Design of Multi-Path Network Topology for Contingency Cellular Network

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Abstract*—When stricken by a large-scale disaster, the efficiency of disaster response operation is very critical to lifesaving. However, communication systems, such as cellular networks, usually crashed due to various causes making coordination among disorganized disaster responders extremely difficult. Unfortunately, rapid deployment of many existing emergency communication systems relies on a good transportation system, which is usually not available in a catastrophic natural disaster. We propose a Contingency Cellular Network (CCN) for emergency communication by connecting disconnected base stations together using wireless links to construct a multi-hop contingency cellular network. CCN can support existing mobile phone users with reduced capability. Such a system can support a large number of disaster responders and victims in the early hours of a catastrophic natural disaster, thus save many lives.

The paper addresses the multi-path network topology design problem of CCN. In which, selected nodes will have multiple path to reach the core network, and thus, have higher resiliency against link failure. The problem is proven NP Hard. Therefore, we designed an efficient heuristic algorithm (LBDK) to solve the problem when it is needed in urgent. Finally, we evaluated the proposed algorithms by simulation. A significant improvement in resiliency by using multi-path topology is reached.

Keywords- Disaster Management, Emergency Communications, Mobile Communication, Ad Hoc Network, Multi-path Topology

I. INTRODUCTION OF LARGE-SCALE NATURAL DISASTERS

A. Communication Systems Crash

It has been known for a long time that a communication system is crucial to disaster response. However, many of seemingly stable public communication networks did not survived in previous disasters. Surprisingly, from the firsthand experiences obtained from 88 Flood and 921 Chi-Chi Earthquake [5] in Taiwan and Hurricane Sandy in the East coast of United State, we found that existing cell phone networks were vulnerable due to the following reasons:

Service disruption of base stations: Common reasons are (1) power outage (the backup batteries usually can only last several hours); (2) broken backhaul; and (3) physical destruction by earthquake/flood/hurricane.

Critical hardware equipment were knocked down: Due to (1) external power outage; (2) fuel for power generator exhausted; and (3) equipment overheated due to cooling system broken.

The cables of power lines or backhaul links are usually laid along roads and bridges for the convenience of cable deployment and maintenance. As shown in Fig. 1, the destruction of roads and bridges, which was a common phenomenon in a disaster, led to power outage and network disconnection.

Figure 1. Broken Bridge Cut Off Communications Cables

Although power lines and communication backhauls usually have redundancy for higher availability, they may not necessarily improve the survivability significantly in a large scale disaster. For instance, a huge flood over a river may destroy many bridges over the same river at the same time breaking all redundant cables completely. As shown in Fig. 2, the backhaul of base stations, the basic structure of mobile communication systems, must be connected to the controllers or switches. Even if a base station remains intact in a disaster, as long as its backhaul is disconnected, it can no longer keep in operation.

Taking 88 Flood for example, the structure of many base stations remained intact and free of flood because they were often located on a higher place. However, when the power lines and backhauls that were laid along the roads and bridges

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were destroyed, mobile communications system was therefore paralyzed. Power lines and backhauls become an Achilles' heel of many existing mobile communications networks. Unfortunately, it is prohibitively expensive to build stronger mobile communication networks.

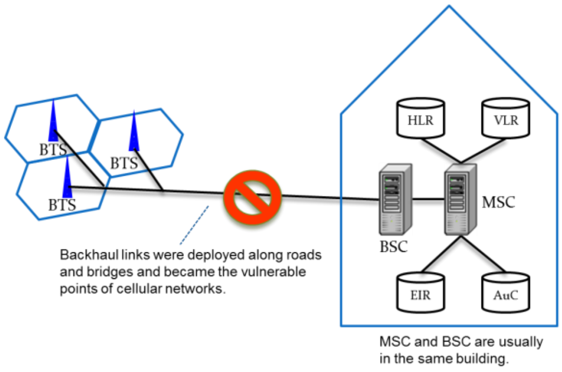

Figure 2. Vulnerable Points of Cellular Network

B. *Requirements of Contigency Comunication Network*

Based on the analysis shown above, we summarized a set of system requirements for large scale contingency communication system in [6], called 7-ability. Among them, the two most ignored by existing contingency communication systems are terminal popularity and practicality. No existing system can afford a large number of mobile terminals for all potential users. Furthermore, due to the lack of commercial incentive, only very limited resources can be devoted to the development of such a system such that it is not practical to design a completely new system from scratch.

