of surveillance are discussed in [32]. Grocholsky et al. describe how the synergy of different mobile platforms and sensor techniques can be exploited by creating a seamless network of UAVs and UGVs. It is stated that the proposed system is able to exploit a proactive sensing network with decentralized controllers, allowing each node to be seamlessly aware of the information accumulated by the entire team. Information aggregation and source abstraction result in nodal storage, processing, and communication requirements that are independently of the number of network nodes. Furthermore, authors show that the collaborative proactive sensing network as a whole has a better performance than that of the individual system components.

Erman et al. present the *AWARE* project: a platform that relies on both static and mobile sensors and addresses the challenges of sensor data aggregation, routing, responders activity monitoring and different mobility issues [22]. The goal of their work is to exploit the advantages of mobility with low-cost embedded devices for improving response time in critical situations. The system provides event detection, autonomous network



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repair and quick operational response by integrating WSN, UAVs and actuators into a disaster response setting. Authors point out their interest in critical data dissemination, therefore their focus is on minimizing the latency and maximizing the reliability and the success ratio of delivery, by exploiting mobility dynamics and self-adaptation of the devices in the network.

Murphy et al. describe the experiences from La Conchita (California) mudslide response in January 2005 [50]. Authors provide a study about information regarding mudslide responses, what tasks robots are needed for, how the rescue robots performed and how responders viewed the robots. The report identifies findings on robot performance, mudslide characteristics and general rescue robot design issues.

Sardouk et al. propose a multi-agent system based on WSN for crisis management [64]. The solution proposed in their work is focused on tracking and data aggregation methods in order to gather the information about the fire status and its evolution, besides the tasks of safe-zone discovery and aggregation of rescue personnel bio-medical signs. George et al. present *DistressNet*, an ad hoc wireless architecture that supports disaster response with distributed collaborative sensing, topology-aware routing using a multichannel protocol, and accurate resource localization [30]. The proposed wireless architecture is dedicated to the disaster areas where there is a need for situational awareness based on a robust, adaptive and distributed collaborative platform. *DistressNet* is implemented on a set of available sensors, mobile and static gateways, and a set of servers providing network services, data analysis and decision support.

Belbachir et al. focus on detecting forest fire using UAVs [11]. In such scenarios vehicles operate in unknown terrain to develop an automatic coverage exploration strategy. Authors of the paper focus on improving the localization mission by a decision-based strategy resulting from a probabilistic model based on the temperature in order to estimate the distance from the forest fire. The UAVs try to optimize their trajectory according to the state of the forest-fire knowledge by using a map that is updated at each step of the exploration. Authors prove the efficiency of their system performing a set of simulations.

Mori et al. consider a system composed of by different types of wireless nodes [48]. Balloon nodes that can remain at a fixed position for a long

Table 4: Performance measurements of major UAV communication technologies from different aerial test environments for line-of-sight links [5].

	Technology	Link	Frequency	Latency	Throughput
Control and coordination	CC	g2a	2.4/0.915 GHz	1–2 ms	80 kb/s
	802.11b/g	a2g	2.4 GHz	2.2–270 ms	11–54 Mb/s
	XBee-PRO	g2a, a2g, a2a	2.4 GHz	~10 ms	up to 250 kb/s
Sense and connect	802.11b	a2g	2.4 GHz	~100s of ms	1.4 Mb/s (2 km)
	802.11a (three-antenna)	a2g, g2a, a2a	5 GHz	~100s of ms	UDP: 14 Mb/s (350 m), 29 Mb/s (50 m) TCP: 10 Mb/s (500 m), 17 Mb/s (100 m)
	802.11n (internal antenna)	a2a	5 GHz	~100s of ms	plane: 1–2 Mb/s (300 m), 22 Mb/s (20 m) copter: 20 Mb/s (80 m), 60 Mb/s (20 m)
Multihop networking	802.11g+802.11s	g2g g2a–a2g	2.4 GHz	~100s of ms	no MAV: 0,064 Mb/s (75 m) 2-hop: 8 Mb/s (75m)
	802.11n+OLSR (fixed rate: 13 Mb/s)	a2g a2a–a2g	5 GHz	~100s of ms	1-hop: 1 Mb/s (600 m) 2-hop: 2 Mb/s (600 m)
	802.11a+802.11s (fixed rate: 36 Mb/s)	a2g a2a–a2g	5 GHz	~100s of ms	1-hop: 5 Mb/s (300 m) 2-hop: 8 Mb/s (300 m, AP mode) 2-hop: 5 Mb/s (300 m, mesh mode)

period of time, electric vehicles, running on the ground and UAVs used for exploration purposes. The study focuses on network coverage, connectivity and connection quality among different components of the system for different numbers of nodes.

Luo et al. introduce a UAV-cloud system for disaster sensing applications [43]. A fleet of UAVs is deployed to gather videos from a hazardous area. To reduce the volume of transmitted data, authors propose to use image pre-processing on the drones, taking into account context information. The framework integrates video acquisition, data scheduling, data offloading and processing, and network state measurement. The data is then sent to the server and processed by the cloud component.

