Targeted Emergency Network Services Deployment Algorithm for Disaster Relief Agencies

Hengky Susanto[1], Jonatan Lassa[2], Benyuan Liu[1], and ByungGuk Kim[1]
[1] Department of Computer Science, University of Massachusetts at Lowell, US
[2] Nanyang Technology University, Singapore
Email: [1] *{hsusanto, bliu, kim}@cs.uml.edu*, [2] *isjalassa@ntu.edu.sg*

Abstract — When natural disasters strike, network infrastructure is often completely destroyed, disabling communication; this significantly hampers rescue and relief efforts. Therefore, emergency communication network infrastructure must be deployed to provide communication at ground zero to rescue and relief agencies. The deployment strategy has to consider these humanitarian agencies' varying degrees of responsibilities which correspond to their levels of communication needs. In this paper, we propose a more precise deployment of emergency communication network based on our field study of how relief organizations collaborated at ground zero in Aceh, Indonesia, post Tsunami 2004. Building on our field findings, the emergency communication deployment is formulated to a *k-Weighted Deployment* problem, achieving a more customized delivery of communication network services to organizations according to their varying level of responsibilities and communication needs, including resource provisioning strategy. Finally, we devise a two-stage implementation protocol to achieve the objective of a more effective and targeted deployment to areas affected by natural disasters.

Index Terms — network deployment, natural disaster, disaster resilient communication infrastructure.

I. INTRODUCTION

In many regions and countries, especially developed ones, critical public infrastructure and support services are designed and maintained to withstand some or most of the impact of major natural disasters, such as earthquake, flooding, hurricane, etc. Then, there are regions in parts of the world where these infrastructure and services have not been built or maintained with similar care and robustness. In these regions, in the unfortunate occurrence of colossal disasters, there is very little surviving critical infrastructure, including network infrastructure. The absence of a working network infrastructure will disable communication, hampering rescue, relief and reconstruction efforts. The emergency network deployment solutions presented in this paper are motivated by, and founded on key findings from a field study on the relief and recovery efforts in Aceh, Indonesia, one of the most severely hit regions by the Tsunami in 2004.

Most existing literature on emergency communication network infrastructure deployment assumes there is some level of surviving communication infrastructure post natural disasters [3,4,5,6,10,11]. Their deployment proposals therefore, rely on these surviving infrastructures. Our paper, on the other hand, attends to situations where the entire communication infrastructure is completely destroyed by a catastrophic natural disaster, a condition that is common in developing countries like Indonesia. Our field study discovers that social and cultural factors lead to inferior infrastructure designs and maintenance. As a result, inferior infrastructure contributes to the total annihilation of communication infrastructure when a significant natural disaster strikes. Further, deployment of emergency communication infrastructure often requires 6-8 weeks administrative and logistics lead time to deliver the network devices to ground zero [17]. The extensive delay leaves relief agencies at ground zero with very minimal, or no communication services during this time, endangering their rescue and relief missions.

With such scenario in mind, we propose deployment strategy and implementation protocol to provide emergency communication services that is considerate to the urgent and varying communication needs amongst humanitarian agencies. The paper begins with a discussion on the social and cultural causes that lead to total destruction of communication network infrastructure as observed in Aceh post-Tsunami in 2004. Next, we present the most important lesson learned from the field study: Social network of collaboration shows that the relief organizations on ground zero have different levels of responsibilities, which results in varying level of communication needs. This finding becomes the cornerstone for our deployment solutions. We formulate the network deployment problem into *k-weighted deployment* (*k*-WD) problem. We propose a solution to solve *k*-WD for a more targeted and accurate network device deployment based on varying levels of communication needs. Since different devices have different strengths, we propose a scheme to assign devices to agencies according to each agency's level of responsibilities. Additionally, the inter-organizational collaboration pattern is incorporated into our proposed *Lagrange form*-based bandwidth provisioning algorithm. Then, simulation is used to demonstrate how relief agencies' varying levels of responsibilities influence resource provisioning. Lastly, based on our field study findings, and proposed deployment and bandwidth allocation strategy, we design an implementation protocol that include anticipatory actions so that when the emergency situation arises, network providers are able to make more immediate and informed decisions to deploy and manage the network services in stricken zones.

The main advantage of our proposal is that the implementation is scalable and adaptable: it can be enlarged or reduced according the areal size of regions affected as well as the number of relief agencies involved. Just as important, the deployment can be easily adjusted according to changes in the communication needs throughout the duration of the rescue and relief missions. The remainder of the paper is structured as follows: in section II, we review related work and the causes of total annihilation of communication infrastructure. The social network of inter-organizational collaboration is presented in section III. In section IV, we discuss the deployment strategies, followed by the simulation and implementation in section V and VI. Finally, we conclude the paper in section VII.

