Motivation for a Step-by-Step Guide to Set up Wireless Disaster Recovery Networks

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***Abstract*—Radio access networks (RANs) have become an integral part of life and are especially important after disasters. However, many disasters also disrupt RANs. Disaster recovery networks connect survivors to the Internet again so that they can inform authorities about their situation, get information necessary for survival, and contact friends and family.**

In this paper we explain why a step-by-step guide in form of a mobile phone application will help survivors construct a multi-hop disaster recovery network of mobile phones. We develop a simple analytic model to describe how survivors should place mobile phones to relay transmissions over long distances. Then we set up a small scenario and compare our measurements to the analytic results.

Our comparison shows that the analytic model only describes the general tendencies of channel quality and that it is necessary to measure the channel quality on each hop. As this measurement is too complex for an average disaster survivor we describe a step-by-step guide which can be implemented in a mobile phone application to guide survivors through the process of setting up a disaster recovery network. This mobile phone application would allow survivors to communicate with the each other and the outside world and thereby save lives in case of a disaster.

I. Introduction

Radio access networks (RANs) connect user equipment (UE), such as mobile phones, to the Internet. To do this, RANs have base stations (BSs), which receive data from the UE and forward it to the Internet using a backbone network. RANs have become an integral part of live and are especially important in case of emergencies. Figure 1a illustrates their operation under normal circumstances on a level of abstraction that is relevant for this paper.

A. Communication after disasters

In small emergencies (e.g., traffic accidents and sports injuries) a RAN helps to alert the emergency services. A RAN also helps coordinate the following rescue operation by medics and firefighters.

Especially during large emergencies – called disasters – (e.g., earthquakes and floods) the amount of coordination and logistics needed is huge [2]. The necessary coordination can only be achieved when efficient means for communication are available [3], [4], [5]. This is evident from the reports of recent disasters:

- 2004 Indian Ocean earthquake and tsunami [6],
- 2005 Hurricane Katrina [7], [8],
- 2010 Haiti earthquake [9], and
- 2011 Tōhoku earthquake and tsunami off the coast of Japan [10].

For example, during the 2010 Haiti earthquake the Ushahidi software platform was used to collect and visualize information about people in need for help. Ushahidi was also one of the tools used during the 2011 Tōhoku earthquake and tsunami [11], [10]. Large scale tests and demonstrations of disaster response and recovery also contain lots of networking, communication, and coordination effort [12].

Keeping social connections between survivors active is also very important [13] and projects such as EmerGent[1] analyze the impact social media have in disaster situations.

After the immediate danger of the disaster has passed, there is no need to make decisions on a split-second basis. However, there are still open questions which can decide over life or death: Where can I find drinking water? Where can I find medical help? Can I use this road to get to safety? Do I need to find shelter from bad whether? Many of these questions can be answered with access to the right information. However, to access this information a working Internet connection is necessary. During their regular operation RANs are able to support communication and disaster information can be accessed from governments or, for example, Ushahidi platform.

B. Networks after disasters

A major problem of disasters is that they often also damage the RANs, which then cannot provide the necessary service when it is needed most. Figure 1b illustrates this loss of connectivity after a disaster.

The providers of RANs are usually quick (on a scale of weeks [14]) to repair the damages to their infrastructure, but coordinating both the survivors of a disaster and the rescue personnel is most important in the first hours and days after the disaster. Hence, any intermediate means of communication helps to save lives until the network operators are able to repair their RANs.

Projects like "Hastily formed networks" [15] describe how disaster relief can be coordinated and which future trends are expected [16]. SPARCCS [17] can provide situational awareness to people in the disaster areas. However, this and

