Post Disaster Resilient Networks: Design Guidelines for Rescue Operations

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Abstract. Establishing resilient communication infrastructures is one of the most prominent and vital requirements for both victims and rescue teams after any disaster (earthquake, terrorist attack,...). While today's life style heavily depends on modern communication technologies, experience has shown that these technologies are extremely susceptible to massive natural catastrophes such as hurricanes or earthquakes. In this paper, we propose a list of design guidelines that every post-disaster resilient communication infrastructure must follow in order to be able to serve victims during the extreme conditions after a disaster. Based on those guidelines, we present a resilient communication infrastructure taking advantage of Vehicular Ad-hoc NETworks (VANETs). In order to evaluate the performance of the proposed approach, we realized it in a prototype. Using a real-world data set, we carried out thorough experimental analysis and showed the applicability of the approach in real-world scenarios.

Keywords: Resilient Networks, Disaster Management, Design Guidelines

1 Introduction

Everyday activities of each individual in today's society are heavily dependent on the Internet and its underlying communication networks. This degree of dependence along with the ever increasing demand for new technologies has changed many aspects of human life style. While these changes have provided numerous benefits for a human being, they may become problematic in the face of disasters, especially, natural catastrophes that may cause loss of life, property damage and shutdown of the electrical grid system [1].

The tendency of today's technology toward heavy usage of cellular networks as the main communication infrastructure along with the utilization of cloud-based services for processing and storage imposes significant drawbacks to the

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post-disaster rescue operations. Experience has proved that cellular networks are one of the most susceptible networks to natural disasters and their recovery may take days. Also, the recovery of the electrical grid system is not achievable in the first few hours after a disaster. Meanwhile, the battery of smart phones which are the only widely available devices carried by each individual can only last for a few hours, and infrastructure (i.e. base stations or switching centers) may be destroyed. Thus, in most scenarios communication is not possible for victims during the precious first few hours after a disaster, which may cause further damages.

Modern technology has also replaced some devices, while that their applicability during disasters has been well-known since the early 1980s. For example, people tend to use Internet-based radio applications instead of utilizing legacy FM radio devices that were widely available a few years ago. This simple evolution has led to almost total withdrawal of those devices from the shelves which poses a serious disadvantage for post-disaster rescue operations. An emergency self-powered FM transmitter could be utilized to broadcast emergency messages to pocket-sized battery-operated FM radio receivers of victims. Internet outage which is inevitable in the aftermath of natural disasters causes the inability of victims to get emergency notifications.

It is also noteworthy to mention that, even if these FM radio receivers were available, they only provide one-way communication. Establishing a basic level of two-way communications between victims and rescue teams is critical. In fact, the communication is so important that communication has made its way up to the list of "Twelve things victims need after a disaster". For example, a simple "I am alive" message that has the geolocation of the sender can expedite search and rescue operations. Moreover, knowing the number of victims in a specific area helps decision makers to manage their available resources in an optimal way.

In this paper, we first propose a list of design guidelines that are essential to any resilient communication infrastructure for post-disaster rescue operations. We further discuss the limitations that the design of such systems faces. Then, we introduce a resilient communication scheme that follows the proposed design guidelines. The proposed approach has been realized in a prototype. The experimental results show the applicability of the approach in real-world scenarios.

The rest of the paper is organized as follows. Section 2 proposes the design guidelines and describes the limitations. Section 3 introduces the proposed approach. Section 4 describes the prototype realization. Section 5 presents extensive experimental results. Finally, Section 6 provides some concluding remarks and outlines directions for future research.

