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Survey on Simulation for Mobile Ad-Hoc Communication for Disaster Scenarios

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Abstract Mobile ad-hoc communication is a demonstrated solution to mitigate the impact of infrastructure failures during large-scale disasters. A very complex issue in this domain is the design validation of software applications that support decision-making and communication during natural disasters. Such disasters are irreproducible, highly unpredictable, and impossible to scale down, and thus extensive assessments cannot be led in situ. In this context, simulation constitutes the best approach towards the testing of software solutions for natural disaster responses. The present survey reviews mobility models, ad-hoc network architectures, routing protocols and network simulators. Our aim is to provide guidelines for software developers with regards to the performance evaluation of their applications by means of simulation.

Keywords mobile ad-hoc communication, simulation, disaster scenario, mobility model

1 Introduction

Every year, millions of people are affected by natural disasters such as earthquakes, tsunamis, volcano eruptions, hurricanes, tornados and floods, and governments all around the world spend huge amounts of resources on the reconstruction and the preparation for such calamities. In 2013 alone, 97 million victims were affected by 330 natural disasters and the economic damage amounted to 156.6 billion dollars[1]. These traumatic events can severely damage public and private infrastructures (roads, buildings, houses, power supplies, etc.) and can dramatically compromise people's welfare. Furthermore, they also hit communication infrastructures such as the Internet and mobile cell networks, making it difficult for affected people and decision makers to communicate and to access information. In addition to the disruptions of communication lines and power supplies which often take many hours or even days to repair, disaster scenarios also consider that peaks of requests generated by users eager for information can seriously compromise communication services. For example, during Japan's 2011 earthquake and tsunami, approximately 1.9 million fixed communication lines were affected, 90 transmission routes were broken, 6 300 km of coastal aerial lines were damaged, and congestion caused 80%~90% of restriction on telephone calls[2].

Among the aspects related to disaster management, communication is crucial for supporting emergency pre-

Survey

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vention, response, recovery and mitigation efforts. Before the event, communication is needed for disseminating information about danger. During the event and afterwards, the coordination of relief operations and damage assessments requires communication. Personal mobile devices such as smartphones can be used during emergency situations to exchange relevant information through text messages, videos, photos and audios. During emergency situations, mobile devices and wireless ad-hoc networks can be powerful tools to palliate destroyed or overloaded communication networks.

The present survey focuses on mobile ad-hoc communication where each participant device cooperates by forwarding messages in order to reach one or more destinations. This technology characteristic can be naturally combined with people's behavior and daily life events and fits the context of emergency scenarios because of their minimal configuration need and deployment. Smartphones can be involved in participatory systems for crowd sensing, or in mobile phone clouds that process information generated locally[3].

Mobile ad-hoc communication covers different paradigms that are originally emerged from mobile ad-hoc networks (MANETs)[4]: wireless mesh networks (WMNs)[5], vehicular ad-hoc networks (VANETs)[6], opportunistic or delay tolerant networks (DTNs)[7], and wireless sensor networks (WSNs)[8]. Currently, there is a broad body of research devoted to improving protocols and algorithms for mobile ad-hoc communication that perform well under challenging disaster scenarios. In this context, simulators can play an important role in evaluating the system performance based on the mobility of participants. Ideally, simulators should provide support for the representation of all aspects and all assumptions associated with mobility. The simulation of near-real scenarios allows testing applications designed for disaster management and assistance to affected people.

In the present paper, we survey routing algorithms and mobility models proposed thus far for mobile ad-hoc communications under disaster scenarios. Our main contribution is to organize this knowledge to facilitate its understanding, thus providing guidelines for developers to evaluate the performance of their applications by means of simulation. We highlight research challenges in the area and gaps between applications, protocols evaluations, and mobility models.

The remainder of this article is organized as follows: Section 2 describes the main issues related to research and development efforts presented in the communication literature; Section 3 presents the state of the art on mobility models used for design and evaluation of routing protocols; in Section 4, we survey mobile ad-hoc protocols in the context of disaster scenarios; we discuss guidelines for developers, future challenges and findings in Section 5, and finally in the last section, we present our concluding remarks.

2 Communication in Disaster Scenarios

Communication in disaster scenarios is crucial to all the different stages involved in an emergency situation: detection of an incident, alerting the involved entities, damage assessment, response and engagement of necessary resources and recovery[9]. We classify entities that participate in this process in three categories: command centers, rescue teams and victims. Each entity can take part of the communication process as source or destination, according to their attributes.

Command centers may communicate information to the entities that take decisions, alert the population about dangerous events, and provide resources to handle the disaster situation. Command centers usually communicate among them using satellite technology and are located outside the dangerous zone.

Communication to support operations of rescue teams or first responders is critical after a disaster. Rescue teams must work fast and rescue operations must be secure and accurate. Each rescuer may be equipped with specialized wireless hardware to maintain team communication and coordinate their efforts, while keeping the team's safety.

The communication process may consider survivors or victims of a disaster. Recently, with the advent of ubiquitous smartphones, more and more applications include the communication between volunteers and decision makers in disaster situations[10-12]. Devices deployed on the field (unattached from people) may also trigger communication towards rescue teams or command centers.

Communication operations among these entities range from simple broadcasting to more complex routing protocols. Messages can be data exchanged between victims (one-to-one), from victims or rescue teams to command centers (many-to-one), and from command centers to victims or rescue teams (one-to-many).

In the remainder of this section, we survey approaches intended for different stages of a disaster, oriented to acting before or after the disaster. Table 1 resumes the main applications that use mobile ad-hoc communication in disaster scenarios.

Table 1. Summary Literature about Applications over Mobile Ad-Hoc Networks for Disaster Scenarios

Stage	Communication Application	References	Participant Entities
Detection	Fire or earthquake detection	[13-15]	Sensors
Alerting	Evacuation guidance	[16]	Victims
	Emergency messaging	[17-18]	Victims
Assessment	Information gathering	[12,19-22]	Comand centers (CC), victims
	Microblogging	[10-11]	Victims
	Sensing for monitoring and tracking	[23-27]	CC, rescue teams (RT), victims, sensors
	Medical triage and monitoring	[28-30]	CC, RT, victims
Response	Basic communication support	[31-36]	CC, RT, victims
	Communication for rescue operations	[37-39]	CC, RT
	Communication for location	[40]	CC, RT, victims
Recovery	Extending Internet connection	[41-42]	CC, RT RT, victims

2.1 Detection

Mobile ad-hoc communication can be used to detect the events that trigger a disaster situation, such as an earthquake, fire or flood[13,43]. The work in [14], for example, uses WSNs to detect forest fire in real time. Sensors built for that purpose may detect temperature, smoke, wind speed and relative humidity, and data is sent to a sink node that gathers and retransmits data towards a command center. Other sensors that monitor earth activity can alert when strong earthquakes occur[15]. WSN protocols can support communication in such cases. Protocols send data from one sensor to another in a hierarchical order to avoid the overflooding of messages in their way to a sink node.

2.2 Alerting

Alerting is oriented to fast disseminating information about a certain danger towards the potential victims, aiming to mitigate the effects of a disaster. In this case, communication likely uses epidemic or flooding techniques to increase the possibility of reaching the destination of messages.

Some applications notify emergency events to the affected population through their mobile phones using social-network services or text messages. For example, warning SMS (short message service) was used in Japan during the 2011 earthquake and tsunami; however, it was learned that the cellular network is less accessible than the Internet during a large disaster event[2].

American Red Cross Apps① and Google Public Alerts② are among the applications that use Internet to disseminate information. The former aims at notifying mobile-phone users when a natural disaster occurs. The software tool Google Public Alerts provides a common alerting protocol that supports the third-party dissemination of emergency alerts.

Information dissemination may guide evacuation in case of a disaster scenario. Fujihara and Miwa[16] proposed a system where smartphones gather information of blocked and congested roads in real time using an opportunistic exchange of messages. Similarly, in the case of vehicular applications, solutions optimize the communication of emergency alert messages[17-18].

2.3 Assessment

Assessing both, the damage caused by an emergency situation and the perception of the environmental elements, is important to take decisions and deploy resources on the field. It requires to identify processes and to understand critical elements of information about what is happening in some vicinity, which is difficult in large-scale disasters.

Different protocols can support this task. For example, a flooding-based protocol was proposed to collect victims' location autonomously using smartphones and vehicular terminals[19]. Similarly, MANETs are used to support a safety confirmation system that integrates sensors with smartphones[20].