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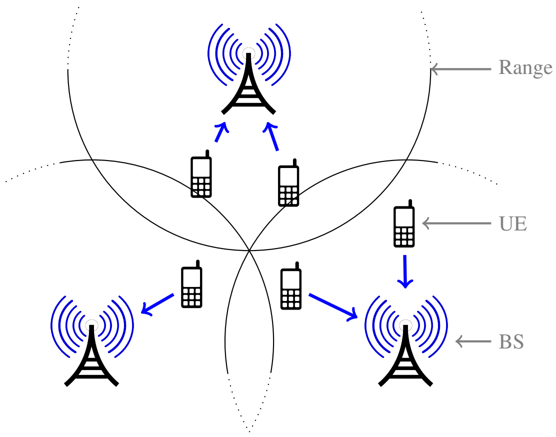
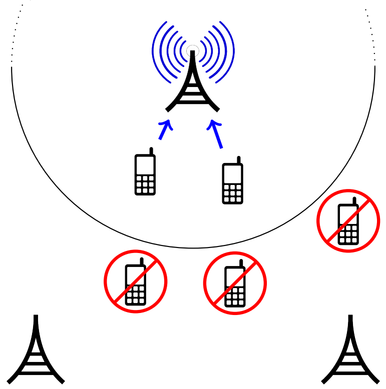
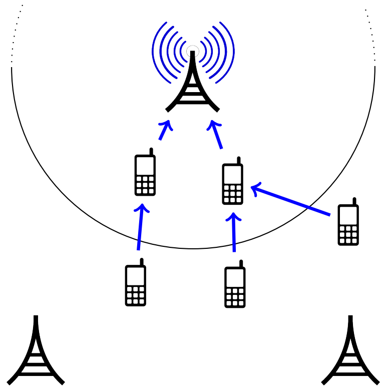
[1]http://www.fp7-emergent.eu/



(a) Under normal operation each user equipment (UE) is associated to a base station (BS).



(b) After a disaster a UE which is not in range of any active BS is cut of from service.



(c) Disaster recovery networks [1] allow UEs to relay data from other UEs to a BS.

Fig. 1: Depending on the situation the same RAN provides different degrees of service.

many other projects depend on the ability to communicate in disaster areas.

Approaches to re-establish the lost ability to communicate after a disaster include:

- portable BSs [18], [19], [20],
- interoperability with other networks (e.g., military) [21],
- balloons to create flying mesh networks[22],
- unmanned aerial vehicles (drones) to relay data [23], and
- satellite communication [24].

However, all these require specialized hardware and/or preparation by each survivor. Although these requirements will usually be fulfilled by many organizations that are involved with disaster recovery, not all survivors will receive this help immediately: rescue personnel might not be able to reach an area quickly or might be tied up in areas were more help is needed. Our idea is not to replace these approaches, but to provide an additional approach, which can be combined with any other approach to allow even more survivors to communicate with the rest of the world.

C. *Survivors that help themselves*

We propose the idea of repairing communication abilities as well as possible without outside help, that is, only with the means that the survivors of the disaster have at their immediate disposal. Ideally these efforts will be able to connect to other means of communication which rescue personnel bring into the disaster area.

We assume that some locations in the disaster area exist which can communicate with the outside world. Survivors can, for example, find these by spiraling outward from their position [25]. Locations that provide Internet connectivity are, for example:

- a working BSs (not damaged by luck or located outside the disaster area),
- a working wired connection,
- a device with the ability to communicate by satellite,
- a location which can connect to a working BS (e.g., a mountaintop or a high building), or
- rescue personnel which bring external equipment that is able to communicate (as described earlier).

However, the location at which communication is possible will probably not be the location where it is needed the most (e.g., an evacuation center).

To connect a location that needs connectivity to a location which has connectivity, we propose to deploy mobile phones at strategic locations, which relay the communication of other phones. We think this is a good choice as mobile phones are ubiquitous in nearly all societies today and are widely available[2]. While they require electrical energy to operate, their batteries will allow them to operate for at least a few hours and many possibilities exist to charge them even after a disaster: cars, external battery packs, hydrogen fuel cells, solar panels, hand cranks, and diesel generators.

One possible approach to use mobile phones to provide connectivity until the RAN is fully operational again is to

[2]World Bank, World Development Indicators: Mobile cellular subscriptions

use on-the-fly established multi-hop RANs [1]. In an on-the-fly established multi-hop RAN the UEs organize into trees with a working Internet connection at the root of each tree. Every UE that is part of an on-the-fly established multi-hop RAN forwards data packets towards the root (Figure 1c). A UE which is part of a tree can both be: (1) a UE which is actively used (e.g., a device a user carries around) or (2) an *infrastructure UE*, which is placed at a strategic location to improve the quality of the overall network. As both hard- and software of the devices is the same, it is only its use that allows this distinction and the network does not have to distinguish between the two types of devices.

