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Capacity-aware Cost-efficient Network Reconstruction for Post-Disaster Scenario

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***Abstract*—Natural disasters can result in severe damage to communication infrastructure, which leads to further chaos to the damaged area. After the disaster strikes, most of the victims would gather at the evacuation sites for food supplies and other necessities. Having a good communication network is very important to help the victims. In this paper, we aim at recovering the network from the still-alive mobile base stations to the out-of-service evacuation sites by using multi-hop relaying technique. We propose to reconstruct the post-disaster network in a capacity-aware way based on prize collecting Steiner tree. The purpose of the proposed scheme is to achieve high capacity connectivity ratio in a cost efficient way. To provide more accurate evaluation results, we evaluate the proposed scheme by using the real evacuation site and base station data in Tokyo area, and utilizing the big data analysis based post-disaster service availability model.**

I. Introduction

The importance of communications was shown in many catastrophic natural disasters, such as the Great East Japan Earthquake on March 11, 2011, and the Typhoon Haiyan in the Philippines on November 8, 2013. Failure in communication and information exchange would lead to further chaos and crises in post-disaster scenarios. Unfortunately, large-scale disasters can damage the communication infrastructure even in well developed countries, e.g., Japan. According to the official report of Japanese government [1], a total of approximately 11.9 million fixed communication lines and $29,000$ base stations were damaged during the 2011 Great East Japan Earthquake. Specifically, Fig. 1 depicts the changes in the number of disabled mobile base stations during that earthquake [1]. It is obvious that a great number of mobile base stations were disabled during the first 24 hours after the earthquake occurred. The major reason for that is the lack of power, which accounts for as much as 85.3% in total. Without a working communication infrastructure, the disaster victims with communication devices such as mobile phones, tablets and so forth on hand, could not share their safety status with or get updated information from the government.

After the disaster strikes, the people in the affected area are supposed to gather at *evacuation sites*, e.g., local community centers or schools. Such evacuation site has a disaster store-

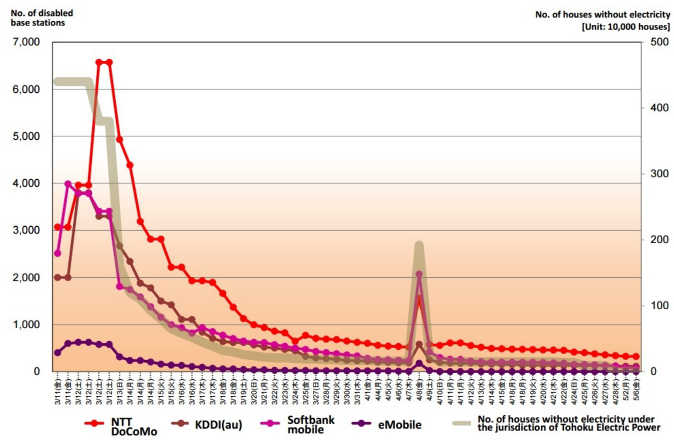

Fig. 1. Changes in number of disabled mobile base stations after the Great East Japan Earthquake [1].

house keeping necessary food supplies and other necessities to support living for a certain time period. For instance, there are around $3,900$ evacuation sites in Tokyo, which are managed by the Ministry of Land, Infrastructure, Transport and Tourism [2]. The evacuation sites are supposed to be safe in terms of food, water and other necessities, however, large part of them probably gets disconnected from the network due to the aforementioned damaged to communication infrastructure.

