Network Topology Planning for Contingency Cellular Network

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Abstract—Large-scale natural disasters often cause great damage and the efficiency of disaster response operation is very critical to life saving. However, communication systems, including Public Switched Telephone System and cellular networks, are usually crashed due to various causes. Without communication systems, the rescue missions are much more difficult. We propose a temporary communication system, which is called Contingency Cellular Network (CCN), to support emergency communication after disaster occurred by connecting physically intact but service-disrupted base stations together with wireless links. This paper addresses the network topology design of CCN. The topology design determines the efficacy of disaster relief. We take the emergency, damage degree of the damage areas and the amount of emergency recovery resources into consideration, choose some high-profit areas to build a communication network by multi-hop relay. The design strategies must maximize the relief efficacy and balance network traffic distribution to increase the stability of CCN. We model the CCN topology problem into an optimization tree problem of graph theory aiming to maximize the total profit of the tree and limit the tree depth in the same time. The problem is proven NP-hard and we design an efficient heuristic algorithm to solve it.

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

I. Introduction of Large-Scale Natural Disasters

A. The impact of Large-Scale Natural Disasters

Frequently occurring large-scale natural disasters have been reported to cause great damage in recent years, claiming many people's lives, rendering millions people homeless, and causing huge financial loss. The earthquake that occurred in Haiti in 2010 alone claimed 230,000 people's lives.

When the disasters come, the destroyed areas are in chaos. Take the earthquake that happened on March 11, 2011 in North-eastern Japan for example. After the 9.0 magnitude earthquake, followed by a 23-meter high tsunami and the combined major natural disasters (i.e. nuclear crisis, earthquakes and tsunami), the world and the already experienced disaster response workers were stunned. We synthesize the impact of large-scale natural disasters, such as 921 Chi-Chi Earthquake (Taiwan) [3], 88 Flood (Taiwan), SiChuan (China) [9] and Haiti earthquakes as follows:

- The collapse of buildings
- Paralyzed traffic in the disaster areas
- Paralysis of entire communications network
- Lack of professional disaster response workers
- Dysfunctional administrative command system:

The bottlenecks of disaster response caused by these impacts are listed as follows:

- The hindrance of the terrain and the paralyzed traffic system
- Difficult allocation and misplacement of resources
- Difficult coordination and communication troubles among the disaster response workers

Due to such factors as poor communication/coordination of disaster response workers and insufficient information, disaster response work tends to procrastinate and its resource is severely limited. It is a pity that many precious lives could have been saved [1,2,4,6,7,10].

B. Communication Systems Crash

Communications system is crucial to disaster response, but when the disasters come, these seemingly stable public communications networks were paralyzed. Surprisingly, we found that during 88 Flood and 921 Chi-Chi Earthquake, the cell phones were vulnerable due to:

Service disconnection in the base station: Common reasons include (1) the destruction of the strong earthquakes; (2) power outage (the backup batteries can last only 1 to 2 hours, and 70% of the 3300 disconnected base stations during 88 Food were out of power); (3) the backhaul of the base station was destroyed.

Critical hardware equipment was knocked down: Due to (1) power outage and (2) broken cooling system and overheated switch.

We notice that cables of power lines or backhaul links are usually set up along roads and bridges for its convenience of deployment and maintenance. The destroyed roads and bridges, the main contributing factor of disconnected mobile communications system service, lead to power outage and network disconnection, as shown in Fig. 1.

As clearly shown in Fig. 2, the backhaul of base stations, the basic structure of mobile communication systems, must be connected with controller or switch. Even though the base

Sponsored by National Science Council NSC 100-2221-E-004-008

station is intact, as long as its backhaul is disconnected, it can no longer be in operation.