C. *Contingency Cellular Network*

We designed CCN for large scale disaster response by connecting disconnected base stations in the disaster areas with wireless links to construct a multi-hop cellular network rapidly in band-aid fashion. Such a system will be able to support many voluntary workers and victims in the early hours of catastrophic natural disasters. A landline broadband network is often used to construct a cellular backhaul network. However, wireless broadband solution such as microwave, long range Wi-Fi, satellite and etc. is also used to serve as the backhaul in the rural area in order to reduce the deployment cost. The IETF Pseudowire Emulation Edge to Edge (PWE3) working group had published standards of Pseudowire, which was a wireless backhaul technology [10]. Hence, connecting disconnected base stations using wireless links is practically feasible.

The design philosophy of CCN is to reuse existing disconnected base stations in the disaster area to save time and resources significantly. The reasons are as follows: (a) wide coverage of mobile communication network; (b) widespread use of cell phones; (c) only a low cost add-on module is needed to repair a disconnected base station; (d) low-barrier of usage, which are mostly needed in disaster response communication. One crucial non-technical reason is that cell phone might be the first thing carried by most victims and people who escape from their homes when a disaster strikes. Therefore, reconnecting disconnected base stations in the disaster area to provide a low-cost large-scale emergency communication service is a good option.

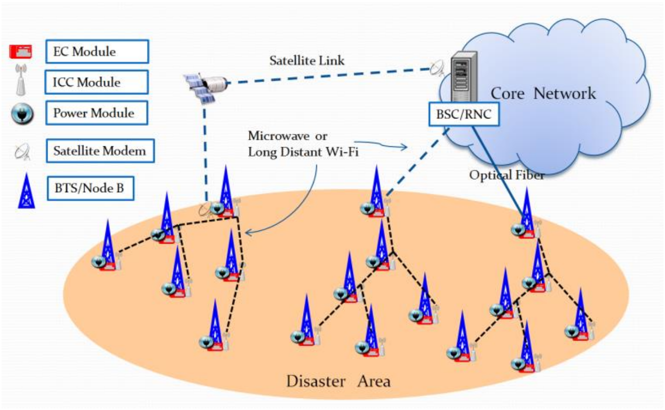

Figure 3. System architectue of CCN

System architecture is showed in Fig. 3. *Contingency Recover Package* (*CRP*) consists of a power module, a number of Inter-Cell Communication Module (*ICC Module*), and an add-on processing module, called Emulated Controller Module (*EC Module*). CRP can be stored in national disaster response centers or cellular operators and delivered to the selected base stations via any transportation means even airdrops or helicopters. The EC-Module is connected to a base station in the first step. Then, ICC Modules are used to connect the base station to its neighbors in the second step via long range wireless links. At lease a pair of ICC Modules is needed for each base station. A multi-hop wireless network overlapped on top of the selected base stations is finally formed. The overlapped network provides the connectivity between base stations and the core network. Anyone who has a cell phone can access the contingency communication service from these base stations. If the constructed CCN is completely isolated from the core network, some CRP may include a Satellite Communication Module (SC Module) to establish a connection to the core network.

Challenges, related researches, design philosophy and system architecture of CCN were discussed in paper [1,4,6,7,8].