#### 3.4. Standalone Communication Systems

Andre et al. provide a comparison of different communication technologies for multi-UAV systems that can be of use in emergency response and disaster management [5]. They identify the key functionalities and building blocks that describe the communication needs of a Multi-UAV system. These building blocks are *control*: enables communication between ground station and UAVs in order to influence and control the behavior of individual UAVs, *sensing*: enables the transmission of on-board sensor data to the ground station, *coordination*: enables the communication among vehicles required for local decision making, cooperation, self-organization and collision avoidance, without explicit input from the ground station and *connectivity*: transmission of data generated outside of a UAV. The comparison of existing communication technologies is presented in Figure 4.

The application that receives the most attention during the disaster management is related to standalone communication systems, where the goal is to re-establish the damaged or destroyed communication infrastructure during the disaster. Its application is most relevant during the disaster response phase, while the re-established standalone communication system can be of use during the recovery phase as well (one of the examples is the Serval Project<sup>4</sup>).

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<sup>4</sup><http://www.servalproject.org/>

In order to facilitate the intercommunication between disaster victims and rescue teams, Bai et al. proposed an integrated emergency communication system that relies on WSN, Mobile Ad hoc NETWORKS (MANET) in conjunction with satellite and cellular network, that are deployed on disaster site for local communication and information collection [6]. The communication with disaster-safe areas is performed by using a cellular gateway and connecting to a satellite mobile network. Emergency end users can select appropriate communication path according to their locations and wireless network coverage conditions. Fujiwara and Watanabe describe their networking scheme and routing protocol for emergency communications that rely on a hybrid wireless network that combines an ad-hoc with a cellular network to maintain the network connectivity [29]. In a disastrous event, where the link between the base station and a node is broken, the node switches to ad-hoc mode in order to restore connectivity via a multi-hop connection. Results show that the connectivity can be restored with low latency and delays, however only for small amounts of data. Therefore, the system is suitable for collecting damage assessment information, but not for real-time video or voice transmission. Fragkiadakis et al. propose a flexible network architecture that provides heterogeneous multi-operator networks with a common networking platform for inter-operation in case of emergencies [27]. A wireless mesh network is the main part of the proposed architecture and this provides a back-up network in case of emergencies. Authors measured the performance of a video streaming application in a real wireless metropolitan multi-radio mesh network, showing that the mesh network can meet the requirements for high quality video transmissions (where the required network throughput depends on the video frame rate, resolution and color). Regarding the video transmission quality for first responders, it is advised to use a minimum of 10 fps (for 360x240 and 720x486 video formats), a minimum of 1 s end-to-end video delay, and a minimum of 1.5 Mbps (MPEG-2) and 768 Kbps (MPEG-4) [54].

Tuna et al. propose an emergency communications system established by unmanned aerial vehicles [69]. In this study, authors propose the use of UAVs in two different scenarios. In the first scenario, radios on the ground are placed at fixed locations and establish a mesh network. The nodes in the network are connected directly or via relaying nodes if a multi-hop

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route between communicating nodes exist. In the case of a disaster, when the mesh network can become disjoint, UAVs are deployed in order to reconnect the network and serve as message relaying nodes. The second scenario relies on the UAV mesh network, where the aim is to maintain connectivity between a ground station and a UAV.

Minh et al. propose a novel approach to on-the-fly establishment of multi-hop wireless access networks (OEMAN) for disaster response [46]. The proposed architecture extends Internet connectivity from surviving access points to disaster victims using their own mobile devices and it is set up on demand using wireless virtualization to create virtual access points on mobile devices. Virtual access points greedily form a tree-based topology which is then used to provide multi-hop wireless Internet access to users.

Carli et al. use a WSN as a communication infrastructure for an emergency scenario [15]. In their work, authors tackle both routing and localization problems for reducing the network communication as much as possible in order to be suitable for transmission by a WSN. They propose a distributed localization algorithm based on ranging technique by mapping the localization into a stochastic estimation problem for systems with uncertainties.

Khalil et al. show how the use of wireless ad hoc and sensor networks (WASN) in disaster recovery can provide valuable services to rescuers when traditional infrastructure communication systems fail [36]. Authors present an identity delegation attack that could be utilized to disrupt the data flow during critical disaster recovery situations and a mitigation technique (SADEC) that can be used against attacks. Their results show that SADEC can achieve full isolation of malicious nodes with sufficient node densities. However, the results reveal that the performance of SADEC in isolating malicious nodes comes at the expense of having higher false isolation rates.

Bupe et al. propose a fully autonomous system to deploy UAVs as the first phase disaster recovery communication network for wide-area relief [14]. Authors propose an automation algorithm to control the deployment and positioning of UAVs based on a traditional cell network structure utilizing 7-cell clusters in a hexagonal pattern using MAVLink. The algorithm uses clustering based on a centralized management of UAV

cells through assigning higher ranked UAVs referred to as *supernodes*. The system autonomously elects supernodes based on weighted variables and dynamically handles any changes in total number of UAVs in the system. The algorithm was verified using software simulation and physical demonstration using a fleet of UAVs.