In order to reduce message size and delay when disseminating information, Fajardo *et al.*[21] proposed to aggregate data using a DTN-based protocol. Mobile phones produce information about survivors, shelter and available resources. Recently, the same authors have proposed a content-based data prioritization method for geotagged images[22] that delivers timely

①American Red Cross Apps. http://www.redcross.org/prepare/mobile-apps, Nov. 2015.

②Google Public Alerts. http://www.google.org/crisisresponse/, Nov. 2015.

and accurate information using mobile phones of people located in the disaster zone. Similarly, victims in the uRep application[12] report problems by sending a geo-tagged photo from their mobile devices using a MANET protocol.

When the fixed communication infrastructure is partially or totally wiped out, applications that normally use 3G connections, such as microblogging, require mobile ad-hoc communication. Microblogging enhances situational awareness, as people broadcast messages of what is happening around them[11,44]. Hossmann *et al.*[10] proposed Twitter in disaster mode, an application that relies on opportunistic communication and epidemic spreading of tweets from phone to phone. In addition, the authors proposed Twimight: a platform for disseminating sensor data that provides information about, for example, the location of drinkable water sources.

Sensors can also support situation awareness[23-25]. They are small pieces of hardware capable of measuring temperature, pollution, and humidity, among others. They are coordinated in networks to generate, share and aggregate information. DistressNet[23] provides situation awareness using on-demand and delay-tolerant routing for collaborative sensing. The network is composed of sensors located in vehicles, in possession of rescue team members or victims, or deployed in the disaster area. SENDROM[24], on the other hand, locates people trapped under collapsed buildings using sensor nodes (deployed prior to the disaster) and central nodes nearby the command centers.

Sensing tools to triage and monitor the state of the victims have been proposed for medical applications[28-29]. For example, CodeBlue[28] tracks and monitors vital signs of victims and first responders using small pulse and electrocardiogram sensors with PDA devices. Also, Martín-Campillo *et al.*[30] presented two applications to triage tags using mobile devices and opportunistic networks. They transmitted the gathered information to a command center, which is then available for the next stages in the disaster relief process.

2.4 Response

Applications for response operations in disaster scenarios are mainly dedicated to giving communication support to the participant entities. Some applications provide basic communication without specifying their use. Among them, Majid and Ahmed[31] proposed to establish communication among survivors prior to the arrival of rescue teams using ad-hoc networks. In the context of developing countries, Jalihal *et al.*[32] proposed a system (DISANET) to exchange text, voice and video messages between rescue workers and the command center. For urban areas, Toral *et al.*[33] proposed the use of Bluetooth-enabled devices, which are positioned in advance, to gather information about collapsed buildings and coordinate the activities of rescue workers.

We survey applications that specifically support the communication between command centers and rescue workers equipped with handheld devices[37]. Lu *et al.*[38], for example, proposed supporting multimedia traffic with different hierarchical models for communication. Communication for search and rescue is analyzed by Lakshmi Narayanan and Ibe[39] proposing a stand-alone system that uses gateways, phones, access points (mobile and static), among other devices, combining existing mobile ad-hoc networks technologies.

Recently, the use of vehicles has also been included in communication[34]. Among them, RescueMe[40] stores information about vehicles' location during normal network operation to facilitate post-disaster rescue planning.

2.5 Recovery

Similar to the response stage, recovery focuses on a post disaster task that consists in restoring the services that were available prior to an emergency situation. We classify literature for this phase by considering the approaches that extend cellular data connection to the disaster area. When the cellular network is unavailable, the communication systems, such as Ushahidi③, are impossible to use because they depend on the cellular infrastructure. Instead, SKYMESH[41] recovers communication by building a backbone over the disaster area using balloons located 50∼100 meters high over ground.

3 Mobility Models

Mobility models simulate the movements of participants communicating in disaster scenarios, and play a role in determining the communication protocol performance. They are also crucial for evaluating communication connectivity in large-scale disaster scena-

③Ushahidi. http://www.ushahidi.com, Nov. 2015.

rios. Well-known mobility models, such as the Random Waypoint Model[45], are the base for others tailored for disaster scenarios. The Random Waypoint is a simple and widely-used model on which mobile nodes randomly select one location in the simulation field as the destination. Then, each node travels towards this destination with a constant velocity chosen uniformly and randomly within a range. Upon reaching the destination, the node stops for a pause time that is also randomly selected. After the pause, it repeats the process. In this section, we identify six main features to classify mobility models proposed for disaster scenarios and summarize the cited work in Table 2.

Aschenbruck *et al.*[46] and Conceiçao and Curado[53] proposed their own classifications of mobility models for disaster scenarios without considering most of the work analyzed in this survey. In [46], the authors considered temporary, spatial and geographical dependencies of the mobility movements, and identified a set of requirements for disaster scenarios: heterogeneous velocity, tactical areas, optimal paths, obstacles, group movement and possibility for units to leave the scenario. On the other hand, recently Conceição and Curado[53] studied mobility models considering: random-based movements, geographic restrictions, temporal dependencies, target area, constant velocity, participants joining or leaving the scenario and obstacles.

3.1 Map-Based Approaches

When a disaster occurs in an urban zone, the map and the geography of the scenario influence the movements of rescue workers and victims[49,52]. The movements of people and vehicles can be described over a map that contains road segments onto a 2-D plane[49]. More elaborated maps can be found in OpenStreetMap, which is a crowdsource application that provides the layered representation of real locations including buildings, streets, water sources, potential obstacles, altitude, and ground conditions[52]. This data can be converted into a format read by the simulator ONE[54] to enable the simulation of opportunistic networks.

Models that take into account map-based movements tend to be more realistic. However, in a disaster scenario, it is very difficult to accurately plot the current map: the infrastructure may be modified or non-existent[53].

3.2 Event-Driven Paradigm

Events, such as a fire, a collapse of a building, or a tsunami, may trigger direction changes of people using mobile devices. Event-driven mobility models for disaster scenarios[47-48,52] aim at reflecting this type of behavior with role-based approaches, which are oriented to representing a different response of an entity to different events. An entity may be a civilian, a victim, a police, a firefighter, or an ambulance, among others; entities may react differently to different types of events. The models that use this paradigm define a specific movement for a specific role in reaction to a different event.

The authors in [47] defined three classes of behavior: fleeing from the event, approaching the event and oscillating from an event to a predetermined location. They used a physical-based gravitational model to determine how entities go to and away from an event, and how entities that are closer to an event are more affected by it. This model establishes stationary events with a constant intensity that defines maximum distance to the affected entities. Also, there is a communication threshold that defines the maximum time until the emergency vehicles are notified and then move towards the event.

Similarly to [47], Huang *et al.*[48] modeled events that attract attention (missions or tasks) and repel (dangerous areas) the movements of first responders.

Table 2. Features of Mobility Models for Disaster Scenarios

Mobility Model	Map-Based	Event-Based	Obstacle	Group-Movement	Area	Movement
DA, Aschenbruck *et al.*[46]			X		X	X
Role/events, Nelson *et al.*[47]		X			X	X
CORPS, Huang *et al.*[48]		X	X	X	X	
PMD, Uddin *et al.*[49]	X					X
Composite, Pomportes *et al.*[50]			X	X		
Cluster, Saha *et al.*[51]				X		X
GoTo, Costantini *et al.*[52]	X	X				X
HBDA, Conceição and Curado[53]			X	X		

Note: X represents that the feature is explicitly supported by the model.

The attributes to model the event are: its central location with sensing range, the attending zone where first responders can move, the event time and lifetime, the attending role list, and the resolution effort needed to resolve the attention of the event. The role of each entity may change along time. For example, a civilian can become a first responder when an event immobilizes a victim. Costantini *et al.*[52] proposed that when an entity works on an event, its effect decreases over time.

3.3 Obstacle Avoidance

Even though obstacles may appear on the map where the entities move in a disaster scenario, some studies have explicitly defined movements to overcome them[46,48,50].

Aschenbruck *et al.*[46] modeled obstacles as polygons, using a visibility graph in order to find an optimal path. These obstacles can only affect vehicles that move between areas and their movement is determined by robot motion planning. The visibility graph is a graph where its vertices correspond to the obstacle's vertices (polygons). The shortest movement path consists of a subset of edges of the visibility graph computed using the Dijkstra's algorithm. Similarly, in [48], first responders move using the shortest-safe path, which is the shortest distance path, avoiding all the static obstacles. Their algorithm assumes a rectangular shape of obstacles and uses the Dijkstra's algorithm considering the corners.