The paper addresses the multi-path network topology design problem. This paper is organized as follows. Section II discusses related works of network topology design. Section III presents the topology design problem of CCN. Evaluation is provided in Sections IV. Discussion of concluding remark and future work are in Section V.

II. RELATED RESEARCHES

Shao proposed an aerial wireless emergency communication system [9]. In that system, aerial BSs and long distant wireless links were used to form an aerial BSs Ad Hoc network. Aerial BSs are connected to GSM core network through the aerial Ad Hoc network. And thus, users can use their cell phone to connect to the aerial BS and to make a cell phone call. Hybrid Mobile Ad-Hoc network [1] are a two hierarchical network. It takes WiFi mesh network as the user access layer and WiMax and GEO Satellite mesh network as network service layer to support multimedia traffic such as VoIP and multimedia streaming. Users can use a notebook or smartphone with VoIP applications to access the communication service.

The network components of aerial BS and hybrid mobile ad hoc network are randomly distributed in the disaster areas. Their network topologies are kinds of ad hoc network and could not be well planned beforehand. On the other hand, CCN reuses existing disconnected base stations in the disaster area such that the locations of these base stations are known and the existing topology is well planned. Overlay the CCN topology on top of the existing topology can greatly simplify the CCN topology design.

Charnrsriponyo and Tipper formulated topology design of 3G wireless backhaul network problem as a mixed linear integer programming (MLIP) problem that aim to find a tree-type network topology with minimum linking cost [2,3]. Due to the limitation of network scale of MLIP, Charnrsriponyo and Tipper also proposed a heuristic algorithm to find a near optimal solution in a reasonable computing time.

Topology design of CCN is similar to 3G wireless backhaul network but has more issues to consider. First, the depth of 3G wireless backhaul network topology is fixed, but the depth of CCN topology is variant. Secondly, all base stations in 3G wireless backhaul network will be selected into the tree-type topology; in CCN, only a part of base stations will be selected. Finally, the goal of topology design of 3G backhaul network is to minimize total link cost; while CCN aims to maximize the efficiency of disaster responses.

III. PLANNING OF NETWORK TOPOLOGY

A. *Motivation of Network Topology Planning*

In CCN, most disconnected base stations require multiple hopping to connect to the core network. The topology can determine the efficiency of CCN, which is the efficiency of disaster response operation and its stability. The considerations of disaster response efficiency include the emergency level of the afflicted areas or the level of the disaster and the number of disaster responders.

Given that the locations of the base station and the direction of the neighbors are predictable, the interconnection between base stations can be pre-planned to reduce deployment difficulty.

In our previous study, we proposed to use tree-type topology for CCN. In which the root node is the only survival base station that has the backhaul connection to the core network. Other base stations have to connect to the core network using multi-hop relay through the root node. Tree topology is simple but vulnerable to a single link or node failure. In this paper, we improve the resiliency of the network by providing multiple path to the selected nodes, called *pivot nodes*, such that every pivot node can reach the core network via two or more disjoined paths.

B. *Mathematical Model of Length Bounded Disjoint K-Path Max-Profit Mesh Problem*

For a given graph with weighted nodes, Length Bounded Disjoint K-Path Max-Profit Mesh (***LBDK***) problem is to find a network topology to maximized the weight under the constraint that the selected nodes all have at least some number of disjoint length bounded outgoing path to any of designed outgoing nodes. Mathematic model of ***LBDK*** are introduced as follows.