Figure 1. Broken Bridge Cut Off Communications Cables

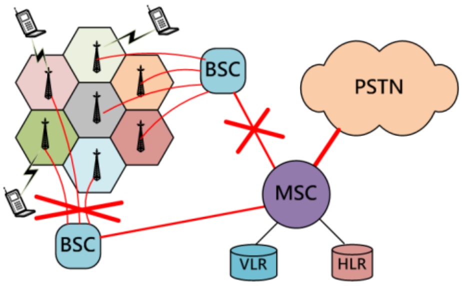

Figure 2. Vulnerable Points of Cellular Network

Take 88 Flood for example. The structure of many base stations remained intact and free of flood because they were often built on a higher place. However, with the communications network embedded along the roads and bridges destroyed, mobile communications system was therefore paralyzed. Power and backhaul has become the disadvantage of mobile communications network. Besides, there are other factors that may contribute to the paralysis of communications system according to our published publication [5,6,7]. It can be confirmed that mobile communications system is actually vulnerable judging from the overall paralysis of mobile communications system in disaster areas over the years. Encumbered by many external factors, it is still futile to build stronger base stations and switches as it cannot greatly improve the availability of communications system. Although National Communications Commission of Taiwan established a number of strengthened base stations with satellite communication for backhauls, the number of such base stations is limited due to fund constraint. Number of telephone calls in the disaster areas exceeds that in usual time. Take SiChuan Earthquake [9] for example. The disaster areas have ten-time phone calls than usual in internal areas; 5-to-6-time phone calls than usual in external areas; and 80-time phone calls than usual from Beijing to the disaster areas. For the victims in the devastated areas and disaster response workers, aid could only scratch the surface [8].

C. Difficulty of Repairing Communications Equipment

Take 921 Chi-Chi Earthquake for example. It took Chunghwa Telecom 15 days to repair the telecommunications network. During 88 Flood, disconnected base stations totaled 3,300, 1,800 of which belong to Chunghwa Telecom. 550 of Chunghwa Telecom could not function properly after two days of the flood. In other words, mobile communication was paralyzed and it could not be immediately repaired in the Golden 72 Hours.

II. Related Researches

A. Introduction of related researches

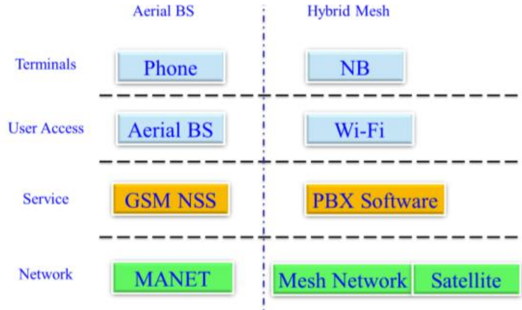

Figure 3. System architectue of aerial BS and Hybrid Mobile Ad Hoc network

In aerial wireless emergency communication system [10], aerial BSs and long distant wireless were used to form an aerial BSs Ad Hoc network. Aerial BSs connect to GSM core network through the aerial Ad Hoc network. And thus, users can use their cell phone connect to the aerial BS and make a cell phone call. Hybrid Mobile Ad-Hoc network [1] was a two hierarchical network. It takes WiFi mesh network as the user access layer and WiMax and GEO Satellite mesh network as network service 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. System structure of aerial BS and Hybrid Mobile Ad Hoc network are showed in Fig3.

Because cell phone may be the first thing carried by people in a disaster and thus aerial wireless emergency communication may have good popularity by choosing cell phones as its terminals. But, deployment of Aerial BSs needs professionals that are not sufficient enough in the disaster area at the first time. Hence, only some special area may have aerial wireless emergency communication.

In Hybrid Mobile Ad-Hoc Network, notebooks are chosen as the terminals. Over the years, we have been devoted to research on contingency communication network, employing the notebooks and smart phones of voluntary workers to construct MANET-based platforms. In addition, we employ VoIP technique to realize contingency communications system [5,6,7], which can, but is limited, provide a small portion of disaster response workers. First, it is to support those who have laptops only; cell phone users cannot be supported. Second, required specialized knowledge is necessary to set up and operate the system. Third, the effective communication range is too short. If there is one convenient system that can readily restore and provide partial communication functions for cell phone users, such as calling each other in the base stations or treating it as Walkie-Talkie, rescue and relief work can be much more convenient. Moreover, we should utilize all the possible resources to aid the rescue and relief work to save as many lives as possible. As a result, it becomes a worth-pursing topic to restore the communication functions of the disconnected cell phones in band-aid style before cellular operators make an effort to repair.

Building on the disaster research over the years, we know that the majority of disconnected mobile base stations stop operation due to power outage and disconnected backhaul, not because the structure of base station is destroyed.