Pomportes *et al.*[50] argued that the visibility graph used in [46] to avoid obstacles puts the entities in danger, moving them close to the obstacles. They proposed instead a Voronoï diagram when obstacles are present in the movement of the entities. The diagram is created with obstacle corners and by adding some points of their projections. This technique allows having a path as far as possible from the obstacles to create a safer path for rescuers.

Graph-based motion planning algorithms are used by the mobility model to route entities around obstacles in [52]. This type of algorithm can be directly inserted into the mobility model.

3.4 Group Movement

Group movements in models for disaster scenarios have been used by [48, 50-51]. Aschenbruck *et al.*[46] stated that people move in groups. However, they assumed that only one person in the group has a communication device, not the entire group.

First responders in [48] are organized into micro groups where a leader is defined and a set of followers move in its proximity. A displace radius is defined to allow movement diversity. Pomportes *et al.*[50] used the Reference Point Group Mobility (RPGM) model, where participants are divided into several groups and each group has a leader. The movements of the leader define the displacement of the entire group and the members have a certain movement freedom around the leader. In this model, the leader's movement follows the Levy-Walk model. Levy Walk mobility model[55] is similar to the well-known Random Waypoint model, except that movement lengths and pause times are drawn from a power law distribution. This model is capable of producing almost the same inter-contact time distributions as many real-world traces.

A cluster mobility model is used to model disaster scenarios in [51]. This model organizes the whole network in a number of clusters. All the entities move around a particular point, called cluster center.

For the case of modeling a group of people searching for victims, the authors in [53] assumed that each rescue worker tends to be physically separated from one another, in order to scout unexplored areas. However, rescuers also tend to maintain an in-range communication to one person (at least) in order to avoid isolation and losing the announcement of the finding of a possible victim. This idea is implemented by using a force vector, where people tend to go in opposite directions, while respecting a maximum separation.

3.5 Target Areas

Areas are defined, either to assign movements to the entities that belong to them, or to assign the entities a separated range of movements. The first model for disaster that proposes the notion of areas was presented in [46], which divides the simulation area into disjoint subareas: 1) the incident location where the disaster happened and people were affected, 2) the patient waiting treatment zone, 3) the casualties clearing station, 4) transport zone where units stand by, 5) the hospital zone, and 6) the technical operational command. Areas have an exit and an entry point to allow the movement between them and only a set of participants are allowed to move between them.

In [47], two areas are formed when an event occurs: 1) the ground zero area (disaster area) where the entities are immobilized, and 2) the event horizon area, where they react to the event using the gravitational model. Similarly, [48] also defines zones related to events. A forbidden zone is defined around the event where danger is present, and an attending zone around which the responders can interact.

3.6 Heterogeneous Movements

Even though some studies focus on defining one general movement for all the participants in the disaster scenario, most of them define heterogeneous movements to represent different interactions and different roles. The simplest separation is between pedestrians and vehicles. In [46], pedestrians move according to the Random Waypoint model, while transportation vehicles move from one area to another following a cyclic route. Similarly, in [47], the default movement is the random walk with appropriate speeds for walking and driving (unlike the Random Waypoint, the random walk does not include pause time between movements). Entities that are close to an event are immobilized in the disaster area. Civilians may go away from the disaster event, and police and firefighters may approach to the event, while ambulances may oscillate.

A separation between transportation vehicles and pedestrians is also defined in [51], where carrier entities move from one cluster to another, while pedestrians move around the cluster center.

A more complex set of movements is found in [49], which defines four movements for different roles: 1) a recurrent motion between centers is used to simulate transportation, 2) a localized random motion is used for rescue workers, 3) a recurrent path motion through multiple neighborhoods is used for police patrols, and 4) a motion switching from center to and back to a random location is used for ambulances.

It is also possible to define heterogeneous movements for one node. In [52], the authors used an initial semi-random movement. Then, they used a GoTo model that moves an entity towards a specific destination depending on its role.

4 Mobile Ad-Hoc Communication Protocol Approaches and Evaluation

Mobile ad-hoc networking paradigms (MANETs, DTNs, VANETs, WSNs and WMNs) have been proposed in the context of disaster scenarios; however, only some of them have been built and evaluated in terms of efficiency in this context.

MANETs and DTNs are the most well studied paradigms to enable communication in disaster scenarios, mainly evaluated through simulation. These approaches are infrastructure-less as they use ad-hoc connection between mobile devices. MANETs are useful in dense areas where it is possible to find an end-to-end path between devices. DTNs are useful when separated zones cause the impossibility of having an end-to-end connectivity between the participant nodes (network partitions). Table 3 summarizes the published studies that analyze the performance of MANET and DTN protocols through simulation in the context of disaster areas.

Relevant studies on protocols for message transmission on VANETs aim at efficiently disseminating warning messages among vehicles moving on a road as a response to some hazard or emergency situation. The main goals include the timely and efficient transmission of safety messages to vehicles located in the same region, mainly for those moving towards the emergency area.

WSNs may consider mobile and static devices. Sensors can be attached to smartphones, as well as be deployed prior to a disaster to early detect an emergency, such as floods or earthquakes. Detection alerting systems and search and rescue teams use sensors to obtain crucial information about victims or assess the area.

In a mesh network, all nodes are connected to each other, and messages can be transmitted through different paths. Typically, it is considered as a type of ad-hoc network where fixed and mobile nodes are interconnected via wireless links. Thus, mesh networks are closely related to MANETs, but they focus on civilian applications.

4.1 MANETs

Routing protocols for MANETs can be classified as proactive and reactive protocols. Proactive protocols maintain routes to all nodes, even routes to nodes for which no messages have been sent. Such protocols use underlying techniques such as link-state or distance vector, and require periodic control messages to update the information and be aware of topology changes. On the other hand, reactive protocols find routes between nodes only when message passing is required.

Destination Sequenced Distance Vector (DSDV)[66] is a proactive protocol where each network node maintains the next hop to all reachable destinations. Johansson *et al.*[56] compared DSDV with two reactive protocols, Ad-Hoc On Demand Distance Vector (AODV)[67]

Table 3. Results Comparison of Performance Evaluation of MANETs and DTNs

Authors	Protocols	Mobility Model	Simulator	Metrics	Best Protocols
Johansson *et al.*[56]	DSDV, AODV, DSR	Random movement + zones	NS-2	Packet delivery fraction (PDF), throughput, delay, overhead	AODV and DSR
Reina *et al.*[57]	AODV, DSR, AOMDV	Disaster area[46]	NS-2	PDF, thoughput, normalized routing load, delay	AODV
Wister *et al.*[58]	AODV, DYMO	Random Waypoint	NS-2	PDF, throughput, overhead	DYMO, AODV in energy
Rafferlsberger *et al.*[59]	AODV, DYMO, BATMAN, OLSR	Disaster area[46]	Inetmanet OMNet++	PDF	AODV (PDF)
Macone *et al.*[60]	OLSR, MQ-Routing and Q-Routing	Random Waypoint	OPNET 16.0	Overhead, delay, thoughput, lifetime and energy	MQ-Routing
Saha *et al.*[51]	Epidemic, PRoPHET, Spray and Wait, MaxProp, Spray and Focus	Cluster-based[51]	ONE	PDF, overhead	PRoPHET and MaxProp
Martín-Campillo *et al.*[61]	Epidemic, PRoPHET, MaxProp, TTR	Disaster area[46]	ONE	PDF, overhead	MaxProp (PDF) and TTR (energy)
Uddin *et al.*[62]	IC, Spray and Focus, PRoPHET, MaxProp	Post Disaster model[49]	ONE	PDF, overhead, delay, energy consumption	IC
Martín-Campillo and Martí[63]	PropTTR, PropNTTR, MaxProp, TTR	Disaster area[46]	ONE	PDF, delivery cost, delay, energy consumption	PropNTTR
Takahashi *et al.*[64]	Direct Delivery, First Contact, Epidemic, Spray and Wait, Binary Spray and Wait and PRoPHET	Random Walk	ONE	Fairness (delivery ratio, delay and overhead)	None
Bhattacharjee *et al.*[65]	Epidemic, Spray and Wait, PRoPHET and MaxProp	Map-based, Post Disaster Model[49], Random Waypoint and cluster-based	ONE	Delivery probability, energy consumption and overhead	MaxProp (delivery, overhead), Spray and Wait (energy)

and Dynamic Source Routing (DSR)[68] under a disaster scenario. Reactive protocols find routes using broadcast requests and unicasts for replies. In AODV, every intermediate node participates in routing decisions, while in DSR, routing is performed at the source node that has all the necessary information to connect to the destination.

