Extending network coverage by using static and mobile relays during natural disasters

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Abstract—**During natural disasters, such as earthquakes, a part of the Internet access infrastructure can be damaged, leaving many users disconnected. At the same time, many people need to communicate to find their relatives and receive official notifications about the current situation. This paper presents an evaluation of different techniques for extending network coverage in such scenarios. We use real-world data to model the power outage probability of cellular base stations in Tokyo area and combine it with information about batteries/power generators to create accurate maps of network coverage for different time periods after an earthquake. In our simulation, we use a real map of evacuation sites, provided by Japanese government. We first considered mobile nodes, moving between evacuation sites, and investigated their impact on network coverage. Then, we developed an algorithm to determine the optimal locations for static relays ensuring different levels of network coverage. Our results show that even a small number of fixed relays, carefully placed between the evacuation sites, can outperform a much higher number of mobile nodes in terms of network coverage.**

I. INTRODUCTION

During natural disasters, such as earthquakes, a part of the Internet access infrastructure can be damaged, leaving many users disconnected. The situation is very unstable, and the number of available base stations can vary substantially over time [12]. One of the main causes of such a situation is power outage. Shortly after an earthquake base stations can be powered by power generators or batteries. However, their lifetime is usually very limited and base stations disconnected from the main power supply shut down fast.

At the same time, during natural disasters, it is extremely important to provide connectivity. Public services want to provide information about evacuation sites, gathering areas, and the current situation. People also want to communicate with their relatives to find them or exchange news. Unfortunately, although people are supposed to gather at evacuation sites, some of these sites may be out of network coverage. Providing Internet access to sites out of the transmission range of working base stations is a difficult task. The distances between these sites are usually too large for direct WiFi communication (cf. Sec. III-B).

To extend Internet connectivity, many authors propose to use mobile devices belonging to people moving between sites to form multihop ad hoc networks [10]. However, such solutions do not assure full network connectivity, may be unable to provide enough bandwidth, and are inefficient during night when people stay at evacuation sites.

To provide full network connectivity with enough bandwidth and minimal use of resources, a combination of static relay nodes and mobile nodes is expected to work best. To investigate this conjecture, we perform extensive simulations based on evacuation sites in Tokyo area and analyse techniques to extend network coverage during disasters. We use real-world data to model the power outage probability of cellular base stations in Tokyo area and combine it with information about batteries/power generators to create accurate maps of network coverage for different time periods after an earthquake. In our simulation, we use a real map of evacuation sites, provided by Japanese government. Surprisingly, our results show that even a small number of fixed relays, carefully placed between the evacuation sites, can outperform a much higher number of mobile nodes. In addition, we observe that mobile nodes added to the static relays do not have a significant effect on network coverage.

The rest of this paper is organized as follows. Section II summarizes recent works in the field of network coverage after natural disasters. Section III presents preliminaries and models of service availability and evacuation sites used in our simulations. Section IV presents our methods for extending network coverage using mobile nodes, while section V focuses on using fixed relays and a combination of fixed relays and mobile nodes. Section VI concludes the paper and describes our future works.

II. RELATED WORK

Recent research in disaster-resilient networks contains many different approaches, as the needs of every situation can vary significantly. Q.T. Minh et al. propose extending network coverage with a solution based on network virtualization [11]. When connecting to the network, mobile phones download a small application allowing them to share the connection with other mobile devices and, thus, creating a multihop ad hoc network based on a tree structure. There is also a lot of effort toward using Wireless Mesh Networks in the context of public safety, disaster recovery, and crisis management communication [15]. However, this type of work usually focuses on gathering and processing data and does not consider providing network connectivity to the users. A similar approach is used to detect and monitor the environment in a flash-flood alerting system [2].

Sterbenz et al. developed a framework consisting of a resilience strategy, metrics for quantifying resilience, and evaluation techniques for Future Internet. It allows to test whether a topology is robust enough for a demanded QoS.

Kumar et al. [7] test the performance of DSR [6], AODV[13] and DSDV [14] protocols on topologies containing both fixed and mobile nodes. This approach, while being similar to ours, does not include any real-world data and focuses more on the protocols than the nodes themselves.