In this paper, we investigate the network recovery issue for post-disaster scenario, where part of the communication infrastructure is damaged. Without loss of generality, we consider to recover the network from the still-alive base stations to the disconnected evacuation sites by exploiting multi-hop relaying technique. There are two distinguishing features for the considered post-disaster network reconstruction issue. Firstly, the evacuation sites vary dramatically in terms of capacity and density. For instance, in Tokyo area, the capacities of evacuation sites vary from 18 people to $43,900$ people, and the distance between two nearest sites ranges from 300m to $26,000$m. Secondly, the first responders who are in charge of the network recovery generally have limited deploying hardware resource or time. To connect more evacuation sites with large capacities with limited deploying budget, we propose a capacity-aware and cost-efficient network reconstruction scheme for post-disaster scenario. To the best of our knowledge, this is the first work to take into considerations both evacuation sites' heterogeneity and deploying cost constraint. The purpose of the proposed scheme is to maximize the connectivity ratio in terms of evacuation sites' capacity, at a given deploying resource budget in terms of limited number of relay nodes. To obtain realistic evaluation results, we use the real evacuation site and base station data in Tokyo area, and utilize a post-disaster service availability model that is based on big data analysis.

The rest of the paper is organized as follows. We present the related work in Section II. In Section III, we introduce the network and service availability models, and in Section IV, we present the proposed network reconstruction scheme in detail. Evaluation results are provided in Section V. We conclude this paper in Section VI.

II. Related Work

Disaster recovery network construction has been an active research field recently. Sun *et al.* [3] proposed a network architecture for post-disaster scenario which is composed of cognitive radio vehicles. It could provide critical wireless connectivity of general public and emergency responders. Casoni *et al.* [4] proposed an architecture based on the integration of satellite and LTE networks to address the vulnerabilities of the network infrastructure in major disaster scenarios. It deploys mobile units that bring LTE coverage to the disaster area through a satellite backhaul. These two solutions [3, 4], however, are expensive and suffer from additional requirements of dedicated hardware. Nishiyama *et al.* [5] proposed a multihop device-to-device communication network system that allows the victims to send out emergency messages from far away disconnected areas. This work focused more on processing and routing protocols than the network architecture such as relay node deployment. Ngo *et al.* [6] investigated the spectrum and energy efficiency problems in a movable and deployable resource unit based disaster resilient network. This work mainly focused on theoretical aspects such as finding the top k spectrum efficient paths in polynomial time.

Our research group also devotes considerable effort to this research topic [7–10]. Minh *et al.* [7, 8] proposed a novel on-the-fly approach to establish the multi-hop wireless access network for disaster recovery, which is effective, fast and transparent to ordinary users. They focused on the implementation issues such as naming and addressing, and left the network construction issue as the future work. To address the network construction issue, Herlich *et al.* [9] compared the distributed and centralized network constructing schemes by running a simulation where the locations of evacuation sites are randomly generated. And Krol *et al.* [10] verified the possibility of using both mobile and static relay nodes to construct the recovery network by performing simulations based on real world data. However, reconstructing the post-disaster network with the consideration of evacuation site's heterogeneity and limited deploying resource is still a whitespace.

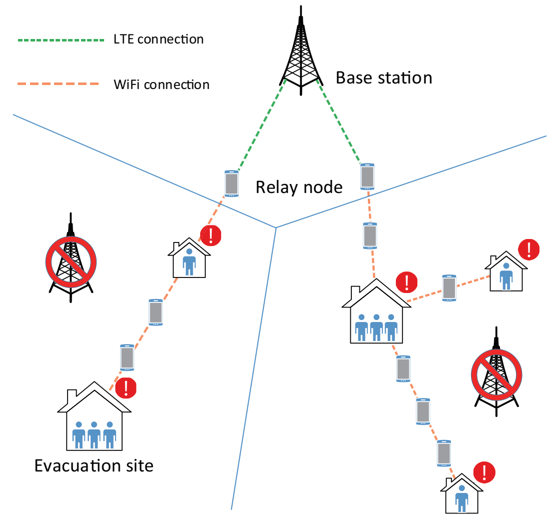

Fig. 2. Disaster recovery network model (The rays from the center depict the coverage area of each base station).

III. System Model

A. Network Service Availability Model

For post-disaster scenario, we need to model the network service availability after a disaster. In this paper, we adopt our group's recent work [11] on the service availability estimation after a considered earthquake, which is based on the big data analysis of the previous earthquakes. This model jointly considers the essential factors in the earthquake such as seismic intensity, building and power outage information, and outputs the spatiotemporal changing service availability. In this paper, we adopt Tokyo Southern Earthquake model [12], which is regarded as the most harmful one that is likely to strike Tokyo in recent future.