The disaster scenario in [56] consists of three groups representing three rescue teams, and two fast moving nodes representing vehicles. Members of the rescue team have personal communicators with ad-hoc network capabilities. Additionally, the scenario contains obstacles that block nodes' movements and constrains which nodes can communicate. Simulations conducted in the network simulator (NS-2)[69] show that proactive protocols should be avoided under these conditions since delivery rates are very small. They are unsuitable for networks with high density and mobility because routing tables maintenance induces high overhead.

Wister *et al.*[58] compared AODV and Dynamic MANET On-Demand (DYMO)[70] for rescue operations. DYMO stores routes to intermediary nodes and optimizes messages passing by piggybacking extra information. The simulation scenario employed the Random Waypoint model. Similarly, Reina *et al.*[57] evaluated DSR, AODV and Ad-Hoc On Demand Multi-Path Distance Vector (AOMDV). AOMDV[71] is similar to AODV, but the request propagation permits establishing multiple reverse paths at intermediate nodes and at destination. The authors in [57] used the disaster scenario modeled by Aschenbruck *et al.*[46] using BonnMotion traces. BonnMotion[72] is a tool to create and analyze mobility scenarios. AODV had the best performance under this scenario, but all the protocols achieved low packet delivery rate.

Raffelsberger and Hellwagner[59] used the Aschenbruck's mobility model for rescue teams[46]. The scenario included a wireless shadowing model to represent realistic first responder movements in a hybrid indoor/outdoor environment. In the shadowing model, nodes that enter the incident locations and temporarily operate inside buildings have a much shorter indoor communication range because obstacles and walls attenuate the wireless signal. They evaluated AODV, DYMO, and the proactive protocols: Better Approach to Mobile Ad-Hoc Networking (BATMAN) and Optimized Link State Routing (OLSR). OLSR[73] maintains a path to all other nodes and BATMAN[74] only determines which 1-hop neighbor is best suited to reach a certain destination. The best packet delivery rate was presented by AOVD, followed by OLSR. This result differs from the ones obtained by Wister *et al.*[58] because this scenario includes nodes with intermittent connectivity, network partitions, and an indoor environment. All four protocols achieve similar latency, but proactive protocols produce temporary routing loops.

Macone *et al.*[60] proposed MQ-Routing, a proactive protocol that aims at maximizing the minimum node lifetime. It considers the node's availability and energy to proactively build paths and uses the Q-Routing protocol as a baseline, which applies reinforcement learning to the shortest-path routing problem in a fixed topology. The results show that MQ-Routing increases the minimum node lifetime compared with OLSR using the Random Waypoint model.

Hybrid approaches using MANETs have also been proposed. The work in [38] studies two hierarchical networks to provide multimedia data support for rescue teams and their command centers. The authors proposed a WiFi/satellite network that uses OLSR for intra-team communication and satellite for inter-team communication. A second approach uses a three-layer architecture WiFi/WiMax/satellite network that uses WiMax for inter-team communication and leaves satellite networks for teams to command center communication. Moreover, hybrid Cellular-MANET was proposed in [11] for supporting a microblogging system for smart devices in disaster areas, extending wireless coverage. The proposed protocol, HMANET, generates a connectivity graph for an energy-aware routing protocol that classifies nodes as gateways, relays and terminal nodes. The authors of [11] compared statistically their protocol with the Hybrid Wireless Mesh Protocol (HWMP) that is used in the IEEE 802.11s standard. The results show that HMANET outperforms HWMP.

4.2 Delay Tolerant Networks

Delay tolerant networks are suitable in scenarios where devices have sporadic connectivity. Typically, in a disaster area, the existing network infrastructure is destroyed, overloaded or saturated due to heavy use. DTNs benefit from approaches such as store-and-forward or store-carry-and-forward (if nodes can move). Nodes carry messages and forward them in an opportunistic manner. DTNs may be categorized as forwarding-based or flooding-based, depending on whether or not the protocol creates replicas of the messages.

Saha *et al.*[51] studied the applicability of different flooding-based routing schemes for DTN in post disaster scenarios, covering the protocols Epidemic[75], PRoPHET[76], Spray and Wait[77], MaxProp[78], and Spray and Focus[79]. Epidemic generates messages to all neighbors at each hop. PRoPHET avoids full flooding by adding a probabilistic decision for exchanging messages based on a history of encounters and transitivity to indicate how likely each node is to deliver a message to a particular destination. MaxProp estimates a delivery likelihood using a graph of encounters, and uses the prioritization of low-hop-count messages to discard the ones with small chance of reaching destination. In Spray and Wait, the number of copies exchanged in the network is limited to avoid extensive flooding. The spray phase spreads the message to distinct nodes, and during the wait phase, the nodes wait for a direct delivery to the final destination. Spray and Focus (S&F) modifies Spray and Wait (S&W) changing the second phase using another forwarding criterion.

The performance evaluation of these protocols employed a cluster customized to disaster scenarios[51]. Simulations over the ONE simulator[54] measured the delivery probability and overhead rate with respect to message buffer size, transmission range, heterogeneous network structure, carrier nodes speed, and message size. Simulations concluded that PRoPHET and MaxProp outperformed all other routing protocols.

Martín-Campillo *et al.*[61] compared the efficiency of a set of routing protocols through simulation: Epidemic, PRoPHET, and MaxProp. Then, they included a protocol called Time to Return (TTR)[80], which adds a value that indicates the maximum time-to-return to a base used to take forwarding decisions. TTR is a forwarding-based protocol because it only keeps one copy of the message within the network. The used mobility model (DA[46]) divides the emergency situation into zones, in this case, zone 0 and zone 1, where 0 is the zone of the incident and 1 the zone of treatment. The simulation experiments over the ONE evaluated performance with respect to the number of nodes, the number of messages, and message size. The results show that MaxProp performed very well in terms of delivery rate in almost all scenarios. However, if overhead and energy are considered, TTR has better performance.

Uddin *et al.*[62] presented a multi-copy routing protocol for DTNs whose objective is to minimize the energy expended on communication. The approach exploits mobility and contact patterns to reduce the number of message copies needed to attain an adequate delivery rate. The authors proposed the notion of inter-contact routing that enables estimating route delays and delivery probabilities. The routing protocol takes advantage of a core of moving entities that revisits overlapping sets of static places to build a stable routing backbone. The protocol presented in [62] uses the post disaster mobility model (PDM)[49] where there are clustered groups and emergency vehicles connecting these neighborhoods. Comparison between their routing protocol and other DTN protocols showed very low message overhead, less delay and higher delivery rate than Spray and Focus, which was the closest protocol in terms of overhead.

Martín-Campillo and Martí[63] proposed a combination of MaxProx and TTR: PropTTR and PropNTTR use the MaxProp protocol for the first hops of message routing, in order to improve the delivery rate while maintaining a low overhead for the rest of the routing steps. The results showed that the best performance was obtained by applying MaxProp for two steps and TTR for the subsequent steps for cases where battery consumption is important.

Takahashi *et al.*[64] studied fairness in message delivery in DTNs. In case of many-to-one communication, fairness is important since a large number of users send messages to a few base stations connected to external networks. Fairness is measured by comparing the number of messages that are successfully delivered by users, as well as their delay. The studied protocols are: Direct Delivery (transferring only to the destination), First Contact (send messages to a node that does not have them), Epidemic, Spray and Wait and Binary Spray and Wait[77], and PRoPHET[76]. Simulations use ONE[54] in a scenario with 500 mobile users and a command center using a Random Walk model. Their results showed that none of the existing DTN protocols can ensure fairness in disaster scenarios.

Recently, Bhattachejee *et al.*[65] compared different DTN routing protocols using different mobility models for post disaster relief operations; however, most of them are mobility models that are not specialized to disaster situations. Their results showed that MaxProp is the best performer in terms of overhead and delivery rate, and Spray and Wait is more efficient than MaxProp in terms of energy consumption.

Raffelsberger and Hellwagner[81] argued that emergency response operations fit the characteristics of the target applications of hybrid protocols with MANET-DTN. They demonstrated their claims by simulating the diversity of connectivity of the networks under the DA mobility model[46]. Similarly, Kawamoto *et al.*[82] proposed the use of MANET or DTN according to the conditions of the devices and the surrounding environment. High speed, acceleration, and low amount of remaining battery are related to the selection of the DTN mode. A prototype of their system is presented in a later work[83], which shows that the algorithm works properly.