The construction of an on-the-fly established multi-hop RAN consists of two parts: (1) Selecting locations for infrastructure UEs and (2) building trees from the UEs. The first part proposes good locations to place UE to aid the overall network. But as these locations will not always be accessible, the second part constructs the "best" possible network from the available UEs.

The contribution of this paper is a detailed description why a step-by-step guide to set up a disaster recovery network is necessary and provides an example of a step-by-step guide. We consider only the problem of selecting good locations for infrastructure UEs in this paper, becasue others (e.g., Minh et al. [1]) already describe how to set up a network once the locations have been determined. This paper reuses figures and ideas from an earlier poster we created [26].

This paper consists of three parts: (1) In section III we describe an *analytic* model to determine the optimal placement of UEs to relay the communication in a disaster recovery network. (2) To determine how useful this model is in practice we describe our *measurement* setup and its results in section IV. Our measurement results show that the overall tendency of our model is correct, but it is necessary to analyze each placed UE's connectivity in detail. As this is not practical for a layperson (and time consuming for an expert) we (3) propose to create a *step-by-step guide* in form of an application for mobile phones that will guide a survivor through all steps to set up a disaster recovery network (section V).

II. Related Work

Minh et al. [1] describe how a multi-hop radio access networks can be implemented on-the-fly. They focus on the implementation and describe how the necessary software can be installed from the Internet even if the software provides the Internet connection in the first place. Minh et al. do not describe how to determine the locations for the UEs, but we do in this paper.

An alternative software to establish a multi-hop network after the UEs are placed is Open Garden[3] and its chat application FireChat. While we construct a multi-hop network based on WiFi in this paper, every other standard which supports multi-hop communication between devices could be used in the same way. Sarshar et al. [27], for example, provide a similar description of the details how to setup a tree-based network.

[3]http://opengarden.com/

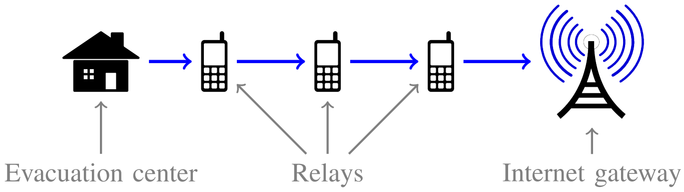


Fig. 2: We consider a scenario in which survivors place relays to connect an evacuation center to an internet gateway.

Gomez et al. [28] explain how 4G radio access networks can be made more disaster resilient by virtualizing and distributing parts of the network architecture. Their core-network-independent device-to-device network architecture is an alternative to WiFi (which we selected). Gomez et al. focus on the communication between the devices, while we assume the technology for communication is given (e.g. by Minh et al. [1] or Gomez et al. [28]) and describe a strategy how disaster survivors can determine locations for these devices. The step-by-step guide we describe in section V is independent from the underlying communication technology and can be implemented using WiFi, 4G, and Bluetooth.

The Collection Tree Protocol [29] for wireless sensor networks also builds a multi-hop tree, but is not helpful in disaster scenarios as it only collects data from a data source and transmits it to a data sink. It is not designed for bidirectional transmissions, which are needed for Internet access. Moreover, Collection Tree Protocol only specifies how a given set of UEs should communicate, but not how they should be placed.

Aurisch and Tölle [30] analyze how rescue personnel can setup a disaster recovery network with relays. Although their approach is similar to ours, they do not consider the specific restrictions that arise when the network is constructed by survivors of disasters: the survivors have no access to prepared hardware and have no prior training to set up a multi-hop network.

Other work determines the performance of WiFi [31] and describes its problems for Multihop use [32], [33]. However, as WiFi is the only widely available protocol on consumer devices, we think that there currently is no alternative.

III. Analytic approach

In this section, we analytically determine the optimal solution for a special case of relay placement in disaster recovery networks. In our scenario a single UE exists which is connected to the Internet and a second UE (or a group of UEs at the same location) wants to connect to the Internet. These can for example represent a working home WiFi and the survivors at a nearby evacuation center. Figure 2 illustrates the scenario. Placing mobile phones which relay the signal between both end points will allow the survivors at the evacuation center to access the Internet. In this section we present a method to analytically determine the optimal number of relays. We use 802.11g WiFi for our calculation, but the approach can be applied to other technologies as well. This section is based on an earlier publication [34], which contains a detailed description of the model and its parameters.