B. Network Model

Our network model consists of evacuation sites where the people in the affected area are supposed to be located after the disaster occurred, and mobile base stations who act as the gateways to the Internet. Based on the service availability model [11], we could obtain the set of out-of-service evacuation sites as $\{A_1, \ldots, A_m, \ldots, A_M\}$, and the set of still-alive base stations as $\{B_1, \ldots, B_n, \ldots, B_N\}$. As shown in Fig. 2, we construct a heterogeneous network to connect those out-of-service evacuation sites to the still-alive base stations with K relay nodes. The considered heterogeneous network consists of both LTE and multi-hop WiFi networks. On one hand, the still-alive base stations communicate with the relay nodes within their transmission range R_{LTE} in LTE transmission mode (green links in Fig. 2). On other hand, those connected relay nodes offer tethering over WiFi, provide network connections to the evacuation sites by multi-hop wireless virtualization technique [7] which is performed in WiFi transmission mode[1] (orange links in Fig. 2). We denote

[1]As currently Device-to-Device (D2D) communication in LTE mode has not become available yet, here we assume communication between two relay nodes can only be done by using WiFi.

the transmission range in WiFi mode as R_{WiFi}.

C. Characteristics of the Problem

The considered problem has two characteristic features. On one hand, in the previous work [7–10], a homogeneous network scenario is assumed where users or sites to be connected are identical. However in reality, the capacities of the evacuation sites vary dramatically, e.g., from 18 people to 43,900 people in Tokyo area [2]. Therefore, it is of great importance to take the heterogeneity of the evacuation sites into consideration. On the other hand, in post-disaster scenario, it is unrealistic to assume that the first responders who are in charge of the network recovery have unlimited resources. Generally, they have limited deploying time or limited hardware resource. Therefore, it is critical to reconstruct the network in a capacity-aware and cost-efficient way.

IV. Proposed Prize Collecting Steiner Tree based Scheme

A. Centralized Scheme

In this section, we propose a prize collecting Steiner tree based scheme to reconstruct the post-disaster network. The purpose of the proposed scheme is to maximize the connectivity ratio in terms of the evacuation sites' capacities (called capacity connectivity ratio for short in the remainder), at a given cost budget in terms of the number of deployed relay nodes. The proposed scheme is centralized which requires all the location and capacity information of the out-of-service evacuation sites, and the location information about the still-alive base stations in the considered area. The recovery could be performed by government's first responder teams or mobile network operators. The proposed scheme consists of two main steps as follows.

1) Construct the Graph: The first step is to construct a vertex-weighted and edge-weighted undirected graph $G = \{V, E, p, c\}$. Specifically, we have

- *Vertex*: $v \in V$ where V is the set of vertices. In our case, V consists of two kinds of vertices, i.e., *original vertices* and *virtual vertices*. Each out-of-service evacuation site A_m $(1 < m < M)$ is regarded as an original vertex v_m in G. All the still-alive base stations $\{B_1, \dots, B_n, \dots, B_N\}$ form a virtual vertex v_0, i.e., $v_0 = \{B_n \mid 1 \le n \le N\}$. The reason is that the still-alive base stations are supposed to be connected with each other by backhaul infrastructures. Therefore, there are totally $M + 1$ vertices in graph G.
- *Edge*: $e \in E$ where E is the set of edges. In our case, the graph G is fully connected, i.e., there exists an edge $e(v_i, v_j) \in E$, $\forall v_i \in V$, $v_j \in V$, $i \neq j$. There are totally $M(M + 1)/2$ edges in graph G.
- *Prize*: $p(v)$ assigns a non-negative weight to each vertex v. In our case, the prize for the original vertex v_m is set to its corresponding evacuation site A_m's capacity, and that for the virtual vertex v_0 is set to a largely enough value, i.e., v_0 has maximum prize.
- *Cost*: $c(e)$ assigns a non-negative weight to each edge e. In our case, the cost $c(e)$ is defined as the number of relay nodes needed to connect the two vertices of edge e, which is inspired by the Steinerization technique proposed in [13]. Specifically, the cost of the edge that connects two original vertices v_m and v'_m is calculated by $\lceil (d(e(v_m, v'_m)) - R_{WiFi})/R_{WiFi} \rceil$, where $d(e)$ is the Euclidean length of edge e which is calculated by the coordinates of vertices. The cost of the edge that connects virtual vertex v_0 to an original vertex v_m is equal to $\lceil (d(e(v_0, v_m)) - R_{LTE})/R_{WiFi} \rceil$, if $d(e(v_0, v_m)) > R_{LTE}$, and 1 if $d(e(v_0, v_m)) \le R_{LTE}$. Here, the distance $d(e(v_0, v_m))$ is measured as the distance from the evacuation site to the closest base station in the virtual vertex, $d(e(v_0, v_m)) = \min_{B_n \in v_0}(d(e(B_n, v_m)))$.