4.3 Vehicular Ad-Hoc Networks

Transmission protocols for propagating urgent warning information in VANETs, such as hazard alarms to incoming vehicles, use broadcast algorithms to provide fast and reliable delivery. The main challenges addressed in VANETs for emergency scenarios include: link unreliability, broadcast storm problem (overlapping wireless communication causes redundancy, contention and collision), interference caused by hidden mobile nodes (called hidden terminals problem) and consumption/waste of resources during transmission, such as link bandwidth, buffers and energy.

In contrast to other mobility scenarios, most published studies consider scenarios where vehicles are moving on a one-dimension, single- or bi-directional road. The road can be composed by a given number of lanes (from one to three) on each direction, with one or two directions. In general, the velocity of a mobile node can be constant or variable, but temporally dependent on its previous velocity. We will refer to this mobility model as Freeway Model from this point on. Vehicles are limited to one lane, and no overtaking is allowed (i.e., the velocity of each car cannot exceed the velocity of its preceding car). Evaluations used simulation tools, mostly NS-2 and the Freeway model in scenarios from 10 to 300 vehicles. Other simulations were performed using OPNET Modeler 16.0, Grovenet[84] and QualNet[4].

Smart Broadcast (SB)[85] is a position-based broadcast algorithm that subdivides the coverage area in adjacent sectors and nodes in each sector randomly pick a backoff value in the contention window assigned to that

[4] QualNet simulator. http://web.scalable-networks.com/content/qualnet, Nov. 2015.

sector. The aim of SB is to maximize the progress of the message along the propagation line and to minimize the re-broadcast delay. The performance of SB was compared with the Urban Multihop Broadcast protocol (UMB)[86] and the Geographic Random Forwarding protocol (GeRaF)[87], providing better message propagation speed.

In the work of Peng and Cheng[88], a protocol that supports the transmission of multiple levels of strict priority for individual emergency packets was proposed for VANETs. In the proposal, safety messages are given higher priority over non-safety and regular service messages. The protocol considers that vehicles can be continuously moving in order to mitigate the hidden terminals problem. Experiments demonstrate the proposed scheme leads to packet loss reduction and timely transmissions[88].

Bi *et al.*[89] proposed a protocol for emergency message dissemination in inter-vehicle communications, called Position-Based Multi-Hop Broadcast Protocol (PMBP). In PMBP, the current relaying node selects a candidate vehicle for forwarding, which is located at the farthest distance from the source vehicle in the message propagation direction. In order to avoid redundancy, the message is only broadcasted once and a handshake protocol provides delivery reliability. Both analytic and simulation experiments with NS-2 were reported in [89], comparing PMBP against simple flooding.

Contrary to SB and PMBP, the authors in [90] did not assume the knowledge of the location of the vehicle. A protocol named Adaptive Probability Alert Protocol (APAL) was proposed to alleviate the saturation from broadcast operations by using adaptive wait-windows and adaptive transmit-probabilities so that the broadcast storm problem is minimized. A performance comparison of APAL with five other probability-based protocols is conducted by means of simulation, demonstrating good performance, with short delays, high delivery probability, and reduced number of collisions.

An alert message propagation scheme that relies upon previous selection of a small number of predetermined forwarders with the responsibility to rebroadcast alert messages is presented in [91]. The proposed scheme aims to mitigate the effects of too many broadcast operations, and to guarantee fast and reliable delivery of alert messages to other vehicles. The proposed scheme requires the knowledge on one-hop neighbors to select suitable forwarders. The forwarding selection is based on the information of the current vehicle position, velocity and movement direction. Simulation experiments, using QualNet and VanetMobilSim traces, showed that the proposed scheme achieved good performance compared with other four protocols.

Another study on improving road safety warning messages dissemination by using a broadcast mechanism on VANETs is presented in [18]. The core idea is a position-based backoff broadcast algorithm, which suppresses re-broadcast by counting the messages received and calculating appropriate redundancy levels. It also chooses relay backoff values based on vehicles velocity and position. For example, a high probability of broadcasts is given to farthest vehicles.

In order to enhance reliability on multi-hop VANETs warning messages dissemination, Li *et al.*[92] described a new scheme called OppCast, which uses two types of broadcasting phases, one that quickly propagates the emergency message using long hops and the other that uses additional make-up transmissions between the long hops. To improve reliability, it proposes to explicitly use broadcast acknowledgements to reduce the number of redundant transmissions.

Lee *et al.*[93] proposed a mechanism named Fast and Reliable Emergency Message Dissemination Mechanism (FR-EDM) that considers three different segments according to their distance to the vehicle that originates the emergency/broadcast message: a hot spot segment where the drivers can still decide to avoid the emergency area taking a gateway; a segment between the accident and the last exit; and a third segment nearby the accident. In [93], the message is fast-forwarded to the hot spot area and within both the accident area and the hot spot area, messages are repeated more than once to improve delivery reliability. The same scenario is used in the design of DEEP[17], which focuses on the reliability for the hot spot area and the fast-forwarding for the intermediary segment. DEEP rebroadcasts the message periodically in order to ensure delivery for the vehicles around the accident area. In order to organize the communication, it is assumed that all vehicles have GPS and they calculate deferral time blocks based on the distance from accident source. The authors of [17] evaluated analytically the performance of the scheme in terms of successful delivery rate and sensitivity analysis on deferral time versus block sizes.

Recently, a time-slotted multi-hop protocol for disseminating warning messages in VANETs is proposed in [94]. In order to reduce broadcast storm, the protocol selects one vehicle on each road segment to serve as a message forwarder. In order to avoid interfering with safety messages, the protocol implements a time-slot allocation mechanism for the transmission of warning messages. The allocation mechanism also sends a black burst signal and a CLEAR packet before transmitting the actual data, in order to eliminate hidden nodes and reserve the multi-hop time slot. ACK packet losses are used to avoid the unnecessary replicated transmission of the warning messages.

Table 4 summarizes the published studies that compare different protocols in this context.

4.4 Wireless Sensor Networks

Wireless sensor networks (WSNs) are commonly composed of a large number of small, low-cost sensor nodes distributed over a given area. Sensors have the capability for sensing the environment, processing data, and exchanging sensory information with other nodes by wireless connections. They are commonly used to monitor physical or environmental conditions such as temperature, humidity, and vibration. WSNs can be used as monitoring platforms for detection alerting systems and search and rescue teams. Furthermore, WSN sensors are usually relayed by multi-hop communication to one or more base stations, which collect useful information.

Solutions based on WSNs should cope with computation and resource constraints, such as battery capacity, memory size, network bandwidth, low-power computation processing as well as network disconnections or failures. Communications bandwidth (e.g., IEEE 802.15.4.) is extremely limited on low-power radios. Therefore, issues like energy consumption and prioritization of critical data transmission must be taken into account.

Location awareness, i.e., tracking sensor nodes location, is an essential aspect in disaster scenarios. Sensor nodes are usually deployed prior to the disaster. Hence, sensor nodes for disaster monitoring should be equipped with RF signals, ultrasound, or some other techniques that allow locating and/or detecting victims in destroyed or damaged areas, considering energy restrictions of the particular sensor. For instance, firefighters and rescuers could track location and monitor

Table 4. Results Comparison of Performance Evaluation of VANETs and WSNs

Authors	Protocols	Mobility Model	Simulator	Metrics	Best Protocol
Fasolo *et al.*[85]	SB, UMB, MCDS, GeRaf	-	OPNET	Reliability and latency	SB
Peng and Cheng[88]	PreempPrio, 802.11	Freeway model	NS-2	Reception rate, delay	PreempPrio
Bi *et al.*[89]	PMBP, simple flooding	One direction Freeway model	NS-2	Delay, channel occupancy	PMBP
Suriyapaibonwattana *et al.*[90]	APAL, simple broadcast, p-persistence, TLO, weighted p-persistence, slotted 1-persistence	Uniform speed model	GrooveNet	Number of collisions, delivery rate and delay	APAL
Lee *et al.*[91]	Proposed protocol, DDB 1, flooding, weighted p-persistence, slotted 1-persistence	Vehicle platoons on 1-way & 2-way highways	QualNet, VanetMobiSim traces	Delivery rate and delay, rebroadcasting rate	Proposed protocol
Lee *et al.*[93]	FR-EDM, SB, RBM, slotted, 1-persistence	Freeway model	NS-2	Delay, delivery rate and reliability	FR-EDM
Li *et al.*[92]	OppCast, CBD, slotted p-persistence	Freeway model, 2 lanes, 2 directions	NS-2, USC VANET	Delivery rate, delay and dissemination rate	OppCast
Fan *et al.*[18]	BCUnit, PBCC, BPAB, Position base, flooding	Freeway model, 1 direction, 3 lanes	NS-2	Propagation delay, message progress	BCUnit
Chuang and Cheng[17]	DEEP, SB, RBM, S1PM, LBS	Freeway model, 1 direction, 3 lanes	NS-2	Delivery rate, propagation delay	DEEP
Javed *et al.*[94]	TSM, DV-CAST, SB	Freeway model, 2 directions, 3 lanes	OPNET 16.0	Delivery rate, average transmissions, message delay	TSM
Cayirci and Coplu[24]	Flooding, Direct Diffusion, SENDROM	Static nodes with uniform distribution	NS-2	Transmitted packets, received packets, energy remaining, failing nodes, events transmitted to sink	SENDROM
Saha and Matsumo[95]	LEACH, WSNDM	Static nodes with uniform distribution	WSNS	Energy dissipation, system lifetime, delivery rate, live nodes	WSNDM

safe exit routes by installing sensor nodes in a building before a fire[28].