Sanchez et al. aim to provide connectivity for rescuers and disaster victims using a fleet of UAVs [63]. First, authors introduce a realistic mobility model for victims in an urban disaster scenario. Using the model, they propose an intelligent strategy that allows UAVs to perform tactical movements in a disaster scenario, combining the Jaccard distance and artificial intelligence algorithms. Finally a comparison among several local search computational intelligence algorithms implemented such as simulated annealing, hill climbing, and random walk for deciding the best tactical UAV movements.

As during natural disasters, network infrastructure is likely to be damaged and not fully operable, many authors use the concept of *Delay Tolerant Network* (DTN) in these scenarios.

Zhou et al. propose a 2-tier UAV-aided architecture for disaster scenarios [78]. Each UAV is assigned to a ground vehicles which becomes its landing/takeoff and recharge station. Ground stations are also deployed in order to coordinate the network. UAVs fly in a given formation to the affected area, where they perform sensing and relaying messages. If a disaster area is too large, UAVs can relay messages in DTN mode acting as data ferries (Figure 3).

Uchida et al. explore the idea of a fleet of UAVs flying in post-disaster areas, seeking for disconnected nodes [71] [72]. Upon finding such a node, a UAV hovers over the point to receive all the data, and delivers it using IBR-DTN routing protocol<sup>5</sup>. The system allows UAVs to fly autonomously and return to the base station in order to recharge batteries.

Saha et al. propose a 4-tier architecture allowing messages transmission between disconnected shelters [61]. Tier 1 consists of users phones and tablets, which act as DTN nodes exchanging informations. In each shelter, data is then gathered by laptops with higher storage capacities (tier 2).

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<sup>5</sup><http://www.ibr.cs.tu-bs.de/projects/ibr-dtn/index.xml?lang=en>

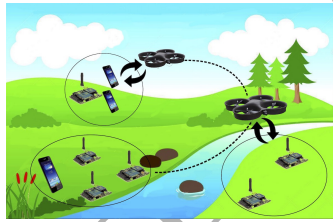


Figure 3: UAVs used as data ferries.

Mobile vehicles, such as UAVs, form the tier 3, transferring data between tier 2 devices. As disaster areas can be large, the system introduces towers with long range WiFi by grouping multiple shelters and tier 2 devices for better efficiency.

Krug et al. adapt a solution developed for MANET networks to DTN scenarios [37]. The system assumes usage of Border Nodes (BN) to connect MANETS with different protocols deployed and drones as data ferries. The authors address also the global name resolution issue in such scenarios.

### 3.5. Search and Rescue Missions

The goal of this set of WSN and multi-UAV applications is to search for and to rescue the unfortunate people that happen to be lost, trapped by debris or injured during the disaster. The search and rescue missions are the most important during the disaster response phase, however their application can be extended to the relief phase as well, depending on the particular type of disaster. Nourbakhsh et al. present an architecture for Urban SAR and a methodology for mixing real-world and simulation-based testing, where a sensor suite and sensor fusion algorithm for victim detection permits aggregation of sensor readings from various sensors on multiple robots [52].

Pogkas et al. present an ad-hoc sensor network for disaster relief applications that provides rescue teams with a quickly deployable and reliable tool to collect information about the presence of people in a collapsed building [55]. Chenji et al. further describe the design, implementation and realistic evaluation of DistressNet [18]. Kuntze et al. propose SENEKA concept (SEnsor NEtwork with mobile robots for disAster management) whose objective is the situation responsive networking of heterogeneous robots and sensor systems used by first responders in search and rescue operations [40].

Tuna et al. propose an approach to WSN deployment with the use of mobile robots for human existence detection in case of disasters [70]. The idea is to use a group of mobile robots that explore an unknown region, perform simultaneous localization and mapping (SLAM) and use a WSN to extend the range of communication (wireless sensors serve as message relays among robots and the control center). Sensors used in this approach are equipped with passive infrared sensors as motion detectors to detect human existence. Ochoa and Santos introduce the concept of a human-centric wireless sensor network, as an infrastructure that supports the capture and delivery of shared information in the urban area [53]. The use of WSN is evaluated using a simulated scenario and through the feedback provided by an expert in urban SAR.

Gutierrez et al. propose a multi-robot collaborative platforms for humanitarian relief actions [34]. The system consists of three main elements: a mobile station, a fleet of UAVs and a group of fast moving robots. The mobile station is deployed in a disaster area and serves as a coordination



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point and an energy supplier. The UAVs explore the disaster area and can carry lightweight objects to victims. After analyzing the situation, land/marine robots can be sent for delivering and rescue missions. Authors define communication patterns between parts of the system, as well as basic operations such as battery replacement or target identification.

A similar approach is presented by Zhang et al. [76]. Their system targets flood disaster and combines advantages of both surface and aerial vehicles. Authors want to use Unmanned Surface Vehicles (USV) as a transporting platform for a fleet of UAVs. Drones take off from special platforms, provide global vision and help USV to find the optimal path. UAVs are provided with a special tracking system allowing them to find the mother ship and land automatically after completing their mission.

