Comparing Strategies to Construct Local Disaster Recovery Networks

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***Abstract*—Large-scale disasters, such as earthquakes and tsunamis, damage communication infrastructure. The damaged infrastructure is then not able to provide the means for communication, which is important after a disaster.**

In this paper we simulate how survivors of a disaster can place smart phones or notebooks (hereafter called devices) as stationary relay chains to connect to other evacuation centers and Internet gateways to access the Internet. To determine the time necessary to set up the network and the number of evacuation centers connected to the Internet, we create a Poisson-based simulation of evacuation centers and Internet gateways. We then compare strategies how to interconnect evacuation centers and gateways.

Our results show that among the strategies to place relay chains we tested, the most promising are: (1) Link every evacuation center to the closest gateway with a relay chain and (2) link each evacuation center to the 3 closest evacuation centers or gateways with relay chains. Both these strategies seem promising and should be tested in field tests in the next step. Together with step-by-step guides for disaster survivors this work will hopefully result in a smart phone and notebook application that lets untrained disaster survivors quickly set up their own recovery network in the disaster area.

I. INTRODUCTION

Radio access networks are an important means of communication in emergency situations. Especially after large-scale disasters (e.g., earthquakes and tsunamis) the need for logistics is huge [1]. To efficiently organize the following rescue operation communication inside the affected area is important. However, large-scale disasters often also damage the communication infrastructure even in well developed countries which prepare for disasters (e.g., Japan [2]). This results in the communication infrastructure not being available, when it is needed the most.

Many approaches try to re-establish the ability to communicate. These include using satellite phones, portable base stations, and drones. However, all these approaches have in common that they need special hardware or some other form of preparation. In contrast to this, we take an approach to set up the network, using any available wireless commodity devices such as smart phones and notebooks, rather than repairing the damaged infrastructure [3]. Based on such a commodity-device-based approach this paper analyzes how well disaster survivors can repair communication capabilities without outside help and preparation.

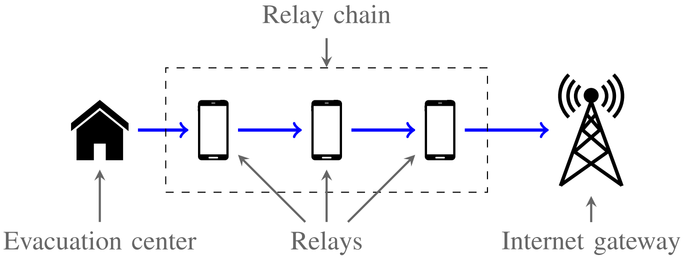

Fig. 1: Because each device relays data packets to its neighbor, this relay chain links the evacuation center to the Internet gateway.[1]

After the Great East Japan Earth Quake, in order to avoid any damage from the tsunami, the survivors first ran to high ground areas where evacuation centers are usually located. Therefore, the evacuation centers are considered safe after the disaster. Examples for evacuation centers are local community centers and schools/universities.

We analyze how disaster survivors can place unused wireless devices (e.g., smart phones and notebooks) as stationary relays to construct a communication network to provide internet access at the evacuation centers. The goal of this network is to connect as many evacuation centers as possible to the Internet with as little work as possible. The scenario we are considering is that survivors gather in groups at evacuation centers, where they are not in any immediate danger. That is, they may have water, food, shelters, battery recharging tools, like emergency engines and cars. However, they may not have any communication link to the rest of the world. While it is not necessary for the survivors to be safe from immediate danger to set up a disaster recovery network, this gives them the free time to set it up. We consider it feasible that survivors can spare some mobile devices as many people have several devices (phone, tablet, notebook), but do not need all of them at the same time. Additionally, a group of people (e.g., a family) might give away some of their phones, which do not have internet connectivity, to gain internet access on the remaining phones (which they can share).