II. Background

A. Related Work

So far, most of the existing discussions on emergency communication network using portable network devices assume the presence, and takes advantage of surviving infrastructure. Authors of [4] propose a solution for wireless mesh network technology to relay network traffic to the closest functioning base station via surviving wireless routers installed in resident and commercial buildings in the disaster zone. In [5], routers are equipped with the capability to autonomously re-route network traffic through surviving routers and base stations to the nearest network devices outside disaster zone. Similarly, in [10], to improve the equipment's survivability, the Japanese telecom incorporates redundancy into their network infrastructure design, which includes redundant multiple routing paths. In addition, Japanese telecom also has mobile emergency communication units that utilize surviving underground optical fiber connection to retain bandwidth from the core network [3]. In other words, the optical fiber connection is expected to withstand natural disasters. However, these proposed network emergency deployment strategies in [3,4,5,11] may be ineffective when communication infrastructure is completely destroyed. Authors of [6] in their proposed deployment strategy seek to achieve maximum throughput without relying upon surviving infrastructure. However, the solution assumes physical accessibility for the deployment, which is unlikely to be the case in the aftermath of a major disaster.

In other words, as this paper is written, there has not been substantial literature on systematic emergency network deployment and management in disaster zones where network infrastructure is completely destroyed. Our paper seeks to contribute to the discussion of emergency communication services by specifically considering the absence of surviving communication infrastructure, and assumes challenging terrain accessibility.

B. Causes for Total Destruction of Infrastructure

One of the key findings from the field research in Aceh is that social and cultural factors contribute significantly to inferior network infrastructure designs and conditions, leading to their low survivability and eventual total destruction catastrophic natural disaster strikes. Firstly, despite the region's vulnerability to natural disasters, people continue to choose to reside there because it is believed to be a sacred site. Since infrastructures tend to be constructed where communities are established, when communities choose to reside in vulnerable regions, infrastructure survivability is compromised or diminished. In addition, it is a common belief among the people that natural disasters are a divine act, forming the attitude of either total reliance on divine protection and/or resignation to fate. As a result of these attitudes and beliefs, long-term durability is not considered to be an important factor in the design and construction of infrastructures.

Further, public infrastructures were also often found to be unreliable, and neglected. It is reported in [7] that 78% of wireless towers located outside the main islands of Java and Bali were found to be unreliable due to an average of 4 hours of power outage per day. Some towers are equipped with backup generators but transporting diesel fuel to run the generator is challenging due to a lack of proper roads. Also, corruptions within the government lead to compromises in the design, management and maintenance of public facilities [8]. Local realities and characteristics like these call for network providers to consider the likelihood of very little or no surviving infrastructure when providing emergency communication services to vulnerable regions like Aceh.

III. Inter-Organizational Collaborations

When the devastating earthquake struck off the northeast coast of Aceh on December 26, 2004, nearly 800 local and international disaster relief agencies responded and came to Aceh. Our study reveals an extensive and intricate social network of collaborations and transactions amongst these relief agencies. For example, the Red Cross agency not only provided food and temporary shelters to survivors, they also collaborated with Doctors Without Borders for medical services, with communication companies like ATT and Cisco to supply emergency communication services, and various engineering firms to recover survivors trapped underneath rubbles. Beyond identifying the linkages between agencies, the study of the network of inter-organizational collaborations provides us with two other important information and these become the cornerstone for our proposed emergency network deployment:

- Social network of collaboration identifies which agencies play the more central coordinating roles;
- It also identifies the different degrees of communication needs in various areas of the disaster zone.

These insights on the social network of inter-agency collaborations are based on our analysis of financial transactions among hundreds of relief agencies at ground zero in Aceh. Data of financial transactions was collected by one of the authors while assisting Aceh-Nias Rehabilitation and Reconstruction Agency in Aceh, and this includes: over 1300 financial transactions during the period of 2005 to 2009, financing over 5000 relief projects that involved 797 local and international agencies. Collaborations between larger and/or international humanitarian institutions were frequently observed in the financial data. For example, organizations such as United Nations, World Relief, Red Cross, might have the financial resources but did not always have the required expertise, and/or local knowledge and/or access needed on the ground. Therefore, they often financially supported the work of more specialized, or smaller or local agencies, such as neural surgeons from Doctors Without Borders or civil engineers from various engineering firms. While email trails would have provided a more comprehensive source of evidence of such collaboration network, acquiring such information was impossible due to the sensitivity of email contents. To compensate for this, one of the authors during one of his visits to Aceh took additional steps to confirm that the financial transaction data collected provided reliable approximation of the reality on the ground.

Fig. 1: Collaborative social network graph of financial distribution.