Another combination of ground and aerial vehicles is presented by Siegwart et al. [65]. Authors present their design of legged robots including a balance mechanism, foothold planning and climbing maneuvers. The system includes also solar airplanes for continuous flight tests in different scenarios, such as SAR and Area Coverage. Authors complement their system by localization, mapping and path planning in unstructured environments.

### 3.6. *Damage Assessment*

During the response and especially recovery phase of disaster management, it is important to assess the scale of the damage by using different methods, such as structural health monitoring and UAV video inspection. In this context, Kruijff et al. describe the experience of collaboration with the Italian National Fire Corps in the post-disaster assessment activities after two major earthquakes that occurred in Emilia-Romagna region in Northern Italy in July 2012 (NIFTi project<sup>6</sup>) [38]. The team used a heterogeneous network composed of laptops, monitors, and a desktop computer. Rescue robots had ROS<sup>7</sup> installed on them, streaming data over 2.4GHz WiFi network to an operator control unit (OCU). Off-board computers were used for processing 3D laser range data (point clouds), and for the OCU and visualization. Two different UAV platforms were used in the

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<sup>6</sup><http://www.nifti.eu/>

<sup>7</sup>Robot Operating System, <http://www.ros.org/>

mission, the first one developed by NIFTi, equipped by a Hokuyo UTM-30LX range-finder, a sonar and a pressure sensor-based altimeter, an IMU module, a 3D magnetic compass, GPS module, a forward looking and downward looking cameras, the 1.6 GHz Intel Atom on-board computer, with the operation time of 10–15 min. The second UAV was equipped with 8 high-power engines and could lift up to 2 kg of payload, the camera had a high-power video signal transmitter (5.8 Ghz, 1.5W), ASUS Xtion Pro instead of laser scanner and Intel i7 2.6 Ghz on-board computer. Authors describe the UAV team that consisted of the UAV Operator who piloted the UAV, a UAV Mission Specialist who watched the UAV video streams and guided the UAV Operator to mission targets, and a Safety Commander (CNVVF) who safeguarded the UAV team. During the operation of a UAV, there is too much information to handle, ranging from sensor information to system- and infrastructure-related monitoring, to be performed safely by a single person. Rescue mission showed that both the UGV Operator and the UAV Operator suffered from cognitive overload.

Robinson and Lauf describe the key challenges to implement fault-tolerant and efficient deployments of collaborative autonomous aircraft to increase operational reliability and performance when performing aerial sensing and assessment [59]. The aircraft that authors propose to use is a native-electric high-wing trainer aircraft (6ft Telemaster Electro), designed to allow the transport of instrumentation, power sources, and on-board computer equipment without noticeably altering aircraft's flight characteristics. The power supply is generally implemented as a rechargeable lithium polymer battery, capable of sustaining flight for over 35–40 minutes at continuous speed of 55 km/h. To assist with autonomous navigation, each aircraft is equipped with an Ardupilot control board. Authors state that through the use of the Gumstix Overo boards and their integrated wireless communications hardware, they established an initial maximum communications range of approximately 350 meters. Ezequiel et al. discuss the use of a low-cost UAV-based remote sensing system for post-disaster assessment, environmental management and infrastructure development monitoring [23]. Results show that the integration of aerial surveys, ground observations and information sharing paves the way towards an efficient decision support system.

Meyer et al. introduce an UAV based platform for rapid survey and

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reconstruction of large scale cultural heritage sites [45]. The task becomes especially important after natural disaster that damaged the sites. Authors choose an aerial platform and integrate it with various sensors to achieve a inexpensive system, able to perform high-resolution 3D modeling. The data is then transferred to the server using LTE technology for further processing. The system includes different tools for visualizing 2D and 3D models.

The cited works represent the effort done by the WSN and UAV community in the direction of solving the global disaster management issues in efficient ways with smart wireless sensors and mobile flying robots. However, there are 3 main application domains that have not received enough attention yet, even though they could be very important for improving the current state of the art.

#### 4. Unexplored areas of application for WSN and multi-UAV systems in Disaster Management

The following set of disaster management applications can still be managed more efficiently by using WSN and multi-UAV systems (Table 5).

- Media coverage,
- Medical applications,
- Infrastructure (re)construction.

In the rest of this Section, we will explore these 3 application domains in depth.

**Media coverage.** Multimedia and press are interested in disaster information broadcasting prior to the disaster (preparedness phase) as well as after the disaster (recovery phase), while the highest information demand and importance is during the disaster response phase. Since the media is, in general, interested in the timely information about the ongoing disaster, its follow-up and news broadcast could be of use to response teams that act in the affected areas. However, the media coverage is mainly focused on delivering timely information to spectators (mainly informational purposes), in contrast to situational awareness where the gathered information is used for reconnaissance, organization and logistics of rescue teams.

Table 5: Unexplored applications in disaster management.