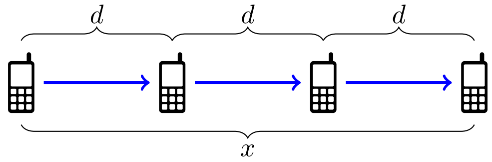


Fig. 3: In our example each device relays data packets to its neighbor over a hop distance of d to cover a total distance of x.

A. Model

We model $n + 1$ devices placed in a straight line of length x in an open environment with a distance $d = x/n$ between neighboring devices (see figure 3). We assume each device (1) connects to its parent, (2) creates a 802.11g WiFi network for its child, and (3) uses network address translation to forward the packets from its child to its parent. Our goal is to determine the optimal number of hops and, thus, the optimal distance between UEs. To determine the quality of the end-to-end connection we use the data rate (throughput in bit/s) as metric. The scenario and software is the same as Minh et al. [1] use. The goal of this section, however, is to determine the optimal distance between neighboring nodes instead of showing the feasibility of the approach.

We model the received signal strength of a single wireless hop using the free space path-loss model. To determine the data rate from the signal strength we use the Shannon-Hartley theorem and reduce the resulting data rate to compensate for the inefficiency of WiFi compared to the theoretical limit.

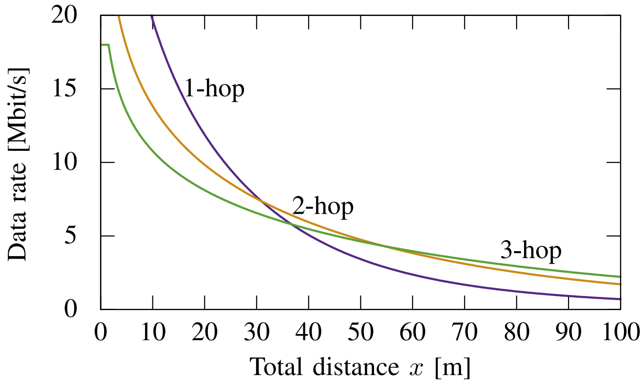
B. Analysis

Next we present the results we obtained by evaluating our analytic model with a set of realistic parameters. While we picked these values to be realistic, their precise values are not important as we only want to determine the overall behavior of the system. In section IV we will determine the parameters which best fit the measurements from our real-world scenario.

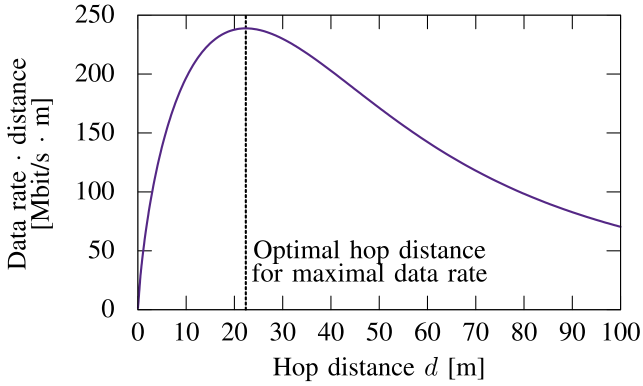
We consider a scenario in which two devices are placed at a distance of x and compare the end-to-end data rate when they are connected by 1, 2, or 3 hops. Figure 4a shows the result. We only consider up to three hops here as this is easier to visualize, but the model will be the same for more hops. We currently estimate at least 20 hops to be possible based on earlier tests.

In our model the optimal hop distance d is independent of the total distance x to cover. To determine the optimal hop distance d we normalize the data rate for a given hop distance *per meter*. This allows us to compare the resulting data rate of different hop distances independent of the total distance. The maximum shown in figure 4b is, thus, also the hop distance d at which the *end-to-end* data rate is maximal.

As this analytic model is very simple, we will compare it to measurements in the next section. If this analytic model would be accurate it would be easy to instruct a disaster survivor to place phones at the optimal distance between the location she wants to connect to each other (but as someone familiar with wireless transmissions might guess this will not work).



(a) The number of relays to achieve the highest data rate depends on the total distance that needs to be covered.



(b) There is an optimal distance to achieve the highest data rate, which is independent of the number of necessary hops.