2 Design Guidelines

In the face of unexpected natural disasters, many usual standards and norms alter. Any system that intends to be helpful in that situation must include some properties specifically designed for those situations. In this section, we present a list of design guidelines that must be considered in order to provide a resilient communication infrastructure for post-disaster rescue operations:

1. The system must operate in a fully distributed manner; any centralized approach no matter how resilient it is, may fail beyond recovery.
2. Instantly self-activated; the first few hours after disasters are the most crucial moments for disaster response, particularly in search and rescue operations. Thus, such system must be activated instantly after the disaster to expedite such operations.
3. Operable without electrical grid system; the system must be designed such that it can provide its own power at least for a significant amount of time after the disaster. In other words, it must be self-powered and also must consume as low power as possible.
4. Applicable by smart phones; assuming that the smart phones are the only devices that are widely available for victims in the midst and the aftermath of the disaster. The system must provide an infrastructure such that the existing smart phones can be utilized without any additional hardware/software installation or complex setup procedures.
5. Interoperable; the system should use standard widely used protocols such that every individual or rescue team can connect to such system.
6. Geographically widespread; the extent of the destruction cannot be predicted, so the system should cover as much disaster area as possible.

Some of the above requirements are orthogonal. For example, the only standard widely used communication technologies available in smart phones are Wi-Fi, Bluetooth, and cellular networks. On the one hand, Wi-Fi and Bluetooth technologies have limited connection range that restricts their coverage, and on the other hand, cellular networks are highly dependent on the electrical grid system. However, a system that claims to be applicable for post-disaster communication must at least partially support all of the above design guidelines.

It is also needed to apply the German BSI-standard 100-4 as Business Continuity Management (BCM) to detecting dangerous risks that endanger the survival of an organization early and to implement safeguards against these risks. BSI-standard 100-4 is a methodology for establishing and maintaining the post disaster resilient network [9].

It must be noted that there are also some limitations that must be considered in the design of these systems:

- Revolutionary approaches for these systems are often too optimistic. It is almost impossible to develop disaster-resilient communication technologies and protocols that quickly substitute existing technologies and devices.
- On the one hand, implementation and widely adoption of the existing standards for disaster recovery services (i.e., ISO/IEC 24762:2008, ISO/IEC 27031: 2011), disaster management (i.e., ITU-T L.92 (10/2012)) and information security management (i.e., ISO/IEC 27001 and ISO/IEC 27002) are affected by several different obstacles such as national cultures [10]. On the

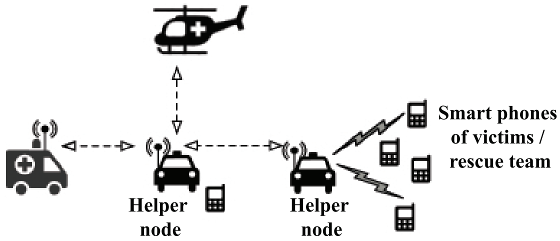


Fig. 1: Communication patterns among various parties in the proposed approach.

other hand, with the advances in information technologies as well as communications devices and services, the existing standards need to be reviewed to inherit the best of emerging smart technologies in post-disaster recovery management.
- When it comes to excessive costs of these systems not everyone is convinced to pay. Thus, it is reasonable to assume that only a portion of the users may adopt the system. Nevertheless, the underlying infrastructure must ensure the establishment of a resilient communication for rescue operations.

Beyond all these limitations, we believe that considering our proposed guidelines in the future information security and disaster recovery management standards, will significantly improve the performance of post-disaster recovery operations.

3 The Proposed Approach

In this section, a resilient communication infrastructure for post-disaster rescue operations is proposed. In this approach, vehicles are one of the suitable possibility for infrastructure communication, because:

1. They possess internal batteries that can provide energy which can last for a sufficient amount of time after the disaster even when their engines are not running.
2. They are geographically distributed, in an ordinary day in an urban area usually there are many vehicles parked everywhere.
3. Vehicles can perform the assigned task in a fully distributed fashion.

An important assumption in this paper is that usually after natural catastrophe depending on the extent of the destruction, vehicles either cannot move at all or they can move at an insufficient speed.