Application domains	Prev	Prep	Resp	Recov	Objective
Media coverage		○	●	○	Timely information about the ongoing disaster
Medical applications		○	●	●	Disease control, first-aid and supply delivery
Infrastructure (re)construction	○			●	Infrastructure health monitoring and analysis during the construction

One of the promising efforts to integrate the individual disaster photo and video material coming from different sources (including media companies, individual UAV owners, UAV professionals, etc) is the UAViators Crisis Map<sup>8</sup> initiative. However, further effort is needed in terms of establishing standards for the use of UAVs in disaster areas (especially regarding the people's safety), as well as the guidelines for sharing and publishing the gathered real-time information.

**Medical applications.** The health and wellbeing of people are among the most critical issues that an efficient disaster management system should take care of. Therefore, different medical applications are widespread prior, during and after the disaster happened. It includes the problems of mitigating the disease risks triggered by the disaster, as well as the first aid and supply delivery. There exist different organizations that are focused on using UAV technology in solving the issues of supply and first aid delivery in devastated areas (notable examples are Digital Humanitarians<sup>9</sup> and Matternet<sup>10</sup>). Although, there is an important volume of research, enterprises and individuals that use UAV technology in order to tackle these issues, the unified approach that leverages the WSN and UAV technologies is not fully employed yet.

**Infrastructure (re)construction.** The last set of applications is linked to the infrastructures that have been damaged during the disaster. Existing applications of UAVs in structural health and inspection could be further extended by using networked UAVs to speed up the process of inspections and improve its efficiency and precision. The challenge here is to develop the system of control and coordination, as well as the server side of the system where an important data volume must be analyzed and understood. The use of WSN and multi-UAV in infrastructural reconstruction is relied on during the phases of recovery after the disaster and in the prevention phase, where the goal is to improve the construction process that will allow the "smart" construction of infrastructure taking into account the knowledge gained in prior disaster occurrences.

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<sup>8</sup><http://uaviators.org/map>

<sup>9</sup><http://digitalhumanitarians.com/>

<sup>10</sup><http://mtrr.net/>

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Other applications that are not mentioned in this analysis are linked to communication security, responsivity and reliability of any of the measures applied during the disaster management. In most of the applications, the challenge is to take advantage of the mobility of the smart sensors (both WSN and UAVs) to improve the performance of the system as a whole. As already pointed out in this work, among different applications domains mentioned, some examples that could take advantage of the node mobility are:

- the construction site monitoring and evacuation of the people: people use smart phones that could be used to track their movement coupled with the video surveillance provided by the multi-UAV system;
- standalone communication system, where the multi-UAV system coupled with fixed or mobile WSN is used as a multi-hop relaying substitution network that allows the communication and information exchange;
- supplies delivery by creating an adaptable delivery system that is responsive to the real-time changes in the field;
- fighting against pests and diseases spread during the disaster.

In this Section we showed the unexplored areas of application that could be considered for future WSN and multi-UAV system. In the next Section we will sketch the limitations of these systems for both these unexplored areas as well as for current investigated applications.

## 5. Open Issues in Disaster Management

Although there are important issues that WSN and multi-UAV systems have to cope with, they still represent one the best technological choice for coping with natural disasters [17]. In this Section, we will sketch out some of these issues and challenges in order to provide the system designers and practitioners with a roadmap for research activities in this field.

Generally speaking, the UAV network still cannot efficiently cope with the issues of power supply limitations, processing power limitations and maximal physical load size and maneuverability in harsh conditions. In

fact, although power generation techniques exist, they are not sufficiently employed and used in practice, and although powerful on-board computers are already being installed in UAV motherboards, their processing power is still inferior to the processing power of a computer server machine. Overall, the WSN and multi-UAV technology intended to be used in disaster monitoring must cope with different issues: increased amount of sensory data, deployment in harsh conditions, heterogeneity of data sources, unreliable communication channel, unexpected node failures and unsustainable power supply.

More specifically, in disaster management scenarios several communicating actors co-exist: UAVs in the air, and the communication infrastructure, wireless sensors, a headquarter (HQ) managing the actions, rescue teams and victims on the field. All these actors participate in creating novel and unsolved networking problems. In the following, we will analyze communication issues among these actors (Figure 4).

#### *5.1. Coverage, mobility and connectivity*

Communication is easier in pre-disaster phase. The infrastructure is fully operational, so the main challenge lies in carefully designing the network to fulfill the needs of the system. If a system assumes involving people using their smartphones in surveying the infrastructure, adequate incentive methods shall be introduced, in order to assure sufficient number of devices. However, different types of applications require different incentive methods and choosing the right one can be the key to success.

During a disaster communication becomes much more difficult. In many cases the infrastructure could be damaged, making 2-3-4-5G connectivity impossible. A big part of wireless sensor could be also damaged or completely destroyed. Furthermore, many victims could be stuck in the affected area with no possibility to call for help. In such scenarios, we can try to connect existing nodes, to form multi-hop network relaying packet to nodes still having Internet connectivity.

The connectivity can be provided using temporally deployed relays or flying UAVs. However, even with many existing protocols allowing to calculate optimal positions for such nodes, it is difficult to use them without a global view of the situation. Hence, the main challenge is

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to gather information about disconnected part of the network in a very dynamic scenario.