Fig. 4: The results of the analytic model are inline with general intuition about wireless multi-hop networks.

IV. Measurements

In this section we test how useful the analytic model we described in the last section is in practice. In others words: is it enough for a disaster survivor to know the theoretical optimal distance to set up a disaster recovery network?

We construct the setup of the last section (figure 3) as well as possible in reality and measure the achieved end-to-end data rate. We will vary the locations of the UEs slightly while keeping the hop distance the same and determine the effects of the data rate. We then evaluate whether the optimal distance is enough to guide a layperson to set up a disaster recovery network or if small changes in the placement are enough to render the theoretically-optimal setup useless in practice.

A. Setup

We selected a roughly straight gravel road in a rural area with a lot of trees as our test site. It should represent an average case with some, but not too many, objects to dampen communication.

Instead of mobile phones we used Windows 7 PCs as we had those available and they are easier to run the measurement scripts on than mobile phones. However, we think the results would be similar with mobile phones as long as they use the same WiFi standard.

To set up (multi-hop) communication between the PCs we used our prototype software MHANS [1], which converts each PC into a virtual access point. Each virtual access point uses network address translation to forward the traffic from the PCs connected to it to the access point it is connected to itself. The MHANS prototype contains features for detecting problems in the setup, but the results should be the same when using other software with the same features.

We set up and measured the performance in two different scenarios: a multi-hop scenario and a single-hop scenario. In both scenarios we measured the data rate with iperf 2.0.5 in its default configuration. We use the multi-hop measurements to test for the validity of our model and use the single-hop measurements to determine the optimal distances and the effects of small changes in the placement.

In the multi-hop scenario we placed 2, 3 and 4 PCs equidistant with a varying total distance of up to 100 m. In the single-hop scenario we only used 2 PCs to determine the single hop performance for different distances, but varied the placement of the 2 PCs slightly to test its effects on the performance. The four placements are: (1) `Ground`, where both PCs are placed on the ground at the side of the road, (2) `Wall`, where both PCs are placed on a small wall (0.3 m to 1 m height) at the side of the road, (3) `Cross`, where one PC is placed on the wall and the other is hung from a fence in a shopping bag on the other side of the road, and (4) `Stand`, where one PC is again hung on the fence and the other is held by one of the authors in the center of the road to minimize damping by branches on the side of the road. We selected these placements as all the means necessary for the setup are available to survivors.

B. Results

Next we present the results we obtained from our measurements. We show the 95% confidence intervals under the assumption the results are normally distributed (dotted line). We moved the marks for the confidence intervals slightly from their original x-coordinates as this makes it easier to see their sizes when they overlap (connected by dotted lines for easier view-ability). We determined the unknown parameters (Path-loss exponent and inefficiency) from our results using the least squares method and plot the analytic result (fully drawn line).

Figure 5 shows the achieved end-to-end data rate for a given total distance. While the general shape of the results is similar to the analytic results, the individual discrepancies (e.g., at 60 m 1-hop) are large.

Next we illustrate that even small changes in the placement of the UEs can cause big changes in the achieved data rate. Figure 6 shows the end-to-end data rate for the different types of placement of the UEs. In the four setups the UEs were only moved by a meter or two, but the change in data rate is large and completely prevents connections at high distances.

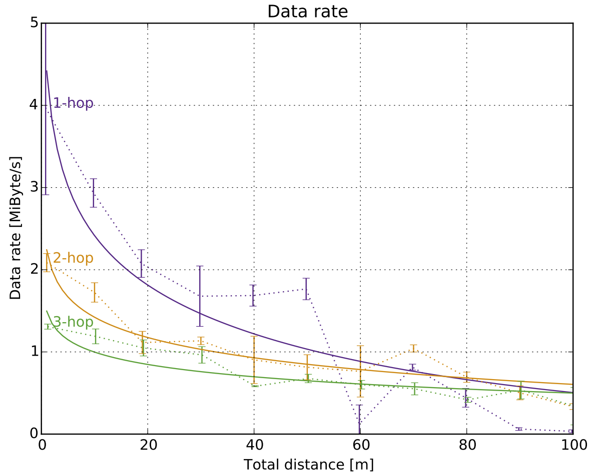


Fig. 5: As expected for short distances 1-hop communication has the highest data rate; for longer distances multi-hop communication achieves a higher data rate.