It is important to understand that we consider the survivors to place their devices specifically for wireless relaying to

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[1] Pictograms created by Mani Amini, NAS, and Creative Stall from the Noun Project.

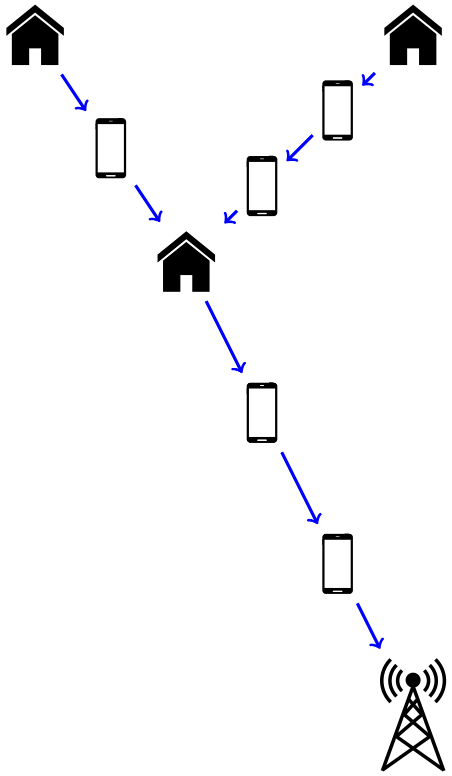

Fig. 2: Building relay chains to neighboring evacuation centers can be less work than building independent relay chains to the internet gateway directly.

connect to any Internet gateway and do not carry them around during the operation of the network. In other words, these devices are assumed to be stationary (once deployed) and not moving. While this does not make the network free from transient changes in connectivity, it reduces them compared to a network of moving devices.

In earlier work [4] we showed how survivors can use relay chains of wireless devices to set up a disaster recovery network. In further work [3] we described how a step-by-step guide implemented in a smart phone application can allow survivors to link an evacuation center without Internet connectivity to a location with Internet connectivity. The basic idea is to place unused wireless devices as stationary relays between the evacuation center and an Internet gateway. As the devices can be heterogeneous, we propose to use WiFi (IEEE 802.11) to communicate, because it is available on many wireless devices. While our earlier work was specific to WiFi, the results of this paper are independent of the technology used. Figure 1 shows a single relay chain that finally connects an evacuation center to an Internet gateway. In contrast to other work, we consider that the relays are *intentionally* placed by survivors to establish the relay chains. That is, relays may not be at the right location by coincidence. While our earlier work was experiment- and implementation-based, this paper takes a systematic and theory-oriented design approach to compare the strategies used to set up relay chains.

In this paper we determine which strategy the survivors should use to set up relay chains to connect their evacuation center to the Internet *when there are other evacuation centers nearby*. That is, we extend our work of linking one evacuation center and one gateway [5], [6] to linking several evacuation centers and several gateways for better Internet connectivity. Figure 2 shows how evacuation centers can be linked to each other and an Internet gateway by relay chains. We will compare the different strategies by (1) the fraction of evacuation centers (of all evacuation centers) that are connected to the Internet and (2) the time the survivors need to set up the network. We assume the time to set up the network is proportional to the number of relays the survivors have to place. Because the number of relays is proportional to the relay-chain length (measured in distance) [6], we use the metric "relay-chain length" to represent the time that is necessary for the survivors to set up the network.

The problem to find the shortest interconnect for a set of points is known as the Steiner tree problem [7]. It is a well studied problem, but is difficult to solve (NP-complete) even when the location of all points is known. In our case, however, the survivors who want to set up the network must not know the locations of all other evacuation centers and Internet gateways. Hence, the survivors need to use simple heuristics which can construct a disaster recovery network without knowing the locations of all other evacuation centers and Internet gateways. We assume the survivors know the locations of other evacuation centers and Internet gateways which are close to their own location. If they do not know this, they should spiral out from their current location to find other evacuation centers and Internet gateways [8]. As the focus of this paper is to compare strategies to set up relays, we do not consider how to find Internet gateways.