The collaboration network is illustrated in figure 1, consisting of nodes with different sizes and shade intensities (from white to black) connected by edges. Each node represents one relief agency on the ground. Lighter color and larger size dots are nodes with higher number of incident edges, and conversely, nodes with the darkest shade and of the smallest size are those with the least number of edges. An edge connecting any two nodes implies at least one occurrence of financial transaction between the two agencies, which is interpreted as collaboration between them. In other words, white color dots are the nodes (agencies) with highest number of inter-organizational transactions and collaborations: they are the largest nodes in the graph with the highest number of incident edges.

Next, we observe that the social network graph of collaboration is actually comprised of many clusters of varying sizes, each with a central node as the hub, connected to other nodes in the cluster forming a star or a hub-and-spoke shape. The central node is always of a lighter shade and larger size than other members in the cluster. These hub nodes represent agencies undertaking the central roles of managing or coordinating other agencies in each cluster. We refer to them as lead agencies. In other words, agencies worked in groups, led by a lead agency. Studies [13,14] affirm that relief agencies are often arranged to work in groups according to their functions, such as shelter, health, food distribution, etc.

More importantly, the number of incident edges attached to a hub node (lead agency) suggests the level of communication services it requires, i.e. the higher the number of incident edges, the more intense is its communication need to fulfill its coordinating role. As explained in [14], some of the responsibilities of lead agencies include being the point of contact with local authorities of the affected country or region, such as, UN Humanitarian Coordinator providing information to other agencies in its cluster, coordinating the provision of aids to its functional areas and managing inter-cluster relief missions. All of these responsibilities translate to higher communication needs.

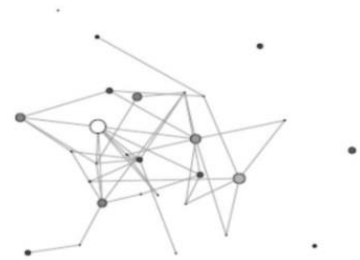

Fig. 2. Graph from figure 1 with nodes with minimum 10 edges.

The social network of inter-organizational collaboration and has provided us with an insightful lead to the identification of lead agencies and varying degrees of communication needs on the ground. This understanding becomes the foundation for our design of portable network devices deployment strategies in disaster-stricken zones.

IV. Portable Network Devices Deployment

A. Problem Formulation

The method of using social network graph of collaborations reveals where the greatest communication needs are at ground zero. Building on these, we convert the deployment problem to *k*-Weighted Deployment (*k*-WD) problem. This enables more targeted and informed deployment of portable network devices.

Fig. 3. Portable network devices [3,10].

In this problem, given n locations and the distances between all pairs of location, one wants to deploy $k < n$ number of portable devices in selected locations. The task is to find the best k locations for these portable devices so that the maximum traveling distance of any location to the selected location is minimal. To do this, we must first identify and locate central nodes in the graph by simplifying the social network of collaboration graph depicted in figure 1. We set the constraint for the number of incident edges to be at least c, where c is a positive integer. Figure 2 illustrates the resulting network graph after c is set to 10, i.e. displaying *only* lead nodes (agencies) that are linked to at least 10 other agencies (some are no longer visible in the filtered graph).

The next step is to rearrange the nodes' positions in the graph to match the lead agencies' physical locations on the ground. We observe that there are freestanding nodes in Figure 2. These represent lead agencies of clusters which are not connected to any other lead agencies in the filtered social network. For these independent nodes to receive network services, they have to be included in the algorithm and the simplest means to do this is by connecting each of these independent nodes to the node closest to them by travel time. Our field study from Aceh shows these independent nodes may be collaborating with other connected nodes in the social network of collaboration, but the nature of the cooperation is non-financial. This finding is also confirmed by [17] that it is very common for relief agencies at ground zero to collaborate both formally and informally.

Each lead agency is weighted according to the number of incident edges as this indicates its degree of responsibilities. In addition, some physical terrains are harder to access. Thus, distances between these lead agencies on the ground are determined based on travel time, instead of the actual geographic distance. For these reasons, the formal problem formulation of portable network deployment is defined as follows.

Problem 1 (k-Weighted Deployment (k-WD)). Let $G = (V, E)$ be a complete undirected graph with edge costs (travel time) satisfying the triangle inequality, and k be a positive integer, where the network size $n = |V| > k$, For any set $S \subseteq V$ and vertex $v \in V$, define $travel\_time(v, S)$ to be the shortest distance from v to a vertex in S. Furthermore, let the weight of v, $weight(v)$ represent the number of incident edges of the node. The problem is to find a set from $S \subseteq V$, with $|S| = k$, such that, $\max_v\{travel\_time(v, S)\}$ is minimized.