Given a graph, $G=(V,E), S, \Phi, R, W, C, U, Q$ where

- $V=\{ v_i | i=1, 2, \ldots, n\}$ *is the set of nodes;*
- $E=\{ e_{ij} | v_i, v_j \in V \}$ *is the set of links, where* e_{ij} *is the link between* v_i *and* v_j*;*
- $S=\{ s_i | i=1, 2, \ldots, m\}$ *is the set of survival nodes, where* $S \subseteq V$*;*
- $\Phi=\{ \varphi_i | i=1, 2, \ldots, z\}$ *is the set of pivot nodes, where* $\Phi \subseteq V$*;*
- $R=\{ r_i | i=1,2,\ldots,n\}$ *is the set of profit, where* r_i *is the profit of* v_i*;*
- $W=\{ w_{ij} | v_i, v_j \in V \}$ *is the weight of the edge* e_{ij}*, representing the noise level of the edge; the lower the level is, the better the quality is;*
- $C \in Z+$ *is the total number of available resources (CRP),* $U \in Z^+$*;*
- Q *is a positive integer representing the minimum number of disjoint outgoing paths from the pivot node to the core network.*

LBDK problem is to find a connected mesh network $M(V', E')$, where $V' \subseteq V$, $E' \subseteq E$, such that the total profit $\sum_{v_i \in V_{v'}} (\frac{r_i}{\Omega_i})$ is maximized, subject to that for each pivot node $\varphi_i \in \Phi$, there exist a set of disjoint outgoing paths of $P_i = \{p_i \mid i=1,2,3,\ldots\}$, where the outgoing path, p_i, connects the pivot node φ_i to a survival node, and $|P_i| \geq Q$, where Q denotes the minimum number of disjoint outgoing paths. And the length of $p_i \leq U$, $|V'| \leq C$. This problem is called the Length Bounded Disjoint K-Path Max-Profit Mesh problem (***LBDK***).

C. ***LBDK*** *is a NP Hard Problem*

(A) ***LBDK*** is in NP:

We first show that ***LBDK*** ∈ NP. Assuming that we are given an undirected graph $G (V, E)$ with positive vertex profits and the number of nodes is a positive integer D, as well as to find q disjoint paths from v_0 to φ_i. We choose the ***LBDK*** $\subseteq G (V, E)$ itself as certificate. The verification algorithm we used here is to make a double loop to verify that single path must be fixed before the network built whether the length of path $\leq U$.

The verification algorithm can affirm straightforwardly in polynomial time.

TABLE I. PSUDO CODE

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LBDK Pseudo code:
LBDK(G, S, Φ, R, W, C, U, Q)
    Set S={ $s_m$|m=0, 1, …, n}    /*the set of survival nodes*/
    Set Φ={ $\varphi_k$|k=0, 1, …, n}    /*the set of pivot nodes*/
    Set R=infinity          /*the set of initial profit*/
    Set W=infinity          /*the weight of the edge*/
    Set M={}            /*the set of edges in G*/
    Set D=infinity          /*the (profit/weight) of the node*/
    Set V'={}            /*the set of vertexes*/
while size of V' < C do
 while path P< Q+1
    find k shortest vertices-disjoint path from each $s_m$ to $\varphi_k$
   Q count ++
 end while
 for i = 1 to n
  W[i]=M[$s_0$,i]
  D[i]=R[i]/W[i}
 end for
   Let v be a highest profit adjacent node to V' such that
   v∈V(G)- V' ,u∈V' and the length of path form $s_i$ to $v_i$  ≤ U
   if v is not violated the length constraint
    add v to V'
    add link (u, v) to M
         v count++
   end if
End while
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(B) LBDK is NP-Hard:

LBDK problem can be reduced to K-maximum Profit Spanning Tree with Bounded Depth (K-MaxSTBD) problem. K-MaxSTBD is proved a NP hard problem in [8], which is to find a maximum spanning tree from a given graph G. The maximum number of nodes to be selected, the depth bound and the total profit of the spanning tree are K, D and P, respectively. Given an instance α:[G, K, D, P] in K-MaxSTBD problem, we can find an instance β:[$G', S, \Phi, R, W, C, U, Q$] in ***LBDK*** problem such that an optimal solution x_β for β is also an optimal solution for α, where $V'=V$, $E'=E$, $C=K$, $U=D$, $S=\{v_0\}$ *and* $\Phi=\{\}$, $R=P$, $W_i=1$ *and* $Q=0$. We denote the total profit of a solution x for α and β to be $p_\alpha(x)$ and $p_\beta(x)$, respectively.