A study on relay placement was performed by Lloyd et al. [9]. In this work, a two-tiered network model has been proposed. Relay nodes are placed in the playing field to serve as cluster heads and to form a connected network topology for information dissemination at the higher tier. The relay nodes are capable of aggregating data packets from the sensor nodes in their clusters and transmitting them to the sink node via wireless multihop paths. The paper focuses on placing the fewest number of relay nodes in the playing field of a sensor network such that each sensor node can communicate with at least one relay node and the network of relay nodes is connected.

Other research consider a similar problem, but focuses on heterogeneous wireless sensor networks, where sensor nodes possess different transmission ranges [5]. This work comprehensively analyses the range of problems introduced by the different levels of fault tolerance (full or partial) coupled with the different types of path (one-way or two-way) and develops an approximation algorithm for node placement in such topologies.

English et al. [4] present an algorithm for Coordinated Relocation of gateways (CORE). Gateway relocation can be used in a set of actions to serve application-level requirements or to better manage the resource-constrained WSN. CORE strives to maintain communication paths among gateways while repositioning individual gateways to better manage the sensors in their vicinity.

Our work focuses more on investigating mobile and static relays placement and providing full network connectivity. However, unlike many other approaches, we verify our system using real-world data and in a specific scenarios.

III. PRELIMINARIES AND MODELS

This section presents our models of service availability and evacuation sites used in the simulations of the techniques for extending network coverage based on mobile nodes and static relays. All the simulations are performed on the ns-3 simulator.

A. Modeling Service Availability

To perform our simulations, we need to model network coverage after a natural disaster. Availability of base stations is influenced by many factors. However the main problem remains power outage [12]. Base stations usually can be backed up with batteries/power generators; however, their lifetime is also limited.

TABLE I
STATICS FOR DIFFERENT MAPS OF THE AREA.

Map	No. of sites	Min. distance	Max. distance	Avg. distance
Tokyo	**719**	**300m**	**26km**	**1.3km**
Tokyo Center	**675**	**300m**	**2km**	**800m**

In our model of network service availability, we leverage the work in [19], and take into account the following components:

- We take a map of the seismic intensity after the Tokyo Southern Earthquake (TSE), which divides the whole area into small regions and assigns an intensity to each small subregion.
- We find a correlation between seismic intensity and the probability of power outage by analysing data from previous natural disasters.
- We integrate the backup battery lifetime into our model. It allows us to create multiple service availability maps for different time periods.
- Finally, we integrate the power recovery ratio, also based on data acquired during previous earthquakes

This modelling allows us to create a set of maps of the Tokyo area with service availability probability for different time slots (6h, 12h ,18h and 24h) after an earthquake. During our simulations, we use this data to associate the evacuation sites with the corresponding service availability.

B. Evacuation Sites

After a natural disaster, people are supposed to gather at evacuation sites. Some of these sites will be connected to the Internet, while others not. In many works, the distances between evacuation sites are estimated or the authors use a fixed average distance [10]. Such an approach may greatly influence the final results.

As the base of our simulations, we considered a real map of the evacuation sites located in Tokyo. Table I presents statistics for these sites. It shows the number of sites on the map, minimum, maximum and average distance between each pair of sites. The data also contains the nearest neighbour of a site and the number of sites in WiFi range (set to 100m). Because a few of the evacuation sites are located far away from the city center and providing relays to connect them is costly (cf. Sec. IV), we decided to create a new map by ignoring the farthest sites. We call this map “Tokyo Center” and use it in our experiments. By slightly decreasing the number of evacuation sites (i.e., by 5%), we greatly reduce the average and maximum distance between the closest neighbors. As shown further in this paper, such a choice allows our methods to connect the sites much more efficiently.

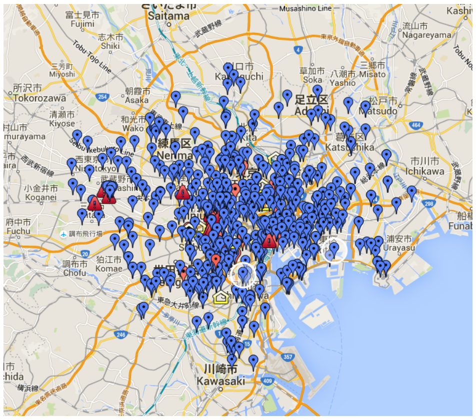

Fig. 1. Map of evacuation sites.