In other words, given n positions of lead agencies with different weights and specified travel time between them, one wants to deploy k portable devices in k selected locations where the lead agencies are. The objective is to minimize the maximum traveling time between each lead agency and the nearest portable network device. Thus, given vertex $v \in V$ and edge $e \in E$ in graph $G = (V, E)$, v denotes lead agency and e denotes the collaboration between two lead agencies at ground zero. To communicate with other agencies in or outside ground zero, the lead agency without the portable communication device must travel to lead agency with one. Thus, for an edge e between two lead agencies v and v', $weight(e)$ is determined according to the traveling time between them, $weight(e) = travel\_time(v, v')$. The network size n is determined by

$$n = min(\, N \,|n_c \geq k), \tag{1}$$

for $N = \{n_0, n_1, n_2, \dots, n_{|N|}\}$ and $0 \leq c \leq |N|$, where n_c denotes the number of lead agencies with at least c incident edges.

B. The k-Weighted Deployment Algorithm

In this section, we will address the condition when $n > k$. It is because, when $n \leq k$, i.e., assigning one portable device to each lead agency on the ground, the problem can be quickly resolved. In this paper, we assume that the entire k devices are deployed. To solve k-WD, we divide our approach into three phases. In phase 1, we propose a solution to find k lead agencies for deployment. Phase 2 addresses the case when $|S_j| < k$, where $|S_j|$ is the solution of the algorithm. In Phase 3, network provider fine tunes the solution generated in phase 2 according to final conditions at ground zero.

Phase 1. The general idea of solving k-WD is to convert $G = (V, E)$ into weighted *maximal independent set* (MIS) in an undirected graph $D = (V, E_D)$, such that D has a dominating set of size at most k. This is true because every dominating set that is independent must be a maximal independent [15,18]. Our proposed solution encompasses the algorithm for k-Center problem in [15]. The mapping of network graph G to D is determined as follows. Edges in G is sorted according to the weight, such that

$$weight(e_1) \leq weight(e_2) \leq \cdots \leq weight(e_{|E|}),$$

where $e_i \in E$ for $i = (1,2, \dots, |E|)$. Let $G_i = (V, E_i)$, where $E_i = \{e_1, e_2, \dots, e_i\}$. We have $S \subseteq V$ in graph D such that every vertex in $V - S$ is adjacent to a vertex in S. Find the minimum number of cardinality of weighted dominating set This problem is a NP-hard problem [15]. By utilizing the approach from [15], solving k-WD is equivalent to finding the smallest index i such that G_i has a dominating set of size at most k. Thus, if i^* is the smallest index with the size of at most k, i^* is OPT (the optimal solution) and $weight(e_{i^*})$ is the weight of optimal solution for k-WD.

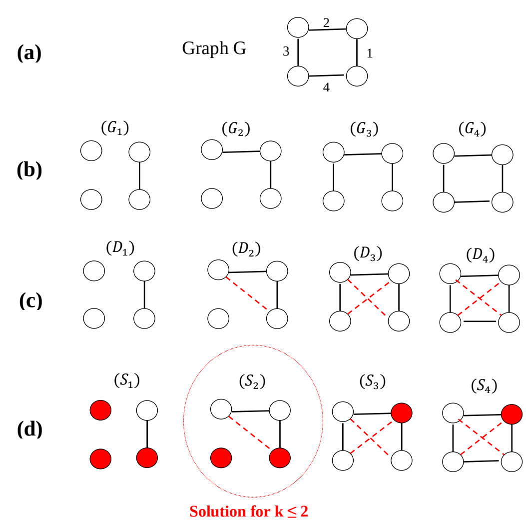

Fig. 4. This example illustrates how the algorithm finds the maximal independent set. (a) Suppose given graph $G = (V, E)$ and $k = 2$. (b) Construct graph G_i from G by including i edges of the lowest weight in E. (c) Construct graph D_i from G_i. (d) Find the maximal independent set S_i in D_i, which are the red vertices. In conclusion, the solution to the problem with $k = 2$ is set S_2 .

Following this idea, we first construct graphs $G_0, G_1, \dots, G_{|E|}$. Next, for each graph G_i, we construct graph D_i by connecting node u and v, whenever there is a path of length at most two between u and v in G_i, for $u, v \in V$ and $u \neq v$, and assign weight of 1 to the new edge(u, v) in D_i. As a result, D_i contains one or more cliques. Since independent set is the complement graph of a clique [15], a vertex v is selected by the algorithm from each clique to be included in S, such that $v \in S$. After vertex v is selected, the clique becomes a star with v at the center. Thus, the algorithm finds the maximal independent S_i set in graph D_i. The algorithm decides the appropriate S_i, for $i = (1,2, \dots, |E|)$, that meets the constraint $|S_i| \leq k$. Assume that S_j is the output of algorithm 1, then S_j is a set of locations of the lead agencies where portable devices should be deployed. We provide an illustration in figure 4 to demonstrate how the algorithm works.