We first proof that there exists a solution x_β' of tree type for each solution x_β for β. Assuming x_β is not a tree, we can always find a spanning tree x_β' on x_β whose total profit is the same as x_β because the set of node in x_β' is the same as that in x_β. Next we proof that every tree type x_β is a valid solution for α with the same total profit. Assuming solution x_β is a tree type solution of β, the number of nodes in x_β is smaller or equal to K, which is equal to C, and every tree of size smaller or equal to C is a valid solution of α. Therefore x_β is a valid solution for α. Because the same tree in α and in β must have the same total profit, thus $p_\alpha(x_\beta) = p_\beta(x_\beta)$. Both of them are denoted as $p(x_\beta)$ thereafter.

Since Q=0, S={v_0} and $\Phi=\{\}$, it is straightforward to proof that every spanning tree is a valid solution for β as long as the number of nodes is smaller or equal to C. Therefore, every solution x_α to α which is a tree of size smaller or equal to C, is a valid solution of β.

Next, we prove that an optimal tree type solution x_β for β is also an optimal solution for α by contradiction. As we have proved, x_β is also a valid solution for α, whose total profit is $p(x_\beta)$. Assume x_β is not an optimal solution for α, there must be another solution x_α, whose total profit $p(x_\alpha)$ is greater than $p(x_\beta)$. Since x_α is also a valid solution for β, whose total profit is $p(x_\alpha)$, which is greater than $p(x_\beta)$, this contradicts to the assumption that x_β is an optimal solution for β. As a result, x_β must be an optimal solution for α. The reduction of ***LBDK*** to ***K-MaxSTBD*** Problem is done. The proof of NP-hard of ***LBDK*** is straightforward. Q.E.D.

D. *Heuristic **LBDK** Algorithm **(HLBDK)***

LBDK is a NP-Hard problem. Optimal solution of ***LBDK*** is difficult to find in a reasonable time as the scale of CCN network grows. Since ***LBDK*** is a time bounding problem, we proposed a heuristic algorithm of ***LBDK, HLBDK,*** to find a sub-optimal solution in a reasonable time.

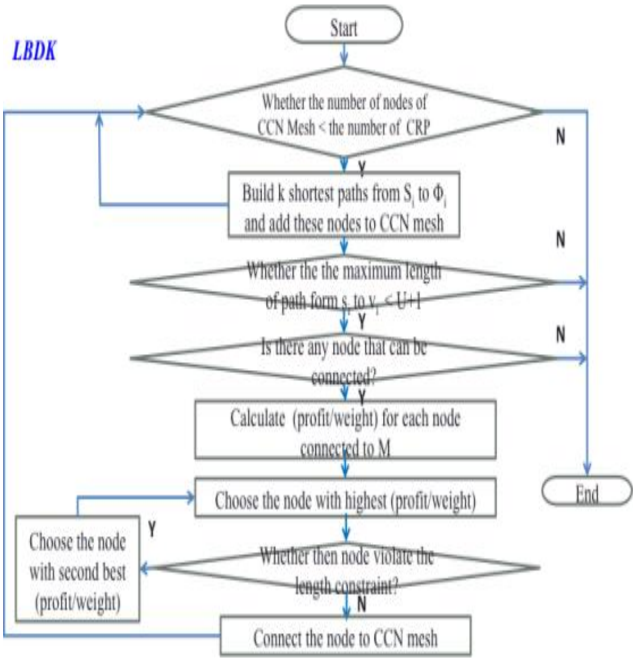

Figure 4. Flow Chart of ***HLBDK*** algorithm

Flow chart and pseudo code of the heuristic algorithm are showed in Fig. 4 and Table I, respectively.

The ***HLBDK*** algorithm is illustrated as follows.