IV. MOBILE RELAYS

During a natural disaster, most people will remain at evacuation sites. However, a part of them will still move between the sites. There are also public service vehicles moving around the city. Mobile devices carried by the people and public vehicles can be used to extend the network coverage. While in most works mobile nodes move randomly and use straight paths between sites, we decided to use a real-world road map provided by Google Maps. In our simulations we query the Google API using the Routes Mobility Model [3]. At the beginning, each mobile node starts at a random evacuation site. As people usually move between sites located in the neighbourhood, we randomly choose a destination site within 1000m. The optimal path is acquired and the node moves with constant speed of 6km/h. Such a solution allows us to realistically model people movement during disasters.

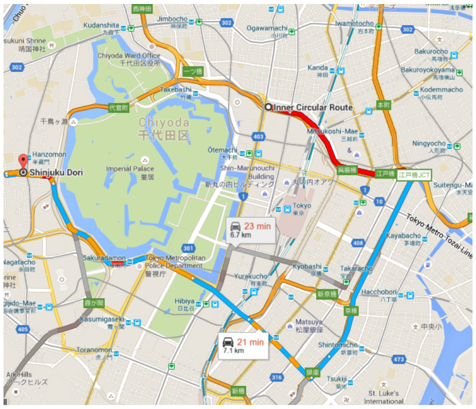

Fig. 2. A path between two evacuation sites obtained using Routes Mobility Model.

Fig. 3 presents the obtained results. Solid lines represent the results for the complete map of Tokyo's evacuation sites, while the dashed ones represent the map of the city center (cf. Sec. III). The tests were performed for different power outage probability map (6h, 12h and 18h after the earthquake). For each result, we present the average over at least 5 runs. Because mobile relays move randomly, we are not able to assure full connectivity even with a huge number of mobile relay nodes (100,000). The situation is significantly better for the city center map. However, we still require about 30,000 relays to connect 90% of the evacuation sites. Note that during this simulation the connectivity was tested using Dijkstra's algorithm, which assumes perfect conditions (no routing problems) and, in many cases, only a single path between nodes, which is not fault tolerant.

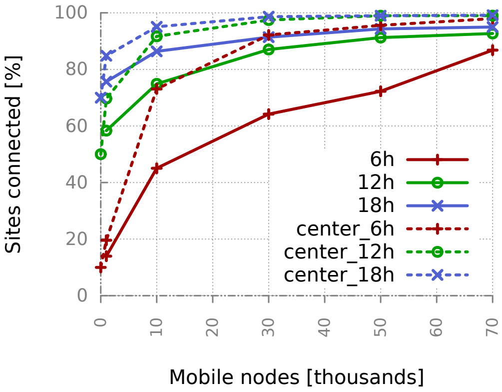

Fig. 3. Connectivity for different numbers of mobile relays.

V. FIXED RELAYS

Mobile nodes do not provide a reliable and realistic way to assure connectivity, given that too many nodes are needed for good connectivity. Especially during the night, the number of people walking on the street can decrease significantly. To provide a reliable way of extending network coverage, we propose to use static relays which can be placed in advance or after a disaster. There are many works focusing on efficient node placement for MANET/WSN [18] [16]. However, most of them cannot be applied in our case, as the presented scenarios do not fit our needs.

Our goal is to provide paths between the disconnected sites and those sites located in the range of the operating base stations. However, to provide enough bandwidth and connection reliability, single paths between sites are not sufficient. Therefore, our problem can be reduced to the k-connectivity problem in a *unity-disk graph*. k-connectivity means that we have at least k different paths between each pair of nodes in the network. The network is thus resistant to failure of $k-1$ nodes. More paths also increase the available bandwidth. This problem, with a requirement to use the minimum number of additional nodes, is proven to be NP-complete even for $k=1$ [8].