Algorithm 1: k-Weighted Deployment Algorithm

1. Sort E according to $weight(e)$, for $e \in E$.
2. Construct $G_1, G_2, \dots, G_{|E|}$
3. Use G_i to construct D_i , for $i = (1,2, \dots, |E|)$.
4. Compute maximal independent set S_i for D_i.
5. Find the smallest index i such that $|S_i| \leq k$.
6. If index i is the smallest, then $j = i$.
7. Return S_j

Next, we state the performance analysis of algorithm 1.

Theorem 1. Algorithm 1 achieves an approximation factor of 2 for the k-WD.

Theorem 2. Assuming $P \neq NP$, there is no polynomial time algorithm achieving a factor of $2 - \varepsilon, \varepsilon > 0$, for the metric k-WD.

Proof *(Sketch)*: The key observation of Theorem 1 and 2 is that a maximal independent set is also a dominating set. In Theorem 1, by the triangle inequality, each construction is at most twice of $weight(e_j)$, where $weight(e_j)$ denotes edge with the largest weight in graph G_j. In Theorem 2, the proof can be done by reducing the dominated set to k- center problem. This can be done by constructing a complete graph G' from graph $G = (V, E)$ with edge cost given by $weight(u, v) = 1$ if $edge(u, v) \in E$, else $weight(u, v) = 2$. Then, we show that the algorithm can only give the solution of $2 - \varepsilon$ approximation only if $P = NP$ (see [15] for formal arguments for both theorems). ■

The running time of *Algorithm 1* to compute weighted independent set S_j is described as follows. The sorting edges in E in line 1 requires $O(|E| \log(|E|))$. Constructing G_i in line 2, for $i = (1,2, \dots, |E|)$, is $O\big(|E|(|E| + |V|)\big)$. Given graph G_i, the construction of D_i is $O(V)$. Thus, line 3 can be accomplished in $O\big(|E|(|E| + 2|V|)\big)$. Given S_i, for $i = (1,2, \dots, |E|)$, finding the smallest index j in line 5 is $O(|E|)$, which is linear. So far the running time in the discussion is polynomial. However, due to the nature of maximal independent set in line 4, computing S_i is very difficult to solve and takes $O\big(2^{O(t)}\,|V'|\big)$ [18].

Theorem 3. Given a tree decomposition of $G = (V, E)$ with nodes V' and *treeweight* t, the running time to find maximal independent set in G with dynamic programing is at most $O\big(2^{O(t)}\,|V'|\big)$.

Proof *(Sketch)*: The general idea is to convert graph $G = (V, E)$ into a spanning tree $T = (V', E)$, which is also the decomposition tree of G. The running time to find maximal independent set is influenced by how close graph T is to being a tree, which is measured by *treeweight* t (the size of the largest vertex set in a tree). The closer T is to being a tree, the algorithm yields faster running time. Dynamic programing is employed to find maximal independent set in G in exponential time of t multiplied by $|V|$. Generally, the tree is decomposed to smaller sub-trees and the algorithm finds the maximal independent set from the smallest sub-trees. After that, these sub-trees are combined into a larger tree. The process is repeated at the larger tree until there is only one tree left, which is the tree T. At each step of the dynamic programing, the algorithm keeps track and stores all the possible maximal independent set in tables of size 2^t. Each of these tables corresponds to each vertex $v' \in V'$ of tree T. These tables are used to determine whether vertices in V of graph G, that are associated with v', are included or excluded in the maximal independent set (See [18] for formal arguments for Theorem 3). ■

Phase 2. Here, we consider a situation when $|S_j| < k$ after Algorithm 1 terminates. Then, the surplus of $k - |S_j|$ portable devices is distributed to the areas which need more communication. Let $D_j = \{d_0, d_1, \dots, d_{|D_j|}\}$, for $i = (0,1, \dots, |D_j|)$, where $d_i = \{v_0, v_1, \dots, v_m\}$ of size m. Set d_i contains a set of lead agencies that form a star as determined by Algorithm 1, with a lead agency assigned to a portable device as the center of the star. In other words, d_i is a cluster of lead agencies. Let $weight(v_i)$ be determined by the level of lead agency's responsibilities. We compute the weighted sum of each set d_i,

$$weight(d_i) = \frac{\sum_{v \in d_i} weight(v)}{1 + |s_i|}, \tag{2}$$

where s_i is a set of lead agencies that receives portable device in d_i. Thus, when a portable device is deployed to lead agency u, then u is included in set s_i, such that $s_i \leftarrow s_i + \{u\}$. The constraint is that only the lead agency with the highest weight in d_i but has not received a portable device *may receive one*.