Step 1: For each pivot node $\varphi_i \in \Phi$, find q disjoint shortest paths from φ_i to the set of survival nodes, S, iteratively;

Step 2: Add the results of step 1 into the mesh network *M(V', E');*

Step3: Select the neighboring node of *V' that* has the maximum weight/profit and satisfies the length bound to α;

Step 4: Repeat step 3, until the number of node of *V'* is equal to the number of CRPs, *C*. Finally, the mesh network *M(V', E')* is the result of ***HLBDK***.

IV. PERFORMANCE EVALUATION

A. *Objective and Enviroment of Experiences*

TABLE II. EXPERIENCE PARAMETERS

Exper-iment	**Graph**		***C***	***S***	***Φ***	***R***	***W***	***U***	***Q***
	N	***E***							
Exp. 1	10	15-20	5	1	1	1-10	1-10	4	1-2
Exp. 2	100	250	50	2	2	1-10	1-10	5-7	2
Exp. 3	200	500	100	2	2	1-10	1-10	7-9	2
Exp. 4	500	1000 - 1400	250	2	2	1-10	1-10	8-10	1-6

We used a desktop PC to evaluate ***HLBDK*** by simulation. 10 random graphs were generated in each case specified in Table II. ***HLBDK*** was evaluated against optimal solution (by brute force).

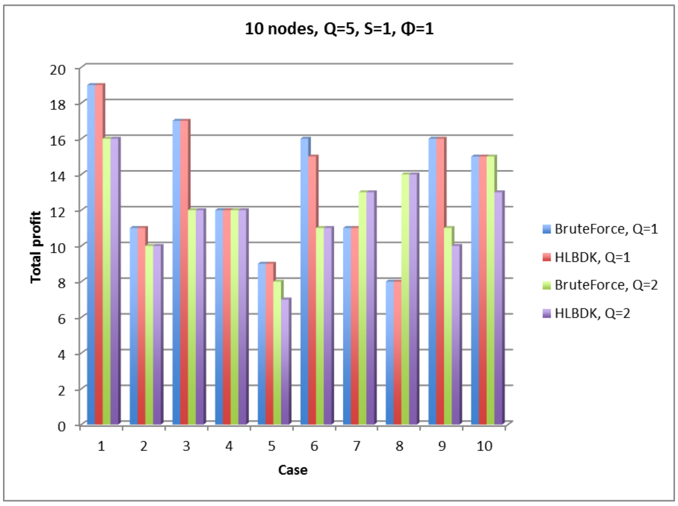

Figure 5. Experiment 1: Total Profit

The network topology may be a tree-type topology when the number of path is one, *Q*=1. Otherwise, the network topology is a connected graph with circles. From Fig. 5, we can see that the total profits of ***HLBDK*** are close to optimum solutions in most cases. The ratio of total profit of HLBDK to total profit of brute force are 0.99 and 0.98 when Q=1 and Q=2, respectively.

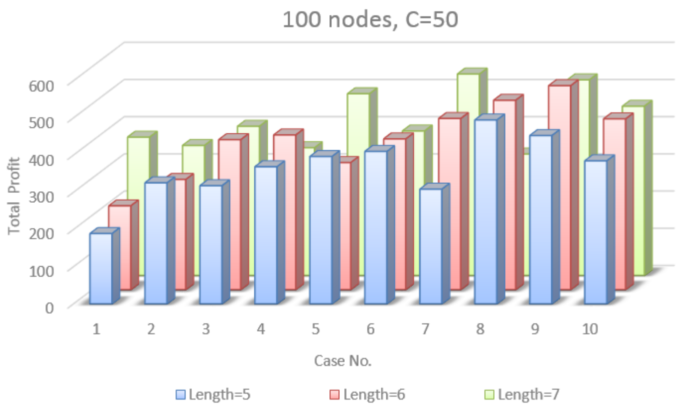

Figure 6. Experiment 2: Comparision of Total Profits

We can see that from Fig. 6 and 7, the total profits increases when the length bound becomes larger. Enlarging the length bound may increase the total profit, but noise level will also increase at the same time. Hence, it has better to relax the restriction of length bound with a tolerated noise level to gain a better profit.