The purpose of the study was to investigate how to connect the disconnected base stations and plan network topology of them in order to building disaster contingency communications system in the most convenient and fastest way so that cell phone in the disaster zone can function partially.

III. Contingency Cellular Network (CCN)

A. Design Philosophy of CCN

Design philosophy of CCN is to employ existing disconnected base stations in the disaster area. The reasons are as follows: (a) wide coverage of mobile communication network; (b) widespread use of cell phones; (c) add-on modules that repair disconnected base stations could be made with low cost; (d) low-barrier of use, which are mostly needed in current disaster response communication. One crucial non-technical reason, as we mentioned before, is that cell phone might be the first thing carried by most victims and people who escape from their homes when a disaster comes. Therefore, reconnecting disconnected base stations in the disaster area to provide a large-scale emergency communication service is a good option.

Contingency Recover Package (*CRP*) includes power module, inter-cell communication module (*ICC Module*), and an add-on processing module, which is referred to as emulated controller module (*EC Module*). CRP can be stored in national disaster response centers or cellular operators and delivered to selected base stations via airdrops or helicopter. First, EC Modules are connected to base stations. Second, we use the inter-cell communication module to construct a multi-hop wireless network and rebuild connections between base stations and core network. And then, these base stations can provide some limited service. Anyone who has a cell phone can access service from these base stations. If there is no way to connect to the core network, some CRP may include satellite communication modules (SC Module) to support the connection to the core network. Depending on the available fund, some number of CRPs can be previously stored in the national disaster response center and transported via helicopters to the selected stations to construct CCN rapidly.

B. The procedures of deployment and operation

The deployment of CCN Network is divided into four stages, with each stage elaborated below:

Stage 1: Damage Assessment Phase
The manager of CCN, which is most likely a government unit, will collect disaster information and carry out a damage assessment to obtain an overall picture of the disaster. The CCN can be activated immediately to perform self-diagnosis if it is pre-installed in the existing cellular system. Before backup power is exhausted, an isolated station can self-diagnose the severity of the damage, find out the routing path to a connected station, and report the assessment to the control center.

Stage 2: Planning Phase: Choose the disaster areas and base stations for recovery. Design the recovery scheme according to the assessment, including network topology planning, deployment schedule of the selected stations, routing, and bandwidth allocation strategies, etc.

Stage 3: Deployment Phase: The construction and set-up of CCN are based on the results of the second stage.

Stage 4: Operation Phase: The service strategies should be stipulated to allow ordered access to maximize the efficiency of disaster response operation. Priority based admission control is the core functionality of this phase.

C. System Architecture of CCN – Level 0

Contingency Cellular Network (CCN) is constructed by reusing the disconnected base stations in the disaster area. The Level 0 system architecture of CCN is illustrated in Fig. 4. Components of CRP are described as follows.

Power module: including a portable power generator and fuel that is sufficient to provide required electricity by a base station for a few days. Note that although most base stations have backup power, the backup power can only last a few hours in general.

Inter-Cell Communications Module (ICC Module): Its main function is to establish connections between base stations. It should be noted that there is no wired connection between base stations in general. Major components are a wireless transceiver and an antenna. Base stations are usually built as high “cell towers” and a few miles away from each other. Therefore, there is seldom a line-of-sight problem between two adjacent cell towers. A long range WiFi or WiMAX may be able to connect two adjacent stations together. An even simpler but more effective solution is to use one out of several (3-6) cellular antennas for inter-cell communication. Nevertheless, this measure had better be taken as the last resort as the users of a whole sector may lose the service. Finally, the topology of CCN is almost fixed over time so that the direction of antenna of this ICC module can be measured or calculated in advance.

Emulated Controller Module (EC Module): EC Module is the core controlling component of CCN. Its main functionalities are establishing connections between base stations and transferring telecommunication signaling and data into VoIP package. Then, it acts as the IP backhaul allowing base stations to provide communication service.