Algorithm 2*:* Deployment of $k - |S_j|$ devices

1. Let $m = k - |S_j|$
2. Compute the weight of each $d_1, d_2, \dots, d_{|D_j|} \in D$.
3. **While** $m > 0$ **do**
4. Find d_i with largest weight in D.
5. Find lead agency $u \in d_i$ with $\max\big(weight(u)\big)$ and $device(u) == 0$.
6. $s_i = s_i + \{u\}$. $m = m - 1$. $device(u) = 1$.
7. **If** $\forall u \in d_i$, $device(u) == 1$.
8. $D = D - d_i$.
9. **End while**

Here, $device(u) = 0$ denotes the lead agency u which has not received a portable device. After *Algorithm 2* is executed, D_j is no longer an independent set. This phase guarantees $|N_j| = k$ and is only implemented if and only if $|S_j| < k$. Otherwise, only phase one is implemented. Let $m = k - |S_j|$.

Theorem 4. Phase 2 has an upper bound of $m\,(|S_j| + |d_i|)$.

Proof. There are $|S_j|$ clusters to consider in phase 2 for each of m devices. Finding a lead agency from cluster d_i is at most $|d_i|$. Thus, $m\,(|S_j| + |d_i|)$ is the upper bound. ■

Phase 3. Network providers may adjust the solution by allocating the devices to other lead agencies with higher weights from the same cluster to guarantee lead agencies with higher responsibilities and corresponding communication needs receive portable network devices. That is,

$$weight(v') < weight(v),$$

for $v', v \in d$ and $v' \in S$, where d denotes cluster of lead agencies and S is maximal independent set. The adjustment can be done by checking every vertex, which is linear.

C. Device Assignment

In this section, we address how a portable device should be assigned to which lead agency. Here, we consider two scenarios: a *homogenous* device fleet and a *heterogeneous* device fleet. In the homogenous scenario, the devices are assigned randomly to each selected lead agency. However, in heterogeneous scenario, we consider different devices may have different strengths (such as larger bandwidth capacity, stronger and longer signal, etc.) and different agencies may have different needs. Thus, the device is assigned according to each lead agency's needs. For instance, lead agencies with most incident edges (or higher responsibilities) are assigned with devices of higher capabilities. Hence, network provider assigns a different weight to each device according to its capabilities. The device assignment can be implemented as follows: sort both lists of X and N_j according their weight, such that $x_i \in X$ and $v'_i \in S_j$, for $i = (0,1,\ldots,k)$.

$$weight(x_1) \le weight(x_2) \le \cdots \le weight(x_k), \quad (3)$$

$$weight(v'_1) \le weight(v'_2) \le \cdots \le weight(v'_k). \quad (4)$$

Then, the assignment of a portable device to a lead agency is implemented according to the order of the sorted list in (3) and (4), such that $x_i \to v'_i$, After the assignment, the devices are deployed to selected positions generated by the algorithms.

After the deployment, other agencies in the cluster use the portable device to establish communication. Depending on the type of the portable device as depicted in figure 3, relief agencies may need to travel to the physical location of the device to communicate if it is only a satellite dish. However, wireless technology can be used to relay information, if the device is equipped with wireless tower. For detailed discussion on portable network technologies, please refer to [3,9,10,17].

D. Bandwidth Provisioning

Network bandwidth provisioning is formulated as a *Network Utility Maximization* (NUM) framework [11,12,16] by maximizing the aggregate lead agencies' utility of given amount of bandwidth b_v.

$$maximize \sum_{v\in d_i} U_v(b_v), \quad (5)$$

$$s.t. \sum_{v\in x_i} b_v \le C_{x_i}, \; b_v \ge 0,$$

for $d_i \subseteq V$ in graph $G = (V, E)$, where b_v and C_{x_i} denote the bandwidth allocated to agency v and the maximum capacity of device x_i respectively. $U_v(b_v)$ is agency utility function of given bandwidth $b_{v'}$, where it is strictly concave and twice differentiable, and defined as $U_v(b_v) = weight(v).log(b_v)$. We solve problem (5) in the Lagrange form, we can write

$$L(b_v, \lambda) = \sum_{v\in d_i} U_v(b_v) - \sum_{v\in x_i} \lambda . b_v , \quad (6)$$

where λ is known as the Lagrange multipliers [16] and $v \in d_i$ implies lead agency v who is communicating through device d_i. Since the utility function is a convex, (6) can be directly solved by

$$\frac{dL}{db_v} = \frac{weight(v)}{b_v} - \lambda = 0.$$

Thus, each lead agency solves bandwidth allocation with $b_v = \frac{weight(v)}{\lambda}$, where λ can be obtained from $\sum_{v\in x_i} b_v = C_{x_i}$ by solving

$$\lambda = \frac{\sum_{v\in x_i} weight(v)}{C_{x_i}} \quad (7)$$

This allocation strategy enables network providers to make more informed and targeted bandwidth provisioning to meet the different and dynamic communication needs based clues revealed from the analysis of inter-organization collaboration network graph. This is especially important in a disaster aftermath where resource is restricted and highly valuable.