2) Solve the Prize Collecting Steiner Tree Problem: The second step is to find the optimal prize collecting Steiner tree over the constructed graph G. The prize collecting Steiner tree is a mathematical optimization problem useful to describe the need to connect a number of weighted elements with the minimum connecting cost. In our case, we find a subtree $T' = (V', E')$ of G that *minimizes λ times the sum of the vertex prizes not included in the tree T' and plus the sum of the edge cost in the tree T'*, i.e., minimizing the objective function:

$$f(T') = \lambda \cdot \sum_{v \notin V'} p(v) + \sum_{e \in E'} c(e), \tag{1}$$

where λ is a factor who tunes the tradeoff between the prizes and costs. Note that

$$\sum_{v \notin V'} p(v) = -\sum_{v \in V'} p(v) + const, \tag{2}$$

so that minimizing $f(T')$ is equivalent to collecting the largest set of high prize vertices while minimizing the set of large cost edges in a tradeoff tuned by λ. Remind that in our case, the prize of a vertex represents the capacity of an evacuation site, and the cost of an edge represents the required number of relay nodes in a link. Therefore, the prize collecting Steiner tree problem accurately models our capacity-aware cost-efficient network reconstruction problem.

By minimizing Eqn. (1) with an appropriate λ, we could maximize the capacity connectivity of the network at a given budget for relay nodes. Specifically, for any given relay node budget K, we solve Eqn. (1) with an initial λ value. If the sum cost of the second term in Eqn. (1) exceeds our budget for relays, we need to reduce λ. If it is under our budget for relays, we can increase λ. Therefore, we can perform bisection on the value of λ to get a good solution for any given K.

Due to the NP-completeness of prize collecting Steiner tree problem, we adopt the non-rooted GW approximation algorithm [14] which could achieve an approximation ratio of $2 - \frac{1}{|V|-1}$. The algorithm consists of a growth phase and a pruning phase. In the growth phase, it loops to grow a forest of edges that is initially empty. At each iteration, the algorithm either merges two components into a new one or deactivates a component. In the pruning phase, the vertices are removed from the root component based on the order in which certain events occurred during the growth phase. The precise details

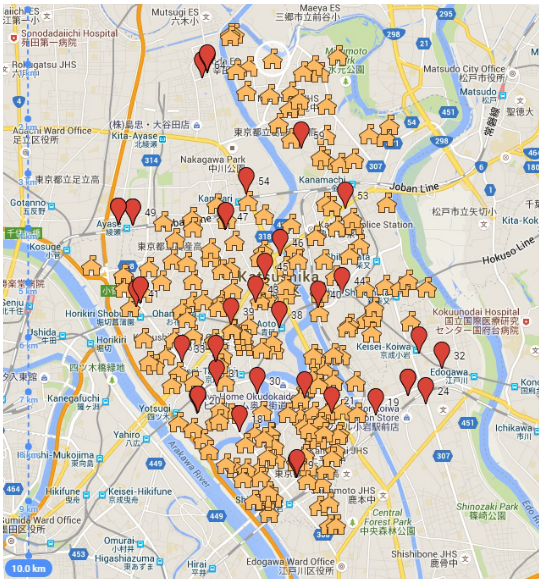

Fig. 3. Evacuation sites and base stations in Katsushika ward. The house icons denote the evacuation sites and red dot icons denote the base stations.

of the GW algorithm is omitted in this paper, the reader who is interested could refer to [14].