The availability of path p_j, β_i, can be estimated by formula (1), where α represents the probability of link being failed and *n* denotes the number of links in a path.

$$\beta_j = [(1-\alpha)^n] \text{ -- } (1)$$

The availability of a pivot node which is the probability that at least one path is available, can be estimated using formula (2).

$$\text{Availability } (\varphi_i) = 1 - \sum(1-\beta_j) \text{ for all path } p_j \text{ in } P_i \text{ --- } (2)$$

From Fig. 8, the total profits decreases and the availability increases when the values of *Q* increases. Availability is critical to CCN. However, the total profits may have to be compromized when persuing higer availability. In order to balance the total profit and availability. ***LBDK*** only designates some important base stations as pivot nodes to maintain the total profit at an acceptable level.

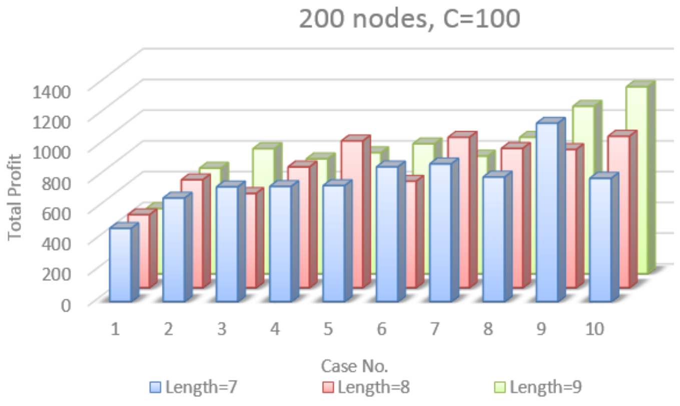

Figure 7. Experiment 3: Comparision of Total Profits

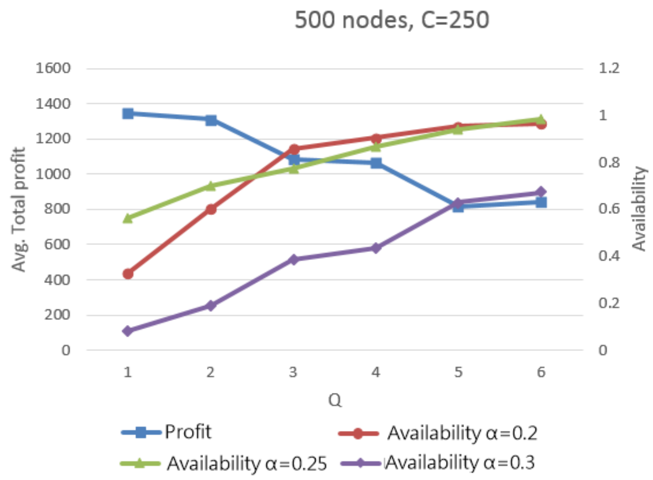

Figure 8. Experiment 4: Total Profit vs. Availability

V. CONCLUDING REMARKS

We propose a contingency cellular network for large scale emergency communication by connecting physically intact but service-disrupted base stations together with wireless links. This paper addresses the multi-path topology design problem. The problems are proven NP-hard and thus we proposed a heuristic algorithms (***HLBDK***) to solve them quickly and efficiently. From the experiment results, we found that the total profits of heuristic solution are closed to the optimal solution when the network scale of CCN is small.

The disaster response profits may be compromised when pursuing better network quality and higher availability. With ***HLBDK***, the operator of CCN can adjust length bound of outgoing paths and the number of disjoin paths to balance the profit, quality and availability.

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