Let us consider an example presented in Fig. 4. Black nodes represent evacuation sites without Internet access, and red ones are the sites within the network coverage. An edge between two sites is established if they are within direct communication range. We want to establish 2-connectivity between every disconnected site and its closest node with Internet connection. The results are presented in Fig. 5. The

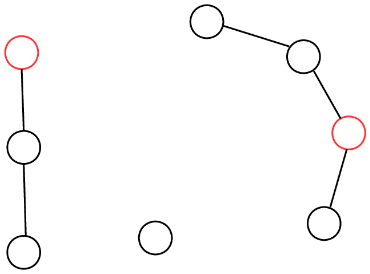

Fig. 4. Connectivity 1

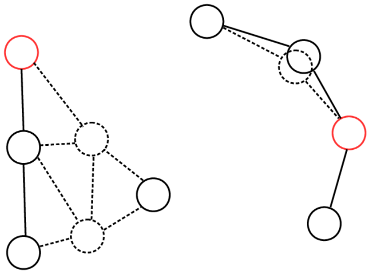

Fig. 5. Connectivity 2

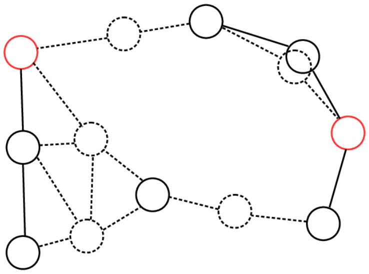

Fig. 6. Connectivity 3

figure show three additional static relays, which can forward the traffic. However, we want to avoid establishing a full k-connectivity in the network (cf. Fig. 6), as this means deploying too many relay nodes and increases the cost of the whole operation.

After a natural disaster, the situation can be very dynamic. Some sites can get disconnected, while others can have their Internet access restored. We adapt a heuristic solution, which is able to quickly find optimal positions for relay nodes and adapt to changing conditions [1]. In this work, the authors consider k-connectivity between all nodes in the network. We need to adapt this solution to our needs, which requires each disconnected node to have k-connectivity with one connected node.

Alg. 1 presents the original version of the solution. For simplicity reasons, we normalize the distances between the evacuation sites, such that the maximum considered WiFi range (100m) is 1. At the beginning, a fully connected graph K is computed, containing edges between every vertices in the network. The weight of the edge between two nodes v and w is defined as: $m[v,w] \leftarrow \lceil ||v-w|| \rceil - 1$, where $||v-w||$ is the Euclidean distance between v and w. The distance is thus zero for sites able to communicate directly. In other cases, it equals the number of relays necessary to connect them by a straight path. Then, we invoke K-CONNECTED-SUBGRAPH (k, K, m) (cf. Alg. 2) to compute the α-approximate minimum-weight k-connected spanning subgraph S of (K, m). In the third step, the edges in the new graph K are translated into positions of additional relays. m clusters of k collocated relays are placed along the line segment connecting the endpoints of each edge of weight m. Additionally, $k-1$ relays are placed at each endpoint of the edge.

```
input : $k$, set $V$ of vertices and their coordinates
$E \leftarrow \{(v,w)|v,w \in V, v \neq w\}$
$K \leftarrow (V,E)$
$m \leftarrow$ new $VxV$ array
for verticies $v, w \in V$ do
    $m[v,w] \leftarrow \lceil ||v-w|| \rceil - 1$
end
call K-CONNECTED-SUBGRAPH $(k, K, m)$ to
compute $\alpha$-approximate minimum-weight $k$-connected
spanning subgraph $S$ of $(K, m)$
for $(v,w) \in E(K)$ do
    for $i = 1, 2, ..., m[v,w]$ do
        $t \leftarrow i/(m[v,w]+1)$
        place $k$ relays at position $(1-t)*v+t*w]$
        place $k-1$ relays at position $v$
        place $k-1$ relays at position $w$
    end
end
```