We call each vehicle that participates in the communication infrastructure as helper nodes. Helper nodes are basically vehicles each of which equipped with a system called emergency relay system (ERS) that is directly attached to the battery of the vehicle. An ERS has two different communication technologies: (1) a low power medium range radio, (2) a Wi-Fi access point. Public vehicles such as taxis (cabs), police cars and other volunteer vehicles are good candidates to serve as helper nodes. Other contributing parties in our proposed scheme are victims that have access to their smart phones and the rescue teams which are equipped with compatible communication devices. These rescue teams may have access to handheld devices, ground-based vehicles such as ambulances, or aerial vehicles. We assume two types of communications among these parties, as follows:

1. Low power medium range radio is utilized to establish a connection between two helper nodes or between helper nodes and rescue teams.
2. Wi-Fi technology provides a wireless connection between victims and helper nodes.

Helper nodes operate in a fully delay-tolerant manner, i.e., they forward their messages whenever a connection exists. Otherwise, they store the message and then forward it upon connecting to another helper node or a rescue team. Delay-tolerant networks have attracted many research studies in the course of past few years [2]. However, various challenges restrict the applicability of these networks in real-world scenarios: first, the inherent nature of these networks imposes high delivery latency and/or data loss; second, users are increasingly concerned about having control over their data, which hinders the popularity of these networks. Our approach, however, can utilize such networks despite the drawbacks mentioned above since in emergency situations some aspects of the privacy of the users may be sacrificed in order to save them from greater risks. For example, the location of the victim must be publicly revealed for every rescue team to be able to help the victim. The helper nodes have the following properties:

- They can broadcast emergency messages received from the rescue teams to the victims.
- Each helper node can automatically count the number of connected victims and send an alert along with the geolocation of victims to the rescue teams.
- Helper nodes can relay messages received from victims toward the rescue teams.

Figure 1 shows various communication patterns that exist among the contributing parties in the proposed approach, i.e., single-hop or multi-hop communication between the helper nodes and the rescue team (i.e., ambulance, helicopter, etc), as well as the victims' smart phone and the rescue team.

The proposed scheme conforms with the above design guidelines. The system is fully distributed in the sense that each vehicle can operate without relying on other vehicles. Each message is forwarded in an opportunistic multi-hop routing fashion [3], which enables the routing of messages even in the presence of multiple failed nodes. Figure 2 depicts an example of such a multi-hop routing scheme. The ERS is designed such that it always remains in active mode, i.e., the

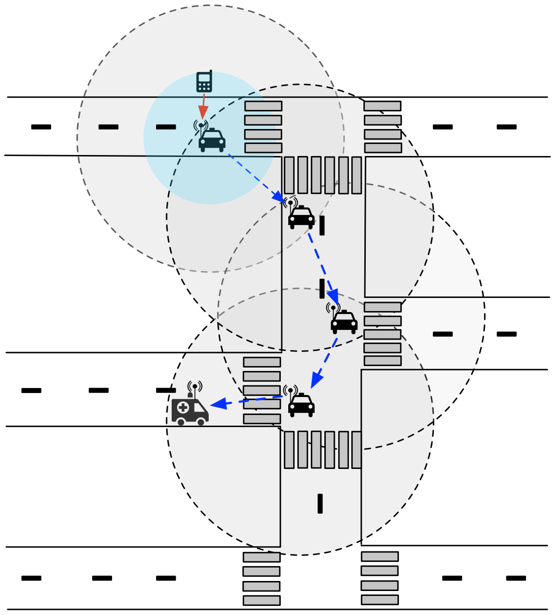


Fig. 2: An example of multi-hop routing in the proposed approach. The smart phone passes its message to a helper node. Helper nodes finally deliver the message to a rescue team using opportunistic relaying of the message. The small blue circle shows the radio range of the smart phone, while the big gray circles show the radio range of the helper nodes.

services offered by the ERS are always available. Although this feature satisfies the condition of being "instantly self-activated", however, it may be abused by malicious users in non-emergency situations. A malicious user can utilize such system to conduct a Denial-of-Service (DoS) attack [5] on the ERS to keep the system busy and finally depletes the battery of the vehicle. Furthermore, the privacy of users can be violated. For remedy this kind of issue and preserve the fairness of the system, the system must accept a certain amount of messages in a given time interval and also keeps a log which contains the identities (such as MAC address) of every connected device for further inspection. Being attached to the battery of vehicle makes the system independent of the electricity grid system. A typical automotive battery can provide the energy for the ERS for several hours even when the vehicle engine is not running.