The goal of this paper is to compare simple heuristics to set up a disaster recovery network. The primary goal is to connect as many evacuation centers as possible to the Internet (via gateways). The secondary goal is to use few relays and reduce the setup time of the network. This paper is intended to filter out a set of strategies which can later be analyzed in more detail (either in a more detailed simulation or in field tests).

II. RELATED WORK

Minh et al. [4] describe the technical details how multi-hop radio access networks can be implemented. It describes how a tree-based WiFi multihop network can be constructed using commodity devices. Our work builds upon their work, which already provides routing and ideas for load distribution. However, we approach the problem of selecting locations for the relay devices.

The Steiner tree problem [7] seeks to find the shortest interconnect between a given set of locations. This is consistent with our simplification that considers relay-chain length instead of the relays themselves as the optimization goal. Generally, however, a Steiner tree requires that every node is linked to every other node, but we only require every evacuation center to be linked to at least one gateway. A Steiner tree is only the optimal solution when only a single gateway is in the considered area. When several gateways are in the area the longest edges that connect two connected components of the graph could be removed and still satisfy the requirement that every evacuation center is in a connected component with a gateway. Gouveia et al. [9] consider the problem of multi-root Steiner trees as optimization problem. Other formulations of Steiner trees consider minimizing the length of the evacuation center to gateway relay chains and survivability of the network after node failures [10]. However, all these approaches cannot be applied by the disaster survivors as the survivors lack precise and global knowledge of the scenario. Although approximation algorithms for Steiner trees exist [11], they are still too complex to be executed by the survivors. Thus, we consider simple strategies that the survivors can execute without global and precise knowledge.

The relay placement problem in wireless sensor networks [12], [13], [14], [15] tries to interconnect a wireless sensor network by placing as few relays as possible. Although this is related to our problem, it has the same difference as the Steiner tree problem: It requires a single connected component and assumes the location of all evacuations shelters and Internet gateways to be known to every device. Although the algorithms are a step into the right direction (for our problem), they still require too much location information to be used by survivors after a disaster.

In this paper we will consider an evacuation center connected to the internet when there is a gateway in the same connected component as the evacuation center. That is, a multi-hop path exists between an evacuation center and an Internet gateway. The problem of setting up the routing has been studied for wireless sensor networks (which can be applied in our scenario) and specifically for disaster-recovery networks [4].

To determine the performance of the strategies in general (and not only for a single scenario) it is necessary to assume a distribution for the evacuation centers and the gateways. Because the distribution of evacuation centers differs widely from one local region/country to another, we use a spatial Poisson process [16] for simplicity. Although Poisson processes and the related stochastic geometry [17] have been extensively studied, we were not able to find an analytic solution for our problem in the literature. Also, we were not able to solve the problem analytically ourselves. Therefore, we use a simulation approach in this paper.

The concept of nearest neighbor distribution [18] and nearest neighbor networks[2] describe the distance between neighboring nodes in Poisson processes and the networks that arise when they are connected. Yanhuai et al. [19] analyze the nearest neighbor network in wireless sensor networks, but vary the range by increasing or decreasing the transmit power. In contrast, we place relays along the path to be connected. Hence, the strategy they describe is only one of the strategies we analyze (we call it `Neighbor`(n)).

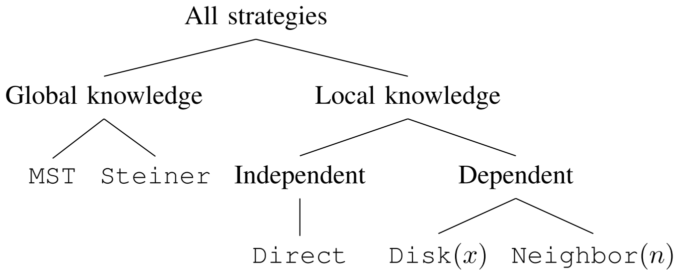

Fig. 3: The strategies we use to interconnect evacuation centers and Internet gateways can be grouped by necessary knowledge and dependency on other evacuation centers.