Both the sensor nodes and the base stations can be mobile or not. Mobility increases the coverage area and may reduce network connectivity, i.e., mobile nodes can provide paths for disaster networks, which are sparse or become disjoint[96]. Ad-hoc routing techniques can, thus, extend the effective communication range providing communication robustness. On one hand, network connections should be reliable in order to tackle with uncertain conditions that lead to partitions. On the other hand, the energy consumed by communication should be minimized. In other words, the management of mobile nodes or dynamic routing based on redundant paths must ensure event transmission with low network maintenance costs[97]. Towards this approach, Miyazaki *et al.*[26] proposed a WSN, denoted as die-hard sensor network that provides continuous monitoring without any maintenance even if some sensor nodes fail. To this end, sensor nodes have an automatic sensing function alternation mechanism. Hence, in addition to dynamic routing features, some sensor nodes, which are neighbors of a failed one, can take over the function of the latter. The authors of [26] applied graph coloring theory to optimize allocation of nodes for saving energy and improve coverage. The technique considers that every pair of graph neighbors must have different colors, where each color represents a sensing capability. Simulations were conducted with different graph configurations.

SENDROM[24] is an architecture to manage rescue operations after large-scale disasters and is composed of sensor nodes and central nodes, named cnodes. The former can be located in fixed places or embedded into personal belongings, while the latter are assigned to rescue teams and placed nearby emergency centers for collecting sensed data from the sensors or querying them in order to detect living victims or report information to the base station. Cnodes continuously update the base station database, which can then be queried from remote sites via Internet.

In [13], the authors proposed a distributed WSN-based real-time event detection platform suitable for meteorological natural hazards and residential fires. Their approach uses a decision tree to detect events and a reputation-based voting scheme for aggregating different sensor detection results aiming at a consensus among different decisions. The authors of [13] presented two distinct reputation techniques and conducted simulation experiments based on a residential fire dataset.

Yu *et al.* presented in [98] a WSN paradigm approach for real-time forest fire detection and fire alert forecast. Sensor nodes, deployed in the monitored forest area, are equipped with GPS and grouped into clusters. They are responsible for collecting measurement data such as temperature, smoke, and forwarding them to the head of the cluster. Cluster headers compute a weather index by applying a neural network method and then sending it to a sink sensor node connected to a manager node (base station) by a wired network. The manager node thus provides information about abnormal events and real-time fire danger information. The authors stated that by applying a neural network approach, individual nodes can perform simple calculations on complex data, making the system suitable for WSNs.

Some studies related to disaster management, such as [95, 99-100], proposed hybrid approach frameworks or prototypes.

In [99], WSNs are combined with access networks. Wireless sensor nodes detect damages and/or victims while the access network, by exploiting both the ad-hoc and the cellular networks, transmits damage assessment information to the base station. This hybrid network dynamically builds a route to the base station by using an ad-hoc network scheme and also provides a stable access by the centralized cellular network. In normal circumstances, nodes communicate in cellular mode, and whenever they get disconnected due to some disaster event, nodes switch to ad-hoc mode.

Saha and Matsumo[95] adopted a similar approach, considering that base stations of cellular networks may become unreachable. They proposed a framework for data collection and a sensor cellular-based network protocol aiming at victim rescue. Ad-hoc relay stations (ARS) in border cells areas support both ad-hoc relay and cellular interfaces and re-route data from failed base stations to their nearest base station. WSNDM was compared with the cluster-based LEACH protocol by means of simulation. Evaluation results show that WSNDM outperforms LEACH in terms of energy consumption and the number of exchanged data messages.

The In.Sy.Eme project[100] aims to study the main features that WSNs for emergency scenarios must have in order to ensure interconnection of several heterogeneous systems which are interested in data sensed by WSN nodes. The authors of [100] argued that WSNs for disaster management cannot operate in a stand-alone way, i.e., a communication infrastructure must deal with WSNs, collecting data from different ones, but must also be able to connect different devices. Thus, sensing devices should be equipped with interfaces to a wireless access network like 3G as well as local (WLAN) and metropolitan (WMAN) wireless area networks.

4.5 Wireless Mesh Networks

In literature, several approaches using WMNs have been proposed, but only a couple use simulations to evaluate their efficiency. Most of them implement prototypes or use mathematical analysis to evaluate their performance in terms of throughput, packet loss rate, and power consumption, and the evaluation is focused on the infrastructure more than on the communication protocol. In the following, we describe studies that use mesh networks in disaster scenarios aiming at quickly recovering network access services when the existing network has been destroyed by a disaster.

Suzuki *et al.*[41] presented a prototype system named SKYMESH consisting of a group of balloons that may be deployed on large-scale natural disaster areas. Balloons are wireless connected to a gateway on the ground to get Internet access using wireless LAN cards supporting 802.11a/b/g. The equipment may utilize commercial power, battery power supply or alternative power sources like solar panels and electric generators. The prototype is evaluated with four balloons in terms of throughput, scalability and video stream communication. The authors concluded that building the system for urgent communication over the affected area is fast.

Dilmaghani and Rao[101] presented a WMN connected to the Internet through a wired backhaul link. This work aims to identify the main bottlenecks during data transmission in an emergency scenario. The proposal was evaluated with 1∼5 nodes, one laptop and a gateway connected to the Internet. The authors evaluated total response time, amount of data transferred, latency and throughput of the mesh network and concluded that the proposed prototype is capable of facilitating communication between heterogeneous systems.

Shibata *et al.*[42] proposed a mesh network built by combining multiple ballooned wireless networks to ensure communication to grasp information within a disaster area. The system uses IEEE802.11j wireless LAN for horizontal communication between wireless nodes and the IEEE802.11b/g standard wireless LAN for the vertical communication between mobile PCs and wireless nodes. The prototype was evaluated with three disaster applications in terms of received signal strength, packet loss rate, throughput, and response time.

Suzuki and Shibata in [102] presented a prototype for power saving in wireless LANs systems. The proposed prototype deploys a ballooned wireless mesh network connected to a fixed access point, which is a gateway to Internet. It combines solar panels, wind turbines and batteries for power supply. The metrics that evaluate the performance of the system are throughput and packet loss rate of each LAN link. The authors concluded that throughput decreased less than 5 Mbp when the distance between mobile nodes is more than 250 m.

Gardner-Stephen *et al.*[36] built a prototype of a WMS with a set of smartphones, called Serval Mesh. The prototype was tested in different scenarios to evaluate its performance for transmitting voice, texts (SMS) and files, demonstrating technical feasibility.

Simulation is used by Ngo *et al.*[103] to evaluate the throughput achieved by gateways connected to users nodes. User nodes are evenly distributed within the affected area and send data to the gateway at the same time with the same load. The authors assumed no congestion between user nodes and the gateway. The performance evaluation uses the QualNet 5.1 simulator showing that the throughput depends on the network configuration; for example, the throughput tends to decrease using two-hop connections.

Li *et al.*[104] proposed a two-stage algorithm that aims to be energy-efficient and to maximize the throughput. The evaluated system consists of a set of renewable energy-enabled base station with the enough power to connect to the outside network with the vehicle-borne facilities. The set forms a mesh network connected to the gateways. The authors assumed the traffic demands of each base station are known. The proposed scheme is compared via simulation with a scheme that only maximizes throughput and a second scheme outside the context of a disaster scenario.

Fouda *et al.*[105] addressed the problem of allocating a fair bandwidth per user. The system is composed of mesh routers connected to gateways, which in turn are connected to a network management center. End-users are connected to routers equipped with many interface cards. This work proposes a balance algorithm to distribute the bandwidth among users. Experiments are performed by means of MATLAB simulations and include the dynamic variations on user demands.