The proposed scheme is also applicable by smart phones since the ERS provides widely available Wi-Fi technology for helper-victim communications. The only problem is that the effective range of Wi-Fi is restricted to few hundred meters [6]. In order to increase the availability of the approach, the number of helper nodes must be increased. Obviously, by increasing the number of helper nodes, the geographical coverage of the areas that have access to the system also

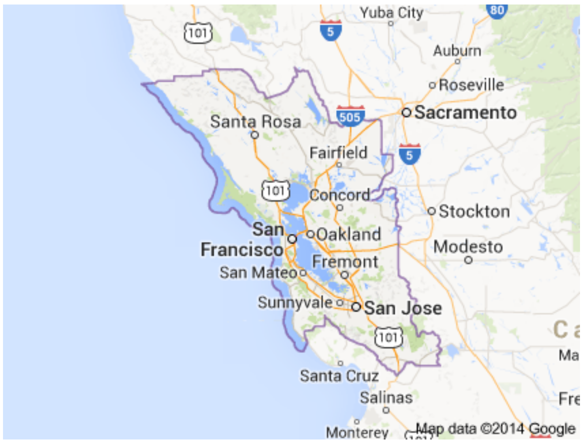


Fig. 3: Map of San Francisco Bay Area acquired from Google Maps

grows. Thus, deploying a sufficient amount of helper vehicles in each urban area guarantees the availability of the proposed system in every vicinity of that area.

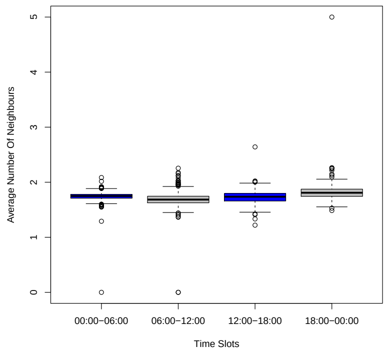
The proposed approach is operable even if only a few number of helper nodes exist. Our experiments showed that indeed a wide area could be covered using a small number of helpers. The approach is also evolutionary in the sense that it is not necessary for every victim or vehicle to adopt a new technology or device. The system can provide its features with a portion of users, and the availability of the system increases as the number of helper nodes increases.

4 Prototype Realization

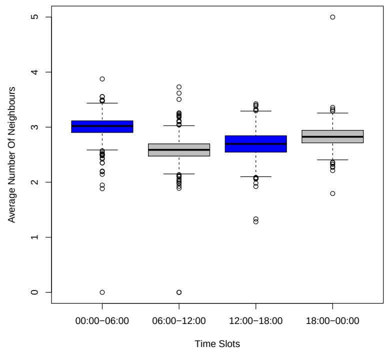
The proposed approach has been realized in a prototype. Our main focus was on developing the ERS and its helper-to-helper communication technology. We utilized a Raspberry Pi as a platform for the ERS. Raspberry Pi is a credit-card-sized single-board computer equipped with 700 MHz ARM processor. We developed the regarding software using the Python programming language. A high gain 100mW wireless USB adapter was used to provide the victim-helper communication. It is possible to provide helper-to-helper communication via Wi-Fi [8] or a long-range energy-efficient Bluetooth module in hundreds of meters effective connectivity range [7]. The system was attached to the battery of a vehicle using an efficient voltage converter. Experiments showed that the system lasted for days in a fully operational mode while the engine of the vehicle was not running.