V. Simulation and Results

In this section, we demonstrate how adjusting a relief agency's weight influences bandwidth provisioning of other relief agencies that share the same portable device. This case occurs when a relief agency takes on more responsibilities. Consider four agencies of the same cluster sharing a communication device with a capacity of 10. We have $weight(v'_1) = 10$, $weight(v'_2) = 5$, $weight(v'_3) = 3$, and $weight(v'_4) = 1$. Following a change at ground zero, relief agency v'_4 is given higher responsibilities. In this simulation, $weight(v'_4)$ is increased by 1 in each iteration.

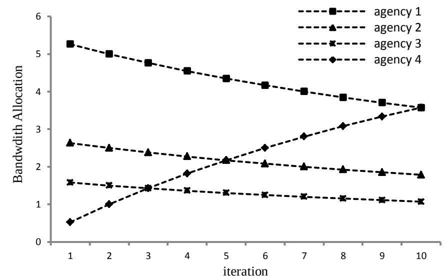

Fig. 5. Bandwidth provisioning.

Figure 5 illustrates that, as more bandwidth is allocated to v'_4 , other agencies receive less bandwidth. Notice that, at 10^{th} iteration, when $weight(v'_4) = weight(v'_1)$, the same amount of bandwidth is allocated to both agencies. As we can observe, higher $weight(v'_i)$ results in higher bandwidth provisioning to lead agency v'_i, and vice versa. Thus, $weight(v'_i)$ can be interpreted as an agency's priority to obtain bandwidth. This approach enables network providers to quickly adapt bandwidth provisioning to agencies according to changes and shifts in responsibilities among agencies at ground zero.

VI. Implementation Protocol on Ground Zero

In this section, we propose an implementation protocol when a region experiences a catastrophic natural disaster. The protocol is a two-stage implementation process: *Groundwork setup* and *post disaster relief mission*.

Stage 1 (*Groundwork setup*). This stage is important in determining the success of the deployment in a post disaster relief mission. As reported in [17], the deployment of portable network devices following a disaster takes between 6 to 8 weeks. The reasons are: *first*, relief IT team has to travel to ground zero to assess the condition and local organizational structure. *Second*, the headquarters decides the number of devices to be deployed and designs a deployment strategy after receiving the report from ground zero. Then, the headquarters arranges the logistics for delivery of devices, which typically involves lengthy administration and logistics efforts. However, this evaluation and deployment process can be sped up if some critical information is prepared and available in advance of disasters. We propose the following steps to relief IT agencies/network providers:

- Consult leading international humanitarian agencies to populate a database of collaborators based on previous experiences, including local relief agencies in various countries, especially vulnerable regions with weaker critical infrastructure.
- Use the social network theory to analyze the inter-organizational collaborations among relief agencies and create social network graphs of collaboration.
- Use the above information to reach organizational agreements over roles and responsibilities, administration, logistics and cost. According to the report in [17], the number of devices k to be deployed is often determined by the number of available portable devices, the budget to rent the devices from vendors at the time of disaster, and requests from ground zero.

Thus, identifying the inter-organizational collaboration patterns in advance provides important clues for the number of devices that may be needed in the future, such that budget and administration work can be prepared in advance. This preparation is crucial in enabling network providers to provide quicker and more informed deployment of portable devices to ground zero.

Stage 2 (*Post disaster relief mission*). In the event of a natural disaster, network provider deploys the emergency network infrastructure by executing the following steps:

- Quickly identify the lead agencies and the organizational structure at ground zero by referring to the social network graph prepared in stage 1.
- Reorganize the nodes of the lead agencies in the social network graph according to their physical locations at ground zero.
- Use the map as an instance to Algorithms 1 and 2 (if $|N_j| < k$) to determine where and how the portable devices should be deployed. Assign devices to lead agencies and determine the bandwidth provisioning utilizing the proposed algorithms discussed in previous section.
- Deploy the devices to the physical locations.

The robustness of the groundwork completed in stage 1 will deliver greater readiness and immediacy in the execution of stage 2. Finally, this deployment strategy and protocol are designed to be scalable and adaptable according to the severity of the impact, such as the size of geographic area affected, and the dynamic conditions and needs at ground zero, for instance an increase or reduction in the number of relief agencies and their responsibilities.