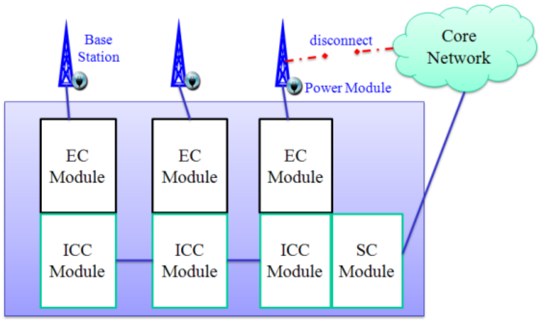

Figure 4. System Architecture of CCN – Level 0

Low-cost solutions to implementing EC Module are many, one of which is a laptop equipped with interface to the ICC module and the target base station.

Satellite Communications Module: provides the connection between CCN and core network. Thus, people in the disaster area can communicate with outside. Satellite communications equipment, which is not confined to the geographical boundaries, can connect to the core network directly. However, only a few base stations can be installed due to its high cost. Disconnected base stations connected to core network through survival base stations or those base stations embedded with satellite communications equipment by multi-hop. Thus, the external bandwidth can be shared by all the recovered BS of CCN.

To satisfy the communication requirements of disaster works, CCN supports three types of communication modes: ordinary, walkie talkie like and agency communication modes.

Ordinary Mode: the original 1-1 communication mode.

Walkie Talkie Like: To increase response work efficiency, CCN supports walkie talkie like communication mode which is the popular communication mode used by life relief teams. Response workers can dial a special number and join a walkie talkie group. One's voice data is multi-casted to those who belong to the same group. Because multi-casting data between different base stations may exhaust too much inter-BS wireless bandwidth, members in the same group is constrained to connect to the same base station in CCN.

Agency Communication Mode: People in the disaster area may not know each other. When a victim needs a doctor, he doesn't know how to contact the nearby doctor and receives medical treatment immediately. Agency communication mode enables victims and disaster response works to contact the one who is nearby and has ability to help them. Before receiving an agency call, professionals need to register to a specialty group which is called agency group. There are two ways to register as the group members. In usual time, CCN registers the phone numbers of professionals and assigned them to agency groups according to their specialties. When disaster happens, disaster response works will receive a unique ID and use the given ID to register to CCN. Each agency group has a unique phone number. And then, when a caller dials the number of an agency group, the phones of the nearest *k* members of the agency group are ringed until one of them pick up the phone. Moreover, with agency communication mode, response workers can contact to the response workers that has required specialty to cooperate. This will help a lot to the efficiency of response work.

D. *System Architecture of CCN – Level 1*

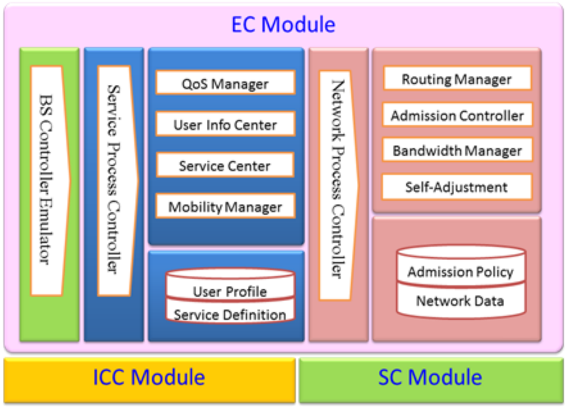

Figure 5. System Architecture of CCN – Level 1

Level 1 system architecture is illustrated in Fig5. Components of EC Module are illustrated as follows:

Service Process Controller: responsible for service procedure and cooperates with the function components to fulfill the service to the users.

User Profile: records user information such as phone number, IMSI, agency group, service level agreement (SLA) and etc.

Service Definition: the definitions of communication services include service procedure and corresponding functions. New communication is added/modified by adding/modifying its' service definition.

BS Controller Emulator: deals with the communications protocol with base stations and transfers signal and data into VoIP package. The existing mobile network base stations come from different companies, and the software and hardware are updated constantly. After the update of the base stations, EC Module may not work properly if it is not updated. EC Module is a kind of emergent equipment and has no ample fund and resources to update constantly. To ensure the utility of CCN, we use BS controller emulator to deal with the problem of base station connection. When the base station is updated, only the BS controller emulator is required for renewal, with other functions unchanged.

Service Center: supplies the necessary function to provide communication service. Since, CCN support three types of communication modes. Service center discriminates the communication mode of an incoming call and uses corresponding function to fulfill user's request by referring to the service definition.