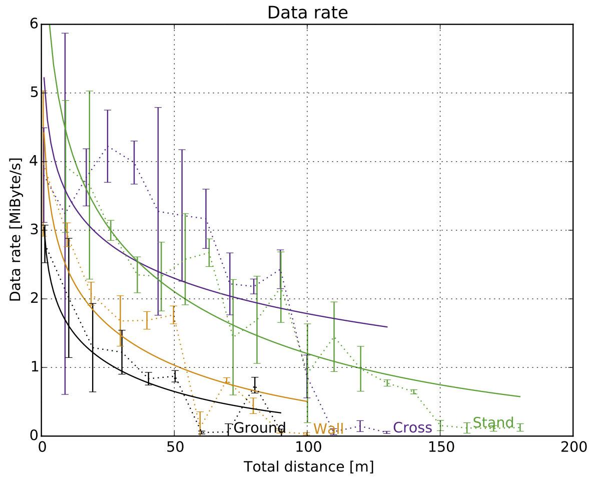


Fig. 6: Slight changes in placement of the UEs results in drastic changes of the data rate.

From these results, we conclude that it is generally a good idea to make sure that no objects are in the Fresnel zone [35] for a transmission. This can for example be achieved by placing the UEs high up. In our case, the measurements `Cross` and `Stand` with one UE in a shopping bag hanging off a fence, while the others are on or close to the ground. Our measurements show that it is possible to give general advice how to improve the channel quality to disaster survivors, but it is still necessary to test each individual channel.

As it is very difficult to determine the channel quality without measuring it, we think it is necessary to measure the channel quality for each hop. This becomes even more important as survivors of a disaster will generally not have any knowledge about wireless signal propagation.

To determine the distance for which the end-to-end data rate

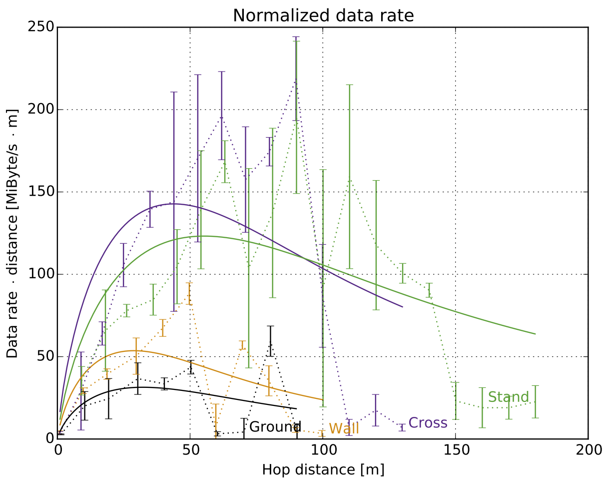


Fig. 7: The distance to achieve the highest data rate changes with only slight changes to the placement of UEs.

is highest we normalize the results to the covered distance. The general shape of the normalized results of the analytic model (figure 4b) is similar to the measurements results (figure 7), but has a high variance. For placements with clear line of sight and mostly empty Fresnel zone (`Cross` and `Stand`), the highest data rates can be achieved between 50 m and 100 m distance. For placements closer to the ground (`Ground` and `Wall`) the optimal distance is between 30 m and 70 m. As from the non-normalized results, we conclude that general hints how to place the UEs are helpful for survivors, but due to high variance in channel quality each channel needs to be tested individually.

C. *Measurement summary*

The analytic model for the data rate roughly describes the achieved data rates in the measurements. The optimal distance to maximize data rate is between 50 m and 90 m for elevated UEs and 30 m to 70 m for UEs close to the ground.

The end-to-end data rate can be increased by hanging UEs from elevated positions (trees, fences, ...) and making sure the Fresnel zone is mostly empty. However, whether the individual channel is good enough for communication is difficult to determine in advance. Hence, we conclude that it is necessary to test each individual channel to be sure it can relay the communication. As measuring the channel qualities is too complex for the average disaster survivor, we propose an idea how to make it feasible in the next section.

V. Vision

In the previous section we showed that the channel quality between two mobile phones can only be roughly estimated and that individual measurements are needed to ensure a good connection. However, running and evaluating these measurements is both time consuming and technical. Hence, only very few survivors of a disaster will be able to do this. Therefore, we propose to develop a step-by-step guide for survivors in form of a mobile phone application to assist survivors to build a disaster recovery network.