In most scenarios, the number of UAVs will not be sufficient to assure permanent connectivity. One can be forced to use Delay Tolerant mode. However, it introduces a whole new group of challenges. UAVs need to determine efficient paths to transfer messages between nodes. It must be done also without a global view of a very dynamic topology. Thus, UAVs shall exchange information about already discovered parts of the network. Delivering messages in Delay Tolerant scenarios can be further complicated by mobile nodes. The recipient can change its position, so tracking mechanisms must be put in place to deliver messages. DTN require a modified network stack, which can limit its use in real-life scenarios.

The lack of global connectivity can complicate name resolution process. Victims or rescue teams will not be able to use DNS or specify IP address of requested devices. A system allowing to specify required data instead of endpoints can be an answer to this problem. However, the ability of sending Unicast packets or querying group of devices shall still be maintained.

UAVs are the main actors allowing to maintain the connectivity in disaster relief scenarios. However, they can operate on different levels of autonomy. UAVs tightly coupled with the HQ, can have much simpler software, but require a stable and reliable connection, as well as a large bandwidth to timely send pictures and video, and receive control information. Designing more autonomous UAV software is a much more challenging task.

### *5.2. Robustness and reliability*

Involving battery powered devices and mobile nodes, such as smartphones and sensors, can cause many topology changes, which must be addressed in order to keep the connectivity. Adequate, dynamic, inter-device reconfiguration protocols shall be deployed. This task becomes crucial without global 5G connectivity, when we have potentially disjoint segments of the network and no central node to coordinate this effort.

Lossy nature of wireless connection (especially with sensor networks) shall be addressed with retransmission, acknowledgement and checksum



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mechanisms to assure correct reception of packets. In order to rebuild the topology after a change we also need to keep track of devices in range. An efficient neighbor discovery mechanism must be deployed. Frequent scanning for new nodes allows a faster reaction to changes, but is occupied with high overhead and battery usage.

Flying UAVs must be able to avoid obstacles and collisions with other UAVs. This can be achieved by image processing, but can be simplified by exchanging information between vehicles about their position, flight trajectory and speed. Inter-UAV communication is necessary to perform collaborative tasks. Scalability is the key issue here, as the number of drones can be large in dense areas. The amount of communication depends heavily on the level of autonomy of drones. More user-control dependent drones, requires less communication with other UAVs, but introduce heavy traffic towards their ground stations. Autonomous drones can introduce more inter-UAV communication to take decision collectively.

### *5.3. Security, privacy and safety*

Security and safety play an important role in every complex system, but becomes even more important in disaster management, where keeping the network operational can influence human life.

Security and privacy are difficult to merge with interoperability. Keeping protocols simple and insecure facilitates the installation process and makes them usable by a wider range of devices. However, a right balance between simplicity and security must be found in order to ensure correct functionality of the network.

Installing a dedicated application on smartphones can be necessary to introduce DTN communication or device discovery. However, it rises many security and privacy issues. Without Internet connection, transferring software between devices is difficult especially on smartphones, where most vendors allow Internet store as the only source of applications. Furthermore, devices have different Operating Systems, which further complicates software distribution. On the other hand enabling software installation from any source can be used to exploit user devices. One possible solution can be to apply p2p versions of social media, such as

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Twister <sup>11</sup> - a decentralized version of Twitter. Data can be easily and securely exchanged by such mechanism, but they must be widely deployed on user devices.

Nowadays, most of the crowdsensing application rise some privacy issues. User do not want their data to be gathered and analyzed by other entities. However, during a disaster, getting the maximum data on victims can improve the efficiency of rescue actions and save human life. Different application modes shall be available in order to let users specify the amount of data they are willing to share.

Sophisticated security and privacy mechanism usually involve a significant amount of memory and computational power translating also into increased power consumption. It can be an issue for devices with limited resources such as sensors or smartphones. Finding a right trade-off between security and resource consumption will be the key to broad deployment of such mechanisms.

Involving UAVs rises additional safety issues. A falling drone can injure people on the ground or damage the infrastructure. Multiple procedures must be introduced in order to assure safe device landing in case of a drone collision, communication link disconnections, or engine failures.

#### *5.4. Inter-operability*

In general, heterogeneity is one of the biggest issue in disaster relief scenario. Ideally, we want all nodes to cooperate with each other, but in practice, this is an almost impossible task. Different capabilities of nodes, communication technologies, operating systems and protocols make cooperation difficult, yet essential task. Even considering development of a common protocol for every type of nodes in the network, we want it to run even on devices with the lowest capabilities, but at the same time we do not want to limit features on every other node. A designed solution should be able to detect capabilities of a given segment of the network and adapt the execution.

Creating direct communication between nodes in the network requires connecting heterogeneous devices using different communication technologies (Bluetooth, WiFi, ZigBee). Nodes require a method of identification, as

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<sup>11</sup><http://twister.net.co/>

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IP/MAC addresses can change and are insufficient. Compatible protocols for routing and device discovery shall be installed on every single node. If this step is not accomplished before a disaster, a mechanism allowing to do this dynamically is difficult to deploy.