III. MODEL AND STRATEGIES

Our model consists of evacuation centers where the survivors are located and gateways to the internet, which can be a base station, a home WiFi, a satellite phone, or others. We use the word entity to describe both evacuation centers and gateways. We model types of entities (evacuation centers and gateways) as independent spatial (2-dimensional) Poisson processes.

We assume no entities are within radio transmission range from each other. If entities would be in radio range of each other they can be considered as a single entity. Instead of direct radio communication we consider how survivors can place relay chains between entities to forward signals. We consider two entities to be linked, when the survivors have placed a relay chain between the two entities. That is, any two entities can be linked (independent of their distance), but the time needed to do so is linear in the distance. We call an evacuation center connected to the Internet when a relay chain links it to a gateway. This link can also be an indirect link via other evacuation centers.

We want to determine the time it takes survivors to construct a network that links all evacuation centers to at least one gateway each. We assume this time is proportional to the number of relays the survivors have to place and maintain. Because the number of relays needed is proportional to the relay-chain length [6], we do not model the relays themselves. That is, we use the relay-chain length as measure for the time needed to set up the relay chain. This has the additional benefit that our results are independent of the communication range: A strategy that needs to cover a shorter distance than another strategy, needs fewer relays, and less time to set up.

Next, we compare strategies to select which entities to interconnect by placing relay chains. We consider strategies which know all locations of all entities (`MST` and `Steiner`) as reference values for local strategies. There are two groups of strategies with limited location information: (1) strategies which work independent of other survivors (`Direct`), and (2) strategies which depend on nearby evacuation centers (`Disk`(x) and `Neighbor`(n)). Figure 3 shows this grouping of the strategies. Figure 4 illustrates the networks the strategies create.

The strategy `MST` constructs a minimum spanning tree from all entities. That is, it makes no distinction between

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[2] http://demonstrations.wolfram.com/NearestNeighborNetworks/

Algorithm 1 `MST`

```
entities ← evacuationCenters ∪ internetGateways
minimumSpanningTree(entities)
```

Algorithm 2 `Steiner`

```
entities ← evacuationCenters ∪ internetGateways
steinerTree(entities)
```

Algorithm 3 `Direct`

```
for all $e \in$ evacuationCenters do
    $t \leftarrow$ closestElement($e$, internetGateways)
    connect($e, t$)
end for
```

evacuation centers and gateways. Similarly, the `Steiner` strategy constructs a Steiner tree between all entities. In short, the `Steiner` strategy does not only create direct relay chains between entities (as `MST`), but also creates additional Steiner points. Efficiently placing and interconnecting these points with relays allows the Steiner tree to be shorter than the minimum spanning tree. Both `MST` and `Steiner` strategies interconnect all entities, but use global knowledge to do this. Note that neither `MST` nor `Steiner` is optimal to solve our problem as both will create a single tree which also interconnects gateways. The optimal solution would only create a forest of trees such that each tree contains exactly one gateway.

Using the strategy `Direct` the survivors link each evacuation center to the closest gateway by constructing a relay chain to it. This strategy simply ignores other evacuation centers and can be executed independently by each evacuations centers. Using this strategy survivors do not need to distinguish gateways and evacuation shelters as they can ignore all WiFis except the disaster recovery network they are setting up themselves. For the `Direct` strategy it is necessary to know the location of the closest Internet gateway. If this is not known, it can be found by spiraling outward [8]. Strategies mentioned so far (`MST`, `Steiner`, and `Direct`) guarantee the each evacuation center is linked to a gateway as long as there is a gateway in the considered region. Hence, they will all link the maximum possible number of evacuation centers to gateways.