Table 5 presents a summary of the studies we have found in literature.

Table 5. Summary of MESH Network Solutions for Disaster Scenarios

Authors	Evaluation	Devices	Metric	Energy	Comparison
Suzuki *et al.*[41]	Prototype	Balloons, gateway	Throughput and scalability	Commercial power, battery, solar panels and electric generators	No
Dilmaghani and Rao[101]	Prototype	Laptops, PDAs, cameras, gateway	Bottlenecks during transmission, throughput	Battery	No
Shibata *et al.*[42]	Prototype	Balloons, wireless IP telephones, fixed access points, mobile PCs	Signal strength, packet loss rate, throughput and response time	Battery	No
Suzuki and Shibata[102]	Prototype	Gateway, balloons, mobile nodes	Throughput and packet loss rate	Solar panels	No
Ngo *et al.*[103]	Simulation with QualNet 5.1	Gateway, user nodes	Throughput		No
Gardner-Stephen *et al.*[36]	Prototype	Smartphones	Communication range between smartphones	Battery	No
Li *et al.*[104]	Simulation (in house)	Base station, gateways, vehicles	Throughput, power consumption	Solar panels, wind turbine, battery	No
Fouda *et al.*[105]	Simulation with MATLAB	Mesh routers, gateway, user nodes, network management center	Total bandwidth, bandwidth utilization		Yes, with a baseline algorithm without load balancing

5 Discussion and Guidelines

In this section, we provide guidelines for software developers who require testing applications for supporting disaster scenarios over simulated environments. Testing an application is required to validate its functionality and evaluate its behavior on a close-to-real scenario. Considering an application for disaster support, the testing phase is critical because the scenario presents extreme conditions, difficult to recreate, in which the application must function correctly to protect or even save lives. Simulation is a tool to carry out experimentation and to validate the application. Building a simulated environment is not trivial: numerous variables play a role, for example, protocols, movements of participants, characteristics of the communication devices, among others. Furthermore, standard scenarios enable fair comparisons for new protocols and applications. We propose a five-level model to guide the creation of such simulated environments considering the application characteristics and key components presented in the state of the art. The proposed model is presented in Fig.1.

5.1 Application Scenario

The first level of the guideline model is to identify the situation in which the application will be used. Disaster management establishes five stages to deal with disasters: detection, alerting, assessment, response and recovery. These stages define the characteristics of applications to support the emergency stage. Applications developed for detection stage are mostly oriented to real-time monitoring to early detect the occurrence of the disaster. Applications for alerting disseminate information, such as warning emissions, or evacuation instructions. In the assessment stage, the focus is on gathering information to support context analysis or situation awareness. Finally, the response and the recovery stages support the different tasks that re-establish the normality to the affected zone.

5.2 Network Architecture

The second level of the guideline model is called network architecture. The application scenario defined in the first level determines the selection of such architecture.

WSNs are used on scenarios related to stages before the disaster strikes where sensors are oriented to gathering information and preventing the disaster occurrence. The detection of possible victims under collapsed buildings may use WSNs. VANETs are used in the alerting and the response phases, to spread warnings and to communicate with distant areas. MANETs may be used in stages of assessment and response. In the stage of assessment, the network architecture is used to support applications that gather information, such as microblogging, reporting alerts, while in the stage of response, the network architecture is used to support

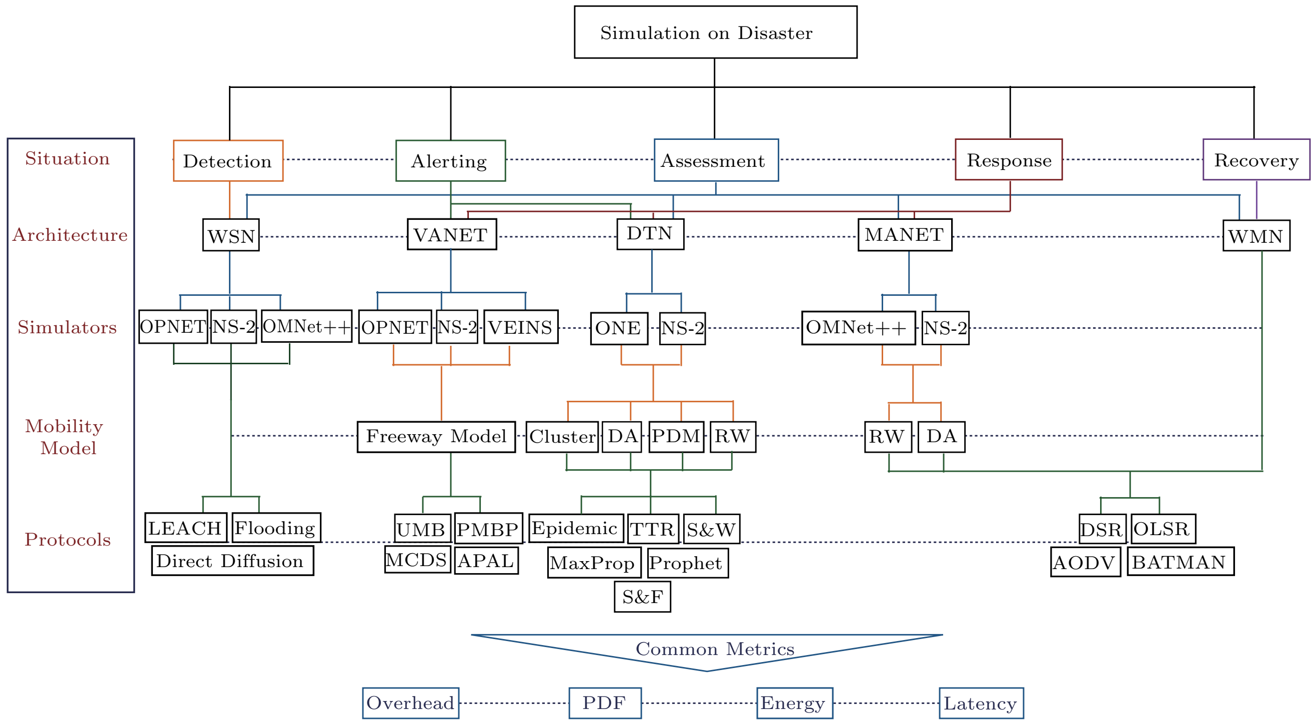

Fig.1. Guidelines for simulation on disaster scenarios.

communication for rescue tasks. WMNs or DTNs are used in scenarios where the traditional communication infrastructure is typically compromised, after the disaster.

5.3 Simulation Tools

We have located the simulation tools to carry out the evaluation of the scenario in the third level of the guidance model. Among the available simulation software, we have focused on simulators frequently used in disaster scenarios literature. Simulation tools may be generic for the implementation of different communication networks, or specialized to reflect the special properties of the architecture.

NS-2[5], OPNET[6] and OMNet++[7] are generic simulation tools. NS-2 is a discrete event simulator targeted at networking research. NS-2 provides substantial support for TCP simulation, routing, and multicast protocols over wired and wireless (local and satellite) networks. OPNET allows simulating heterogeneous networks with various protocols. Initially it was developed for military needs, but it has grown to be a leading commercial network simulation tool. Another generic simulation tool is OMNet++, which is a discrete event simulator primarily used for building networks: wired and wireless communication networks, on-chip networks, queuing networks, etc. Generic simulators can be used to simulate any architecture.

For DTNs, ONE[54] is a specialized well-known simulator for the research community. It was specially developed to simulate DTN routing protocols and mobility models used to evaluate different architectures and protocols. Another example is VEINS[106], which is an open-source framework built for running vehicular network simulations. It is based on two well-established simulators: OMNeT++ and SUMO, which is a road traffic simulator.

We find no particular association between WMNs and simulation tools since most studies evaluate proposals using prototypes implemented at small scale.

5.4 Mobility Models

Mobility models are located in the fourth level of our model. They represent movement patterns of individual simulation objects (people, vehicles). The movement models reflect the behavior of the application users over

[5] NS-2. http://www.isi.edu/nsnam/ns/, Nov. 2015.

[6] OPNET Modeller 16.0. http://www.opnet.com, Nov. 2015.

[7] OMNet++. https://omnetpp.org/, Nov. 2015.

a geographic area. In literature, it has been shown that mobility models affect the performance of the protocols used in the communication[107]. The definition of the mobility model determines the effectiveness of the application tested on top of it. Contact time, nodes speed, mobility patterns, among others, may impact the performance of the underlying protocol.