Data, especially sensor readings, need to be timestamped to be used efficiently. However, synchronization of disconnected parts of the network and damaged infrastructure can be a challenging task.

As many sensors may be deployed, the network scalability should be considered. Actors in the network have different resource constraints, ranging from practically unlimited capabilities of laptops to low resource sensors and light UAVs. There are many existing solutions allowing sensors to operate with low amount of memory and calculating power, however they are tuned to perform WSN tasks (ex. transmitting readings to the sink). Introducing more nodes with different tasks and capabilities to WSN can be a challenging tasks.

Devices operate in different environments (WSN in the ground/water, UAVs in the air, smartphones on the ground) are often optimized to work under given conditions. Making them communicate with each other can significantly decrease radio performance.

##### *5.5. Quality of service*

Some messages have to be delivered to different nodes in the network. However, it is inefficient to transmit them to every single recipient, while many of them can be retransmitted locally within the remaining segments of the network. Providing a mechanism that permits to easily determine connected subnetworks in a very dynamic scenario, and transmitting this information to UAVs or to the HQ, can decrease the amount of required bandwidth.

UAVs have limited flight time and due to their potentially high cost, their number is also constrained. Even with unlimited storage capacities and protocols allowing to hover around a node, UAVs cannot deliver all the messages in the network. Prioritizing the traffic can be a key challenge in this scenario. Delivering only the most important message, data aggregation and merging redundant information, can significantly improve system efficiency.

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Node can gather and transmit different types of data, so the routing protocol and data exchange schemes have to be adjusted accordingly. For example continuous video streaming requires a fixed amount of bandwidth, while event-based crowdsensed data will arrive in rare, large batches. The priority of data should also be taken into account. With limited capacities of the networks, information crucial for rescue mission must have the highest priority.

Those policies shall be probably applied by every node, as coordinating the efforts by a central entity can be impossible or inefficient.

During disasters people tend to gather in small areas, such as rescue shelters. With huge amounts of devices the scalability must be addressed to enable communication. Additionally to developing scalable protocols, introducing content-centric solutions can significantly reduce the bandwidth required to exchanged information.

Data gathered by different sources (crowdsensing, sensors, UAVs) can contain a significant amount of errors, which should be handled. There are many existing solutions allowing to reduce errors for homogenous environment. However, designing system dealing with errors introduced by different sources of data is still a big challenge.

#### *5.6. Conceptual system for disaster management*

As mentioned in Section 2, the first 72 hours after the disaster are the most critical, and the major problem is the lack of communication and situational awareness during a disaster, where the first responder teams need to improvise, thus degrading the efficiency of the disaster response mission [53].

We advocate the use of unified system comprising integrating both WSN and UAVs, in the sense where a pre-deployed WSN serves as a trigger for automated launch of UAVs for the surveillance, inspection and supply delivery purposes. In an example scenario of UAV usage for disaster monitoring, we propose the use of UAV stations equipped with a fixed-wing and rotary-wing UAVs. Specifically, we propose the use of a fixed wing UAV that can quickly survey the disaster area for an overall view of the situation, and after the critical spots are identified using an approach for people or vehicle detection, rotary-wing UAVs can be sent to gather the real-time information from the spots. These UAV stations

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could be deployed on previously identified critical spots, and we foresee two types of UAV stations: fixed and mobile.

A conceptual design of a fixed (or static) UAV station is presented in Figure 5. The concept proposes the use of multiple heterogeneous UAVs, where fixed-wing UAVs are used for long distance and wide area surveillance, and the rotary-wing UAVs are used for Point-of-Interest (PoI) surveillance and structural inspection. Bearing in mind the autonomy, duration of airborne operation and recharging cycles, we estimate that we would need 4-5 UAVs per PoI, to which we add an extra UAV in order to offer sufficient redundancy in the constant surveillance of a PoI. The fixed UAV station could be connected to a wired Internet link, as well as to a constant power supply for UAV recharging.

A mobile first-response UAV station can be envisioned as a vehicle with a storage space for multiple rotary-wing and fixed-wing UAVs, equipped with a long-distance communication antenna, electricity generator and a system for automatic UAV battery recharging (Figure 6). The mobile UAV station could be operated by a single human operator, mostly to maintain the station and to act as a safety supervisor, if something goes wrong during the UAV network operation. The main advantage of the mobile UAV station is its flexibility regarding the location of the disaster, as well as the possibility to track the disaster progress and act accordingly if in danger. The disadvantage is the necessity of local power generation and well as the cellular or satellite internet antenna that needs to be installed on the vehicle, which significantly increases its cost.

The proposed UAV stations could also implement an approach for automatic battery replacement, together with an approach for vision-based formation control in order to allow a simplified yet effective control of a group of UAVs. We assume that the system can rely on the GPS positioning, while the operator can manually correct the hovering position of a UAV based on the multimedia input. A good UAV management software can allow the UAV network to be operated to a minimal number of personnel. According to the extension of the area to monitor the numbers would grow, but still the system will be feasible and rapidly deployable.