5 Experimental Results

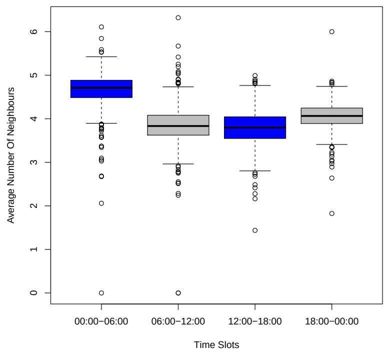
A real-world data set has been utilized to evaluate the proposed approach. We adopted a data set of mobility traces of taxi cabs in San Francisco, USA. The



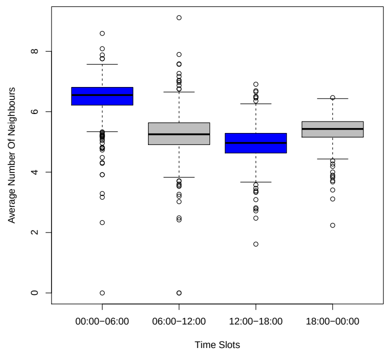
(a) For helper-to-helper radio range equal to 500 meters



(b) For helper-to-helper radio range equal to 1000 meters

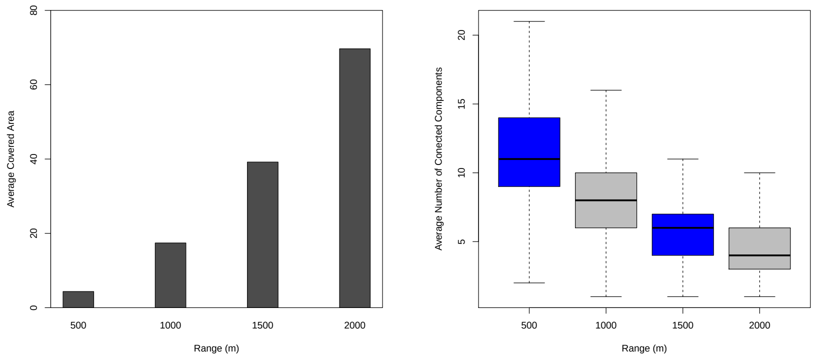


(c) For helper-to-helper radio range equal to 1500 meters



(d) For helper-to-helper radio range equal to 2000 meters

Fig. 4: Average number of neighboring helper nodes for various communication ranges in various time slots of a day



(a) Helper's radio range versus average covered area

(b) Helper's radio range versus average number of connected components

Fig. 5: Experimental results for various radio ranges

trace contains GPS coordinates of approximately 500 taxis collected over 30 days in the San Francisco Bay Area [4]. Figure 3 shows the map of the area. For our purposes, we assumed that when two taxis encounter, i.e., become in each others' radio range, they opportunistically exchange their stored messages. Figures 4 and 5 illustrate the experimental results.

Figures 4(a)-(d) show the effect of the helper's radio range on the average number of neighboring helpers, i.e., the average number of helper nodes that reside in each others' radio range for different time slots. Evaluating the number of neighboring helpers is important since it implicitly shows the number of alternative routes that each node has the rescue teams and vice versa. It is also important to observe the variation of this parameter during different hours of the day since some of the natural disasters cannot be predicted in time, e.g., earthquakes. As shown in the figures 4, as the radio range expands the number of neighbors grows significantly. It is also evident from the figures that the average number of neighbors is slightly larger during midnight hours.

Figures 5(a)-(b) present the effect of the helper's radio range on two different parameters. Figure 5(a) shows the variation of the average covered area when radio range varies. As shown in the figure, as the radio range expands the average covered area grows significantly which suggests that more victims can connect to the system and send and receive emergency messages. As the helpers are scattered in the area, they are not always fully connected, i.e., they are partitioned in different connected components. It means that each helper node may not be able to send its message to every other node. However, a smaller number of connected components suggests that it is sufficient for a rescue team to encounter with at least one helper node from each of these few components to be able to send and receive emergency messages to/from all of the helper nodes.

As shown in the Figure 5(b) the average number of such components decreases significantly when the range increases.

6 Conclusion

In this paper, a list of design guidelines for resilient communication infrastructures for post-disaster rescue operations was presented. We provided a resilient communication scheme based on those guidelines that operate in a fully distributed fashion, taking advantage of Vehicular Ad-Hoc Networks (VANETs), Bluetooth and Wi-Fi communication. A prototype of the proposed system was also realized. Moreover, we conducted extensive experiments to verify the applicability of the proposed approach in real-world scenarios.

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