The following two families of strategies (`Disk`(x) and `Neighbor`(n)) are distributed and do not guarantee that all evacuation centers are linked to gateways. However, they hopefully will reduce the number of relays and time necessary to set up the relays compared to the `Direct` strategy.

Using the `Disk`(x) family of strategies the survivors link each evacuation center to all entities with a maximum distance of x from the evacuation center. For this strategy it is necessary to know the location of all entities in a radius of x. The `Disk`(x) family of strategies creates a unit disk graph which is often used to analyze wireless sensor networks [20]. Note, however, that the unit disk model in our case does not arise from uniform radio propagation (as in wireless sensor networks), but from the way the `Disk`(x) strategy links neighboring entities by relay chains. That is, the unit disk graph is not a result of unrealistically simple modeling, but of the `Disk`(x) strategy.

Algorithm 4 `Disk`(x)

```
entities ← evacuationCenters ∪ internetGateways
for all $e \in$ evacuationCenters do
    for all $t \in$ entities do
        if $e \neq t \land$ distance($e, t$) $\leq x$ then
            connect($e, t$)
        end if
    end for
end for
```

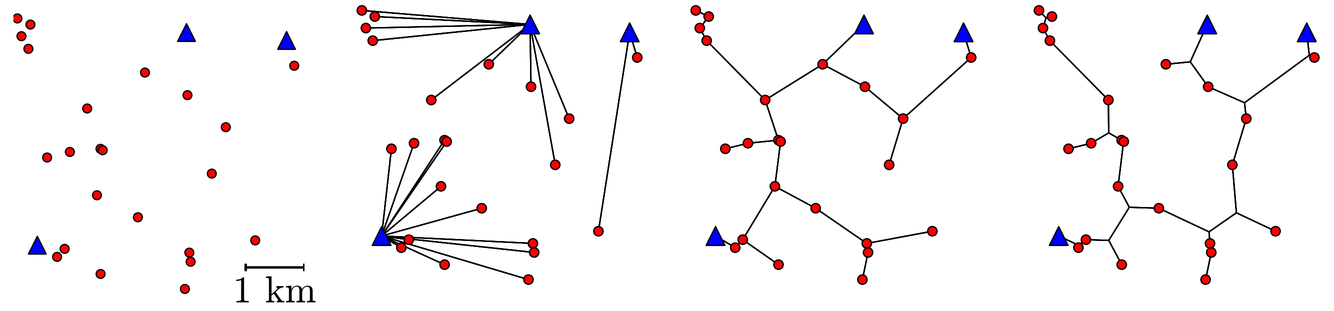
Algorithm 5 `Neighbor`(n)

```
entities ← evacuationCenters ∪ internetGateways
for all $e \in$ evacuationCenters do
    entities ← sortByDistanceTo(entities, $e$)
    for $i = 1$ to $n$ do
        connect($e$, entities[$i$]) {entities[0] is $e$ itself}
    end for
end for
```