## 6. Related Works

Nowadays, there are multiple works surveying UAVs, WSN and networking issues in post-disaster management. However, to the best of our knowledge this is the first one taking into account all those components in disaster relief scenarios.

Bekmezi et al. introduce an extensive studies on FANETs (Flying Ad-Hoc Networks) [10] [62]. Reynaud et al. discuss networking issues while using all kinds of aerial vehicles from balloons and gliders to satellites [58]. Zhao et al. [77] focuses on topology control techniques for UAV-based ad-hoc networks , while Hayat et al. [35] provide an extensive survey on UAVs and their civil applications. A similar work is presented by Gupta et al. [33], analyzing networking issues in FANET scenarios. All those papers focus on UAV-based networks, but do not take into account the ground component of the system and do not focus on disaster relief scenario, which can be significantly different from classic conditions. Another group of authors discuss UAV-based post-disaster management, but either also ignore the ground components of the network [23] or focus on a single aspect such as imagery collection [2].

Ghafoor et al. presents works on cognitive radio for post-disaster management [31]. Multiple aspects are discussed with a presentation of different industrial solutions and projects.

Multiple work focus WSN component. Shah et al. discuss 3-dimensional sensor networks taking into account infrastructure, localization, topology design, and position-based routing. Topology management systems are discussed by Younis et al. [75] with particular emphasis on node failures. Celandroni et al. focus on sensor networks communicating through satellites [16]. A survey on WSN applications in disaster monitoring is presented by Silva et al [66]. This group of paper does not include UAVs or they do not consider disaster relief scenarios.

## 7. Conclusion

In this paper we focused on the joint role that WSN and multi-UAV systems can play in the context of natural disaster management. The first main contribution of the paper is the classification of recent research

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efforts that use WSN and multi-UAV for disaster management, into the following application domains:

- Monitoring, forecast and early warning systems;
- Disaster information fusion and sharing;
- Situational awareness, logistics and evacuation;
- Standalone communication system;
- Search and rescue missions;
- Damage assessment.

The second main contribution of the paper is the presentation of a number of issues and challenges that still remain unsolved. In order to provide the system designers and practitioners with a roadmap for research activities in this field, we analyzed the following set of open issues in disaster management:

- Coverage, mobility and connectivity;
- Robustness and reliability;
- Security, privacy and safety;
- Inter-operability;
- Quality of service.

By analyzing the current state of the art in the applications of WSN and multi-UAVs in the domain of disaster management, we aim on envisioning the future system that will tackle the identifies issues and challenges and thus push the state of the art one step forward in the definition of a complete disaster management system.

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ACCEPTED MANUSCRIPT

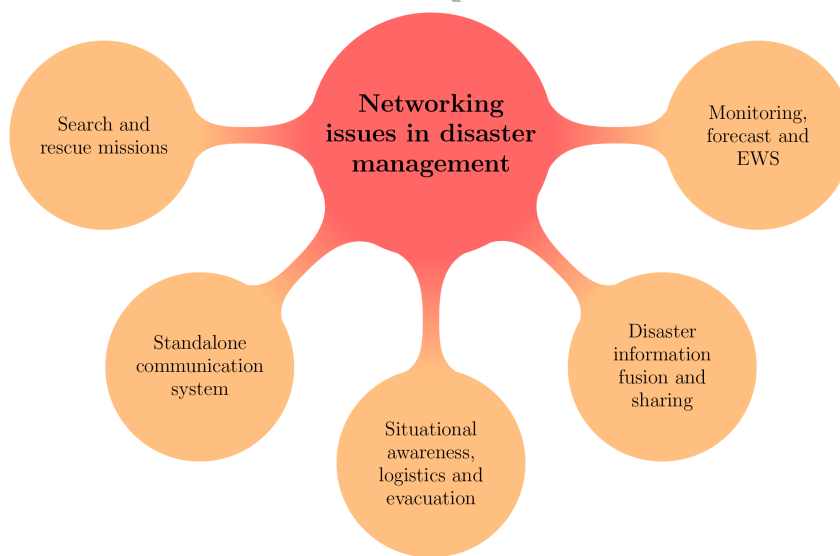


Figure 4: Networking issues in disaster management.

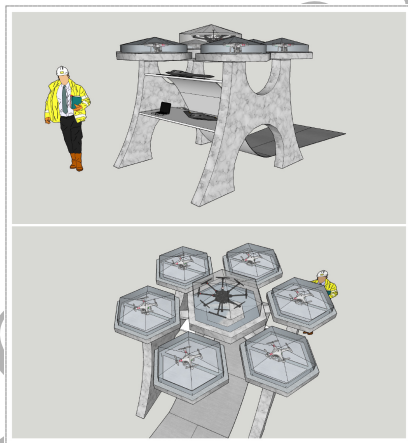


Figure 5: A conceptual fixed UAV station for disaster management.



Figure 6: A conceptual mobile UAV station for disaster management.