VII. Conclusion

Our field study on post Tsunami relief works in Aceh has yielded critical insights on inter-organizational collaborations among relief agencies. We used social network theory to analyze the collaboration relationships and learnt that: (a) some agencies collaborate more extensively with other agencies than others, and this translates to (b) varying degrees of coordinating responsibilities and communication needs. Building on these ideas, we formulate the deployment of portable network devices as a k-WD problem and the bandwidth allocation problem as NUM. Our solution for k-WD achieves approximation of $2-\varepsilon$, and our solution for NUM allocates resources according to unique needs on the ground. Our deployment and bandwidth allocation strategy for emergency communication is more informed and targeted, and sensitive to varying needs and conditions at ground zero; and it is usable even in situations where there is no surviving communication infrastructure. By understanding how humanitarian work at ground zero, this interdisciplinary paper has sharpened the purposefulness of emergency network communication deployment and provide customized provision of communication service. Finally, these findings and our works are dedicated to those who work tirelessly in providing relief to survivals of natural disaster.

References

[1] H. Masyrafh and J. Mckeon, "Post-Tsunami Aid Effectiveness in Aceh (Proliferation and Coordination in Reconstruction)", *Washington, DC: Wolfensohn Center for Development*, p. 46, 2008.

[2] Jian Zhou, Xin Zhang, Laxmi Bhuyan and Bin Liu, "Clustered K-Center: Effective Replica Placement in Peer-to-Peer Systems.", IEEE Globecom'07, Washington DC, USA, Nov. 2007

[3] T. Sakano, Z Fadlullah, T. Kumagai, A. Takahara, T. Ngo, H. Nishiyama, H. Kasahara, S. Kurihara, M. Nakazawa, F. Adachi, and N. Kato, " Disaster Resilient Networking – A New Vision based on Movable and Deployable Resource Units (MDRUs)", *IEEE Network*, Vol 27, No. 4, 2013.

[4] A. Athreya and P. Tague, " Survivable Smart Grid Communication: Smart-Meters Meshes to the Rescue", *Int. Workshop on Communication Technologies Support for the Smart Grid (SGCom)*, January 2012.

[5] J. Sterbenz, D. Hutchison, E. Cetinkaya, A. Jabbar, J. Rohrer, M. Scholler, and P. Smith, " Resilience and survivability in Communication Networks: Strategies, Principles, and Survey of Disciplines", *Computer Network*, Vol. 54, 2010.

[6] F. Truck and A. Lazar, " Modeling Wireless Shadow Networks", *ACM MSWiM*, 2004.

[7] M. Crouch, "Fuel Cell Systems for Base Stations: Deep Dive Study", *GSMA Report*, April 12, 2012.

[8] E. James, "Clean or Corrupt: Tsunami Aid in Aceh", *Canberra: Australian national University, Asia Pacific School of Economics and Government*, 2006.

[9] K. Morrison, "Rapidly Recovering from the Catastrophic Loss of Major Telecommunication Office", *IEEE Communication Magazine*, Vol. 49, Issue 1, January 2011.

[10] T. Kitaguchi and H. Hamada, "Telecommunications Service Continuity and Disaster Recovery", *IEEE Communication. Society Communication Quality & Reliability Workshop*, April, 2008.

[11] H. Susanto and B. G. Kim, "Congestion Control with QoS and Delay Utility Function", in *IEEE ICCCN*, Sep. 2013.

[12] H. Susanto, "From Self-Regulate to Admission control in Real-Time Traffic Environment", *IEEE AINA 2014.*

[13] J. Moroney, S. Pezard, L. Miller, J. Engstrom, A.Doll, "Lessons from Department of Defense Disaster Relief Efforts in the Asia-Pacific Region", RAND Corporation, July 2013.

[14] "Disaster Relief 2.0: The Future of information Sharing in Humanitarian Emergencies", United Nation Foundation, 2011.

[15] V. Vazirani, " Approximation Algorithms", Springer, 2003.

[16] F. P. Kelly, "*Charging and rate control for elastic traffic*", European Transaction on Telecommunication, 1997.

[17] A. Grop, L. Tchouakeu, C. Maitland, D. Saab, A. Tapia, E. Maldonado, R. Orenovici, K. Zhao, "VSAT Deployment for Post-Disaster Relief and Development: Opportunities and Constrants for Inter-organizationl Coordination among International NGO", Conference of International Telecommunication Society, 2008.

[18] D. Williamson and D. Shmoys, " *The Design of Appoximation Algorithms*", Cambridge University Press, 2011.