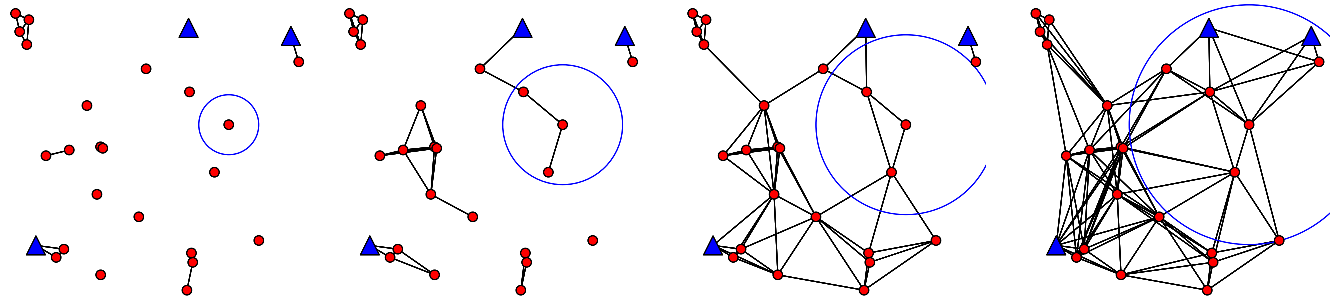
Using the `Neighbor`(n) family of strategies the survivors link each evacuation center to the n closest entities by relay chains. They do not link the gateways to their nearest neighbors, but let the gateways be targets of their neighbors (this makes a difference because not all links created in this way have a corresponding link in the other direction). The closest entities can be found by spiraling outward, if they are not known [8]. The `Neighbor`(n) strategies result in a variant of the nearest neighbor network as we have two different kinds of nodes (in the nearest neighbor network all nodes are of the same type). Please not that the algorithms displayed are those implemented in our simulation and not as they would be implemented by the survivors. The major difference is that survivors would have to search an area for entities, while our algorithms look at all entities and check whether they are in the area. this makes our simulation simpler, but leads to the same resulting graph for connectivity.

To get a sense of how the strategies behave, we illustrated the relay chains they create for a single scenario in Figure 4. The `Direct` strategy results in a star-like shape. The strategies with global knowledge (`MST` and `Steiner`) appear visually to be more ordered and not redundant. The distributed strategies seem to have two different problems at the low and the high end of their parameter range: At the low parameter end, they only link very few evacuation centers to gateways and at the high parameter end create a lot of redundant links. Although these redundant links are not a problem from a network management perspective the survivors will still need to place relays chains along these paths as they do not know which are redundant beforehand.

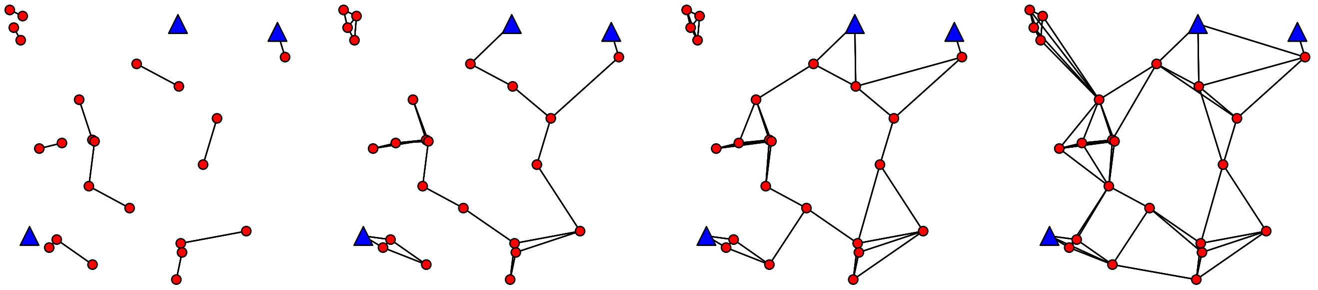
To compare the different strategies we use the metrics: "mean relay-chain length per evacuation center" and "fraction of connected evacuation centers". We determine the mean relay-chain length per evacuation center by summing up the



(a) Scenario (b) `Direct` (c) `MST` (d) `Steiner`



(e) `Disk`(0.5 km) (f) `Disk`(1 km) (g) `Disk`(1.5 km) (h) `Disk`(2 km)



(i) `Neighbor`(1) (j) `Neighbor`(2) (k) `Neighbor`(3) (l) `Neighbor`(4)

Fig. 4: The strategies create different interconnections between evacuation centers (red dots) and gateways (blue triangles). The circle in the `Disk`(x) figures shows its maximum distance parameter x. The lines do *not* represent direct wireless connections, but links by relay chains as shown in Figure 1.

length of all relay chains and dividing by the number of evacuation centers. The fraction of connected evacuation centers is the number of evacuation centers which have a gateway in their connected component of the graph divided by the total number of evacuation centers.