The research community has adopted some mobility models to evaluate their implementations. For DTNs, the ONE simulator has implemented a large set of mobility models as built-in packages. Other architectures, such as VANETs, only consider one basic Freeway model. In MANETs, the most frequently used ones are random models, such as Random Waypoint.

In Fig.1, we can appreciate no association between WSN and MESH networks with mobility models since they are basically built over devices which are independent of the movement of the network participants.

5.5 Communication Protocols

The final level is composed of the routing protocols that establish communication among the participants. In literature, a large number of protocols have been specially developed to establish communication in different architectures. There is no consensus about what protocol has the best performance on a given scenario. For this reason, instead of suggesting a given set of protocols for each mobility model, we present a general set of protocols. Nevertheless, we can find some guidelines in literature. For example, for MANETs routing protocols, DSR or AODV presents good performance results on well-connected scenarios[56]. On scenarios where battery is limited, DTNs protocols such as Spray and Wait, and PRoPHET are good alternatives[51,65]. Despite that DTN and MANET protocols seem to have similar communication standards, they were conceived differently. While MANETs are oriented to almost-connected scenarios, DTNs are oriented to scenarios where connections are sporadic. In the case of WSNs, protocols are designed considering the restrictions in sensor devices resources: energy, processing power, and storage are limited. For this reason, the protocols are simpler compared with the DTNs or MANETs architectures. Finally, WMNs and MANETs rely on the same protocols.

We believe that the five levels model (Fig.1) can help software developers to configure their simulations for disaster scenarios. There are particularities on each protocol that are not considered in our model, for example, parameters such as TTL, buffer size, message size and simulation time. However, all these parameters depend on the scenario dimensions, or devices characteristics, and many other factors difficult to manage due to the large number of possible choices.

5.6 From Servers to Smartphones

Software applications devised to support disasters must run on complex computational infrastructure that ranges from clusters of processors acting as servers to smartphones deployed in the terrain. The scalability to thousands or even millions of users is a relevant issue to be considered when designing these applications. This is a wide area of study related to the performance evaluation of software applications by means of simulation that has not been developed for disaster scenarios. To our knowledge, currently, there is no literature concerning this issue.

Fortunately, practice and experience from other application domains can be useful in the disaster context. In particular, Web-based applications share several of the main issues to be taken into consideration in disaster applications such as a very strong performance dependency on the dynamics of user behavior. Likely, another feature that helps to simplify the complexities associated with predicting performance on a particular hardware is the fact that these applications tend to be coarse grained with respect to hardware cost. Namely, they are built of a set of main operations whose individual costs tend to be several orders of magnitude higher than the cost of single hardware instructions in the computer architecture. This gives place to the use of small benchmark programs devised to measure the cost of operations at both the server side and the user smartphone side.

In the following, we provide general guidelines from [108] for Web applications that we believe they can be useful for software developers in disaster scenarios. We refer to simulators representing a good compromise between the precision of performance metrics and the efficient running time of the simulations. We suggest that they can be achieved by considering the following guidelines.

- Include user behaviors by feeding simulators with user traces (hopefully) generated by actual users from the application running at least at small scale. This implies executing simulations with large user logs with traces considering different arrival rates and cost trends expressed in the different application services.

- Hide complexities of simulating data center hardware or servers by using models of parallel computation devised to represent key features of hardware cost. The particular model drives the construction of benchmark programs used to measure the key costs on the actual hardware.

• Determine the cost of relevant application operations by executing benchmark programs on actual instances and use cases of the application. Typically there are available uni-thread implementations of these operations, or it is fairly simple to prototype them, and the aim is to study performance of very large systems.

• Organize the simulation of individual operations triggered by the user traces as directed graphs where arcs indicate the order in which operations take place and vertices represent the cost of executing these operations on the hardware resources (threads, processors, shared memory and communication layer). Each operation competes for using the resources with co-resident operations.

Namely, the entire simulation is reduced to emulate the competition for hardware resources that simplifies performance evaluation ranging from a few hundred to many million users, under a wide range of possible dynamics for the rate of user triggered operations executed on the hardware.

Note that simulators such as SimGrid[109] are suitable to evaluate the cost of executing applications on computer systems such as servers and clusters of processors. APIs are available to make these simulators operate together so that complex systems can be simulated with little effort.

5.7 Possible Mistakes

5.7.1 Unrealistic Scenarios

Some applications for disaster management assume ideal scenarios, where Internet access and power supply are not compromised, which may be optimistic in this context. In 2010, for example, a destructive earthquake in Chile caused damage thousand kilometers away from its epicenter⑧. Communication infrastructure and power supply were severely damaged, compromising information diffusion concerning dangerous zones and thereby the ability to trigger any early warnings. Network disruptions are a common consequence in a disaster scenario.

Another factor to consider is the size of the disaster scenario. Only few participants (20∼30) grouped on high-density clusters composed most of the simulations we have found in the literature. Optimistic routing protocols, certainly, will reach good performance over the reduced number of mobile participants. However when the number of participants grows or density diminishes, the efficiency of these protocols seriously degrades.

5.7.2 Simulation Parameters

When creating simulation scenarios, the selected parameters of the simulation play a role in performance. First, other interested people have to be able to reproduce the experimentations. With this in mind, the authors in [110] recommended to consider homogeneous devices characteristics (bandwidth, energy, processing power, storage, etc.), thus reducing the number of variables of the simulation.

5.7.3 Mobility Models

Many mobility models, oriented to emulating people's movements on different scenarios, have been proposed in the recent years. In the context of disaster scenarios, some studies model only rescue teams' movements[46,53]. Such election ignores that mobile devices nowadays are widely used and most of people carry one with them. One approach that represents survivors' movements is in [51] that models a cluster of people moving around over a few interest points.

In our experience, based on the Chilean earthquake and data collected during that event from the social network Twitter, people are active participants in post-disaster scenarios. They employ their mobile devices to generate and search for information. Once people find shelter, they search information about the state of the current disaster, government announcements, missing people, and services such as water, food, fuel, medicines, among many others. It is within this context, where the use of dynamic architectures such as DTNs or MANETs becomes relevant.

In the literature, we have found the use of unrealistic mobility models. Most of them employ simple mobility models, such as Random Waypoint, which are far from being a close representation of people movements over a disaster scenario.

6 Conclusions

In natural disaster scenarios, communication is a critical resource for software applications designed to support participants during the different stages of the

⑧Cepal information about the earthquake in Chile on February 27, 2015. http://www.cepal.org/noticias/paginas/4/35494/2010-193-Terremoto-Rev1.pdf, Nov. 2015.

emergency. Current software applications tend to assume idealistic scenarios where Internet access and power supply are not compromised by the disaster. However, these assumptions have proven to be unrealistic during recent major catastrophes.

Modern civil communications are based on highly pervasive technologies such as Bluetooth and WiFi. These technologies are present in smartphones, tablets, notebooks, televisions and many other handy devices. Even cars include communication devices and software to interact with these devices. In case of a disaster, software applications should have the ability to exploit these communication technologies, building MANETs, DTNs, or VANETs to take advantage of their capabilities in challenged environments.

Simulators such as ONE, NS-2 and OMNet++ have been used to evaluate protocols for communication and applications. Performance evaluation ought to take into account the resources of the devices that enable networking, and the context of the emergency, as well as the priorities, mobility, and behavior of the entities involved.

In this survey, we described and analyzed the characteristics of mobility models for disaster scenarios, which range from very simple adaptations of general mobility models to high-level complex definitions. We raised three main issues with respect to the current state of the art on mobility models. Firstly, existing mobility models are very hard to compare against one another, partly because there are no real mobility traces under disaster situations that are available to the research community. Secondly, every mobility model is designed for specific scenarios: this limits the validity and usefulness of each solution to the considered scenarios. Finally, most mobility models only consider the movements of rescue teams; yet nowadays, mobile devices are highly accessible for the population and thereby it makes sense to use them as communication elements and sensors.

Based on our review of the literature, we also formed three main observations regarding the evaluation of disaster response protocols. To start with, protocol evaluations seem limited to small scenarios with a dense distribution of people, which is unrealistic for many disaster scenarios. Another issue is that most protocol evaluations fail to use different mobility models, thus decreasing the impact of the performance assessment. Finally, there is no implementation that goes beyond the prototype level for approaches that rely on hybrid protocols for communication. A more exhaustive evaluation of such solutions would require full-fledged simulations with large-scale scenarios.

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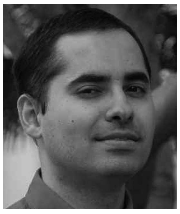

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