Algorithm 1: K-Connecivity algorithm

Alg. 2 presents the pseudocode for the Greedy K-CONNECTED-SUBGRAPH routine. It consists of two stages. During the first one, we greedily add new edges until our graph is k-connected in ascending order (regarding edge weight). However, this step adds many unnecessary connections. To reduce the number of edges, during the second stage, we try to remove each edge in the graph in descending order. If it remains k-connected, the edge is permanently purged. However, if the graph looses its k-connectivity, the edge is put back. This process can remove up to 50-85% of the added edges [1].

```
input : $k, G = (V,E), m$
$G' \leftarrow (V, 0)$
$E' \leftarrow \{(v,w)|v,w \in V\}$
for $(v,w) \in E'$ in increasing order of $m[v,w]$ do
    $E(G') \leftarrow (E(G) \cup \{(v,w)\}$
    if $G'$ is $k$-connected then
        break
end
for $(v,w) \in E(G')$ in decreasing order of $m[v,w]$ do
    $G'' \leftarrow (V, E(G')\ \{(v,w)\})$
    if $G''$ is $k$-connected then
        $G' \leftarrow G''$
end
return $G'$
```

Algorithm 2: Greedy K-CONNECTED-SUBGRAPH

As stated before, in our simulations, we do not need full k-connectivity, we need to adapt the protocol to our needs. The modified version of the protocol is presented on Alg. 3. At the beginning, we divide the whole network into clusters. Each cluster C_i consists of an evacuation site in the transmission range of an operating base station c_i and a group of disconnected sites s_j for which c_i is the closest connected evacuation site.

$C_i : c_i, s_j, \forall_{k!=i}, ||s_j, c_i|| \leq ||s_j, c_k||$

The algorithm is then applied for each cluster separately. Unlike in the original version of the protocol, we add only edges between the connected site and all the other sites. The last modification is the procedure checking for k-connectivity (cf. Alg. 2). We test only k-connectivity between our cluster head and the disconnected sites.

```
input : $k$, set $V$ of vertices and their coordinates
$C* \leftarrow$ call SPLIT-INTO-CLUSTERS($V$)
for $C \in C*$ do
    if $|C| < k$ then
        k = $|C| - 1$
    $c \leftarrow$ clusterHead($C$)
    $E \leftarrow (v, w)|v, w \in C, v \neq w$
    $K \leftarrow (V, E)$
    $m \leftarrow$ new $1xV$ array
    for verticies $c, v \in V$ do
        $m[v] \leftarrow \lceil ||h - c|| \rceil - 1$
    end
    call K-CONNECTED-SUBGRAPH $(k, K, m)$ to
    compute $\alpha$-approximate minimum-weight
    $k$-connected spanning subgraph $S$ of $(K, m)$
    for $(v, w) \in E(K)$ do
        for $i = 1, 2, ..., m[v, w]$ do
            $t \leftarrow i/(m[v, w] + 1)$
            place a sensors at position $(1 - t) * v + t * w]$
        end
    end
end
```

Algorithm 3: Our modification of K-Connecivity algorithm

To check the k-connectivity in our network (i.e., check the number of independent paths between nodes - cf. Sec. V-A), we need to use an approximation based on Dijkstra's algorithm. It does not assure the discovery of all possible paths, but it achieves 99%-100% efficiency and substantially lower computational complexity [17]. We use the Dijkstra's algorithm to find the shortest path between two nodes, mark all nodes present in this path as "unavailable", increase the number of found paths by 1, and rerun the whole process. For each consecutive iteration, we eliminate some nodes from the network and the algorithm ends if no more paths can be found.

We used our algorithm to calculate the minimum number of additional static relays necessary to provide k-connectivity for different values of k. Fig. 7 shows the results.

Static relays, placed in optimal places are significantly more effective than mobile nodes moving randomly between the sites. To achieve 1-connectivity for the "Tokyo Center_6h" map, it is enough to place 879 nodes. On the same map even 10,000 mobile nodes achieve less than 90% connectivity. Achieving higher connectivity (higher values of k) requires significantly more nodes. As the time passes after an earthquake, more and more base stations get shut down; thus, the required number of additional relays is also much higher. For example, to achieve 4-connectivity after 24 hours have passed since an earthquake, we need to place 13052 relays.