B. Distributed Extension

When the damaged area is too large or the global knowledge is unavailable, the proposed scheme could be distributively implemented by clustering. We consider two different cases as follows.

- Case 1: the network reconstruction is performed by multiple first responder teams, since the area to be recovered is too large. In this case, the number of clusters is determined by the number of first responder teams. Specifically, the whole area could be divided into several grids, and the still-alive base stations and out-of-service evacuation sites are assigned to different grids based on their coordinates. The first responder teams run the proposed scheme according to their relay node budget, and reconstruct the networks of the grids that they are responsible.
- Case 2: the network reconstruction is performed by victims themselves where the global information is unavailable. In this case, the relay nodes could be victims' unused wireless devices. Due to the lack of global information, the victims in each out-of-service evacuation sites need to find the location of its closest still-alive base station, which could be obtained by [15] that suggested in [9]. Then, the still-alive base station is aware of which out-of-service evacuation sites try to get connected to it. Upon this, it collects all the unused wireless devices as the relay node budget and acts as the cluster head to run the reconstruction scheme.

V. Evaluation Results

In this section, we evaluate the proposed capacity-aware cost-efficient network reconstruction scheme in a real world

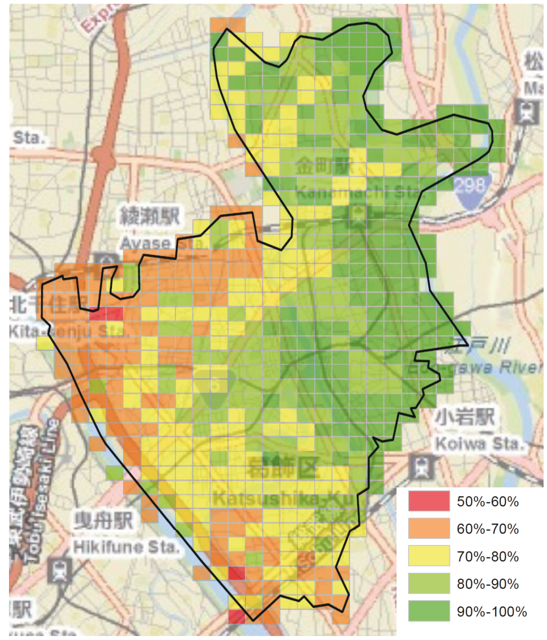

Fig. 4. Estimated network service availability in Katsushika ward in 24 hours after the earthquake.

scenario. Specifically, we adopt Katsushika ward which ranks 9 by population and 7 by area in all 23 wards of Tokyo[2]. As shown in Fig. 3, there are approximately 190 evacuation sites [2] and 30 mobile base stations[3] [16] in this ward. Based on the availability model [11], we could obtain a map that consists of multiple 250m × 250m grids with respective service probability value in different time period. For instance, Fig. 4 shows the network service availability in Katsushika ward in 24 hours after the earthquake. Based on this map, we generate 50 different possible topologies for post-disaster Katsushika ward. Therefore, all the evaluation results are averaged by 50 trials. In the evaluation, the distributed scheme is performed based on case 2, where every still-alive base station acts as the cluster head, and the out-of-service evacuation sites are assigned to the clusters based on the closest distance. For simplicity, we consider the communication ranges of the access point in evacuation site and the deployed relay node $R_{WiFi} = 100$m (based on WiFi outdoor transmission range), and that of the base station $R_{LTE} = 500$m (based on 3GPP standard [17]).