The application can either be preinstalled on a mobile phone or can be installed after the disaster at a location with Internet connectivity. The application should provide the user with options of what the user might want to achieve. In this paper we focus on the scenario that we already considered through the rest of the paper: "Providing Internet access by placing phones to relay wireless signals". Other modes could include: "Find a location with Internet connectivity" or "Setup a local communication network".

Having a step-by-step guide (which must not necessarily be interactive) will help survivors set up a disaster recovery network as the task is complex. Making the step-by-step guide interactive by implementing it as a mobile phone application allows the application to automate everything for which no user action is required. For example, testing channel qualities while setting up the network, monitoring channel qualities later on, and warning users if batteries are running low. Hence, the application will support the user both while setting up the network and while maintaining it. This way the application can ideally detect if the network is about to break down and instruct the user to take preventive actions (e.g., "Please move the solar panel from phone 5 to phone 6; let me guide you there by GPS").

When the step-by-step guide is implemented in a mobile phone the user only needs to do the steps which the phone cannot do by itself: moving phones. When a GPS is available, it can even be used to support the user in finding locations for the relays.

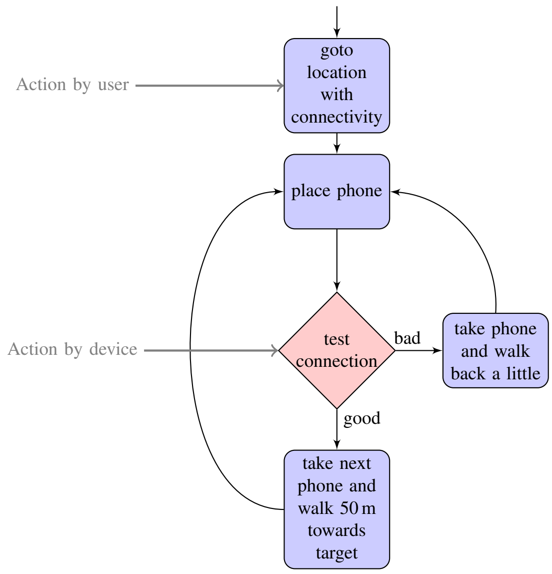


Fig. 8: A possible step-by-step guide for survivors of a disaster to set up a multi-hop disaster recovery network with an interactive smart phone application. The mobile phone will only show the current step to the disaster survivor.

The step-by-step guide will consist of two different types of steps: (1) Steps which the phone can do on its own and (2) steps which the user has to assist with. Hence, the user will never see the full step-by-step guide as only parts of it are meant to be executed by him or her.

Figure 8 shows a simple first version of a step-by-step guide. While numerous changes and additions to this basic step-by-step guide are possible our intention here is only to illustrate the idea and not compare different versions. Alternatives could for example be to increase the distance until the channel is not good anymore (and then go back one step).

Future work on the step-by-step guide consists of developing more detailed step-by-step guides and implementing them in a prototype application (based on our prototype or on, for example, OpenGarden). This will allow to hand phones with the application preinstalled to laypersons and let them set up a disaster recovery network. Then the success probability and the time to set up and general comments about the application can be collected. When comparing different step-by-step guides we think the focus should be how well laypersons are able to set up the network and not on the performance of the network.

To conclude this section, we think it is necessary to implement a step-by-step guide, hand mobile phones to uninstructed volunteers and see how the network they set up behaves. In addition, observing which problems the volunteers encounter will give valuable feedback how to improve the application.

VI. Conclusion

We first described both why wireless communication is important right after a disaster and why it is difficult to provide. Next, we proposed the idea to let survivors of a disaster construct a disaster recovery network with mobile phones without depending on outside help. We described an analytic model to determine the optimal distances of mobile phones. The measurements we did next, show that the analytic model describes only the trend of the channel quality, but measurements of the channel are necessary to ensure a good quality for each channel. Lastly, we illustrated how a step-by-step guide in a mobile phone application can make it possible for survivors of a disaster to build a disaster recovery network even without prior knowledge of wireless communication. The next step will be to implement such an application and let laypersons set up a disaster recovery network on their own and see how well they do.

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