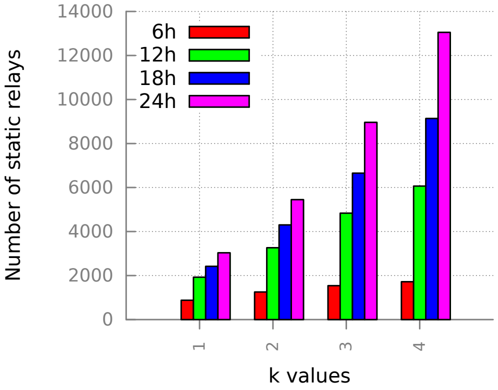

Fig. 7. Number of static relays required to achieve k-connectivity for different values of k and different time periods after an earthquake

To assure full 1-connectivity for the whole Tokyo area, we need significantly more nodes, as the average distances between sites are much larger.

A. *Final Simulation Results*

As the final step of our simulation, we wanted to obtain results for a combined solution that includes fixed and mobile relays together. In our previous experiments, we focused on assuring full k-connectivity. However, equally important is to provide enough bandwidth for the communication. If a network is k-connected, it means that we have at least k paths between every disconnected nodes and its closest cluster head. However, many of those nodes can have more such paths, thus increasing the available bandwidth. Experiments were performed using "Tokyo_center_12h_map". Fig. 8 presents the connectivity distribution for different values of k (which determine the number of static nodes used) and no mobile nodes. Increasing the value of k has a strong effect on connectivity distribution. For different values of k, most of the evacuation sites will have k and more paths to the closest connected site. The only exceptions are sites located in small clusters with number of nodes lower than k. Note, that increasing k value is achieved with a relatively small amount of fixed nodes (cf. Fig. 7).

Fig. 9 shows the connectivity distribution for $k = 4$ and different number of mobile nodes. We observe that increasing the number of mobile nodes has very little effect on providing paths to the closest cluster head. Even adding 15 000 mobile nodes does not significantly change the number of paths between sites.

VI. CONCLUSION AND FUTURE WORKS

We have presented our work on extending network coverage after natural disasters. We use data gathered during previous earthquakes in Tokyo area to model base station failure probability. We then verified the possibility of using both mobile

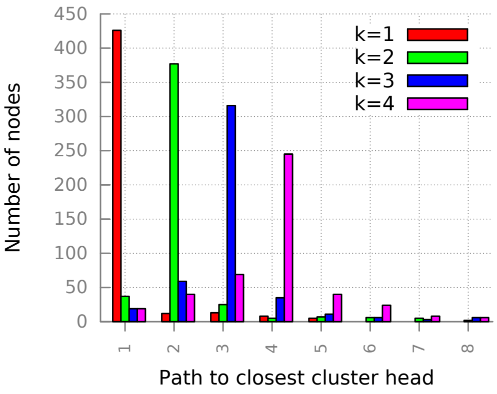

Fig. 8. Connectivity distribution for different k values.

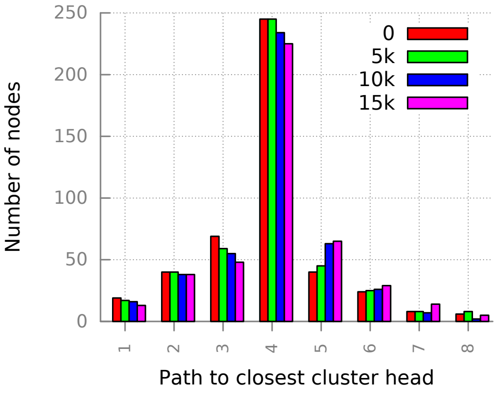

Fig. 9. Connectivity distribution for different numbers of mobile nodes.

relays and static relays to provide connectivity for every evacuation site. We also modified and adapted an algorithm allowing us to calculate the optimal positions for static relays. Our results showed that static relays are much more efficient and reliable way to extend network coverage. However, mobile nodes can still benefit from connectivity provided by static relays and locally increase available bandwidth.

In our future work, we plan to extend our simulations to test the behaviour of different routing protocols [6] [13] [14] in different scenarios. We also plan to verify our simulation results in a real-world scenario for clusters created by our algorithm. Finally, we will perform a more extensive study of the traffic patterns, including the capacity of evacuation sites, and integrate the results into this research.

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