IV. RESULTS

We tried to derive analytic results from our model, but due to the complexity involved we were not able to gain noteworthy results. Instead, we will use simulations to compare the strategies. We use a simulation of a square area of size 5 km by 5 km and assume the evacuation centers and gateways are located in this area as described in the previous section. If not stated otherwise we assume the density of evacuation centers is $1\,\text{evacuation center}/\text{km}^2$ and the density of gateways is $0.1\,\text{gateway}/\text{km}^2$. We selected these parameters as they seemed reasonable to use, without further justification. However, because these parameters will vary strongly with the type of disaster, no single parameter will be representative of all disasters and a range of parameters needs to be analyzed. In this section we also test how sensitive the strategies are to these parameters.

To evaluate the strategies we created 100 scenarios and applied each of the strategies to each of the scenarios. We evaluated the metrics mean relay-chain length per evacuation center and the fraction of connected evacuation centers. In this section we show both the mean and the 95% confidence intervals under the assumption that the values are normally distributed and independent. We have not applied the Bonferroni correction to 2-dimensional confidence intervals. We implemented the simulation in Python 3.4.1 using NetworkX 1.9.1. We used Geosteiner 3.1 to calculate the Steiner trees. The code of the simulation is available online[3].

Figure 5 shows the basic trade-off between the fraction of

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[3] https://bitbucket.org/herlich/disastersim

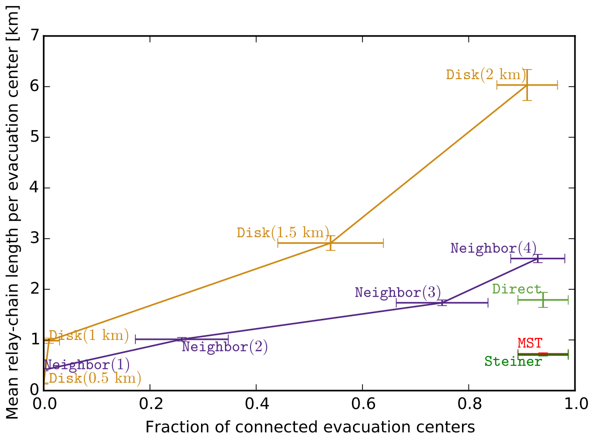

Fig. 5: The parameter of the local algorithms allows to select different trade-offs between the metrics.

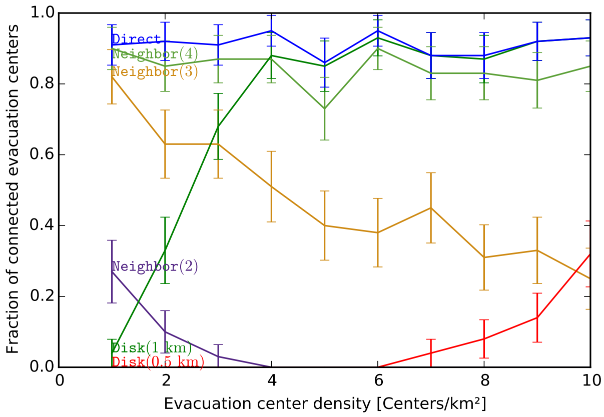

Fig. 6: Using the `Disk`(x) strategy the fraction of connected evacuation centers depends heavily on the density of evacuation centers. `Neighbor`(3), `Neighbor`(4), and `Direct` result in a constantly high number of connected evacuation centers.

connected evacuation centers and the time needed to set up the network (as chain length per evacuation center). The reference strategies `MST` and `Steiner` provide the same very good trade-off. For our parameters the `Direct` strategy provides a better trade-off than `Neighbor`(n) and `Disk`(x) as our primary goal is to connect a high number of survivors and it is only secondary to keep the mean relay-chain length low. From Figure 5 we conclude that `Neighbor`(3), `Neighbor`(4), and the `Direct` strategy provide good trade-offs.