Figs. 5 and 6 demonstrate the capacity connectivity ratio varying with the number of deployed relay nodes for different time periods after the earthquake of the centralized and distributed schemes, respectively. It is straightforward that we could obtain higher capacity connectivity ratio with higher cost budget. For the considered post-disaster scenario, it is critical to investigate the tradeoff between the achieved capacity connectivity ratio and the cost constraint. As shown in Fig. 1, the mobile service unavailability increases sharply in the first 24 hours after the earthquake. Therefore, to achieve

[2]The reason we do not evaluate the whole Tokyo area is that the evacuation site capacity information in some wards are still unavailable.

[3]We use one of the three main mobile operators' data in this paper, since the other two are unavailable right now.

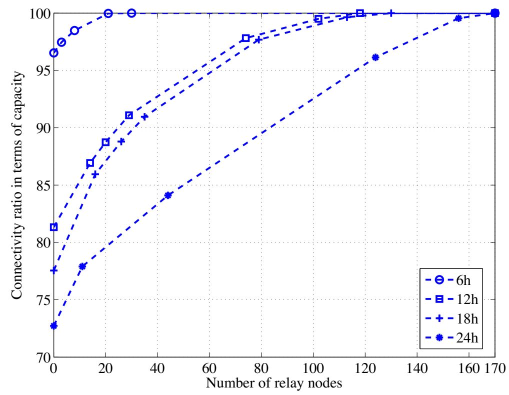

Fig. 5. Number of relay nodes required to achieve different capacity ratio for centralized scheme at different time period after the earthquake.

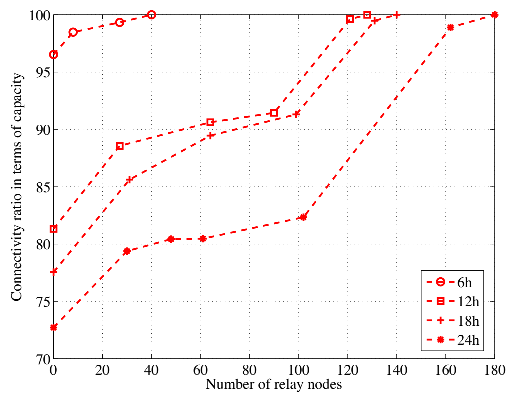

Fig. 6. Number of relay nodes required to achieve different capacity ratio for distributed scheme at different time period after the earthquake.

the same connectivity ratio, we need to deploy more relay nodes after 24 hours than that after 6 hours. For instance, to guarantee 99% capacity connectivity ratio, for centralized scheme in Fig. 5, we need to deploy 158 and 25 nodes after 24 and 6 hours, respectively. For distributed scheme in Fig. 6, we need to deploy 175 and 35 nodes after 24 and 6 hours, respectively. Comparing the centralized scheme with the distributed scheme, as we expected, the skylines of the centralized scheme is more cost-efficiently. Since the forest that generalized by the distributed scheme is based on the clustered graph instead of the original one.

In Fig. 7, we depict the required number of relay nodes for different capacity connectivity ratio at 24 hours after the earthquake. We could observe that the centralized scheme always outperforms the distributed one. For instance, to improve the capacity connectivity ratio from 80% to 85%, the distributed scheme requires about 70 additional nodes, which is only around 20 for the centralized scheme. In other words, for a given deploying resource budget, the centralized scheme could achieve better connectivity ratio compared to the distributed one.

In Fig. 8, we show the number of hops in the longest path from an out-of-service evacuation site to a still-alive base station. We can observe that although the distributed

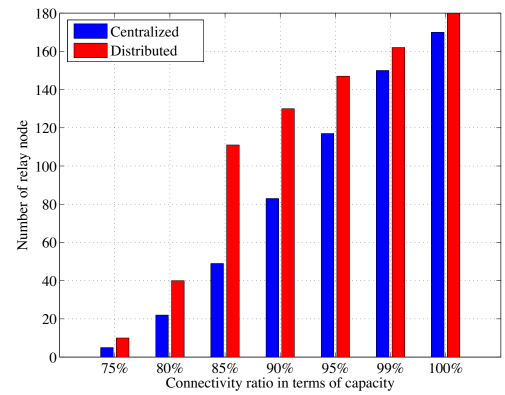

Fig. 7. Comparison of required number of relay nodes between centralized and distributed schemes. (24 hours after the earthquake).