As we suspect the metrics to depend on the density of evacuation centers, we compare different densities in Figure 6. As the density of evacuation centers is not known to the survivors it is necessary to select a strategy which results in a high number of connected evacuation centers for any density. The `Direct` and `Neighbor`(n) with $n \geq 3$ seem appropriate as they are independent of the density of evacuation centers for a wide range of densities.

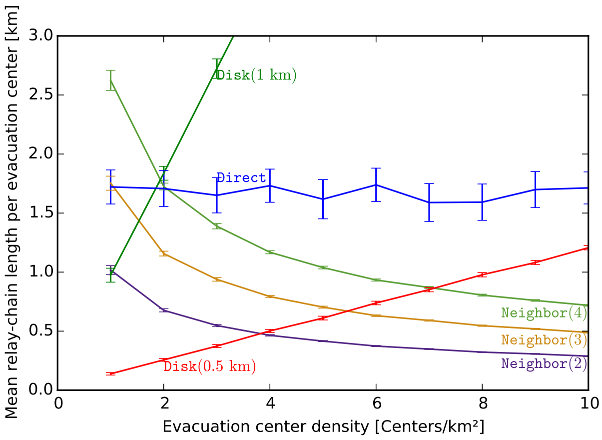

Fig. 7: The mean relay-chain length per evacuation center for the `Direct` strategy is independent of the density. The `Neighbor`(n) strategies benefit from neighboring evacuation centers, whereas the `Disk`(x) strategies create longer relay chains when the number of neighbors increase.

Figure 7 shows how the `Neighbor`(n) strategies benefit from a higher density with a lower relay-chain length. It also shows that the `Disk`(x) strategy with a too high parameter x creates high relay-chain lengths. Because the `Disk`(x) strategies connect to *every* entity in its range, the total work increases when the density of evacuation centers increases. Although both the `Direct` and the `Neighbor`(n) with $n \geq 3$ strategies result in a high fraction of connected evacuation centers, only the `Neighbor`(n) strategy benefits from neighboring evacuation centers. Because the `Neighbor`(n) strategy only connects to the n closest neighbors, its amount of work decreases with increasing density of evacuation centers. Although it would be possible to create an adaptive `Disk`(x) strategy that changes x depending on the number of neighbors in range x, this is only a complicated way of expressing the `Neighbor`(n) strategy.

From Figures 6 and 7 we conclude that the `Direct` strategy achieves a good trade-off, but in cases of high density the `Neighbor`(3) strategy can improve upon this. Which strategy is used in practice should probably be determined by field tests, but the comparison we did in this paper provides a preselection of strategies (`Direct` and `Neighbor`(3)) which seem promising.

V. CONCLUSION

We presented the general idea of disaster recovery networks. We extended our earlier work, which links one evacuation center to one Internet gateway by relay chains, to consider multiple evacuation centers and gateways. To determine the minimal time needed to link all evacuation centers to gateways an extension to Steiner trees would be necessary. However, as Steiner trees depend on global knowledge, which is not available to survivors, building a Steiner tree is not practical.

We considered simple strategies to interconnect the evacuation centers and gateways, which could be implemented in a disaster recovery application. We set up a simulation based on spatial Poisson processes to determine the number of evacuation centers which are connected to the Internet and the relay-chain length per evacuation center for each strategy. Our analysis showed two promising strategies which do not depend on location information of all entities: `Direct`, in which each evacuation center sets up a relay chain directly to the closest gateway, and `Neighbor`(3), in which each evacuation center sets up relay chains to the closest 3 entities (evacuation centers or gateways).

Although both the `Direct` and the `Neighbor`(3) strategy seem viable for practical use, future work will have to run detailed simulations with channel models or even better field tests. Hopefully, this will lead to a software which allows survivors of a disaster to set up a disaster recovery network without preparation.

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