scheme performs worse in the connectivity-cost tradeoff, they could reduce the length of the longest path in the constructed network compared to the centralized scheme. The reason is that for the distributed scheme, the longest path from the base station to the evacuation site is restricted by the cluster size. For the 24 hours case, the number of hops in the longest path for the centralized scheme is around 15, which is questionable to achieve for multiple relaying technique based on our group's experiment results [8]. In [8], it is verified that the network services worked well when the path length is less than 9 hops in the indoor 50m hop-distance experiments, and 15 hops in the outdoor 30m hop-distance experiments, respectively. Therefore, for the recovered area like Kashitsuka ward or even larger area, it would be more appropriate to divide the target area to two or more clusters, and run the scheme distributively.

At last, we show the computation time for the centralized and distributed schemes, respectively. The running environment is Intel Core i7-3770 CPU at 3.4 GHz and Windows 8.1 operating system. Since the evaluation is only performed based on one ward in Tokyo, both schemes' running time is negligible. However, if we run the centralized algorithm on the whole Tokyo area with about $3,900$ evacuation sites, the computation time will increase exponentially. In that case, it would be more appropriate to utilize the distributed scheme to reconstruct the post-disaster network.

VI. Conclusions

In this paper, we have proposed a capacity-aware and cost-efficient network reconstruction scheme for post-disaster scenario. To the best of our knowledge, this is the first research on disaster recovery network that takes into considerations the heterogeneity of evacuation sites and limited deploying resource. The proposed scheme is based on prize collecting Steiner tree, which accurately models the tradeoff between the capacity connectivity ratio and the deploying cost. To obtain realistic evaluation results, we have utilized the service availability model that is based on big data analysis on the previous earthquakes, and used the real world data in Tokyo area.

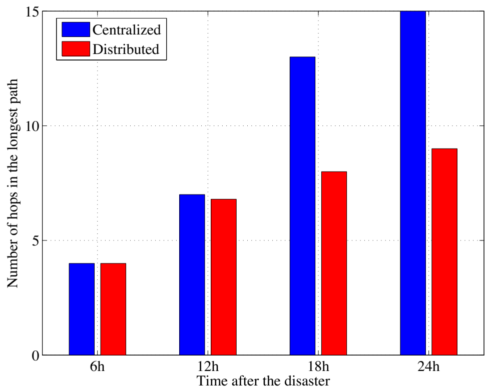

Fig. 8. Comparison of number of hops in the longest path between centralized and distributed schemes. (When 99% capacity ratio is achieved).

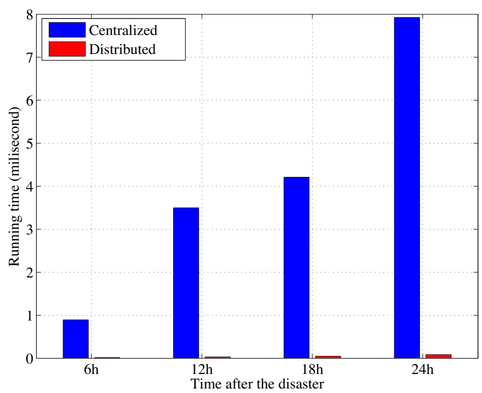

Fig. 9. Comparison of running time between centralized and distributed schemes. (When 99% capacity ratio is achieved).

Interestingly, the evaluation results show that to recover an area like Kashitsuka ward, the centralized scheme could achieve good capacity connectivity but with a questionable longest path length. Therefore, for large recovery area, it would be more appropriate to divide the target area into several clusters and, run the reconstruction scheme distributively. In our future work, we intend to test different routing algorithms in the constructed network, and also consider the case that relay nodes cannot be deployed in arbitrary positions.

ACKNOWLEDGMENTS

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