User InfoCenter: responsible for user identity. There are two kinds of users, one is agency group member and the other is anonymous who has no user information in CCN. When an anonymous user connects to CCN, user infocenter records its' user information with default agency group and SLA.

QoS manager: responsible for deciding the QoS of the incoming calls. The incoming calls have different emergency degrees. According to the emergency degree of the phone call, different phone call quality is provided. The more urgent one receives high bandwidth to provide better service quality, and vice versa. The emergency degree of the phone call is determined by the registered agency groups of the callers and receivers. If the callers and receivers are not registered, the priority will be given to those who have registered. The main purpose of giving different bandwidth according to the urgency of the phone calls is to answer as many phone calls as possible without affecting the life-saving efficiency.

Mobility Manager: responsible for finding out the location of the callee.

Network Process Controller: responsible for network service procedure and cooperates with the function components to fulfill network service.

Network Data: records the network related information such as network topology, allocated bandwidth, bandwidth utility rate and etc.

Admission policy: records the admission policy of network resources such as inter-BS bandwidth and satellite bandwidth.

Admission Controller: prioritizes emergent phone calls to access the telephone service. The capacity of CCN is smaller than usual public network, making it difficult to handle massive phone calls. Also, the degree of urgency varies, ranging from regular care phone calls to emergent calls for rescue in the disaster areas. Since not all phone calls can be answered, every possible means should be made to prioritize emergent phone calls to access the telephone service in the communications system.

Routing Manager: responsible for planning network topology and routing path from source to destination. Network topology is planned in planning phase firstly. And then, network topology is dynamically re-planned according to the change of communication requirement to maximize the benefits of disaster-saving

Bandwidth Manager: responsible for wireless bandwidth allocation and management. Because the information needs to be transmitted through the neighbor station, which occupies its bandwidth, the number of users of each base station needs to be rationally distributed to meet the disaster-saving demands regarding the number of communications channels of each base station to avoid allocation disequilibrium. If this task is not done well, the bandwidth of some base stations may be occupied by the transmitted information. Thus, communication service cannot be provided. The worse-case scenario is that the bandwidth may be occupied by the less disastrous areas; the more disastrous areas may not receive any bandwidth at all. Given the optimal disaster-saving benefits, it is necessary to allocate appropriate number of communications channels to each base station.

Self-Adjustment: responsible for re-planning network topology and bandwidth allocation when the environment is changing.

IV. Planning of Network Topology

A. *Motivation of network topology planning*

Network topology planning is the function of routing manager. Because most base stations cannot be linked to external network, it requires multiple hopping to get connected. The plan of network topology can determine the whole efficiency of the network, the benefits of disaster-saving and its stability. The considerations of disaster-saving benefits include the emergency of the afflicted areas or the degree of the disaster and the number of committed disaster-saving personnel. The design strategy should maximize the benefits of disaster-saving and maintain the number of deployment to increaser its stability. The design of bifurcation is based on the estimated possible telephone calls number and its number to avoid Internet congestion and to increase the percentage of the overall network so that most phone calls can be provided to avoid Internet congestion and maintain network stability given limited resources.

Every second of disaster-saving is crucial. If EC Module and ICC Module can be planned and constructed to reduce the latent period of communications service, more precious life-saving time can be obtained. 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 and two modules can be constructed. When the disaster comes, EC/ICC Module will be activated through minimum spanning tree to construct CCN network automatically before back-up battery power is lost. By doing so, all kinds of gathered information can facilitate CCN post-construction. The service will be terminated following the power-cut of the system.

After CCN is constructed, Routing manager can also be applied to the establishment of the network topology adjustment and planning. For example, for the disaster-rescue needs, base stations will be added. Routing manager detects the adding of a new base station, it will activate the planning of new topology to meet the rescue needs of CCN dynamic adjustment. In addition, when the base station loses connection out of the blue, Routing manager will activate and organize new network topology to maintain the network operation.

B. *CCN Forwarding Tree*

In our CCN, all base stations are equipped with an ICC Module to from an Ad Hoc network. Goal of network topology planning is finding a CCN forwarding tree (CCN FT) of the Ad Hoc network. A survival base station is chosen as the root. And thus, other stations can connect to core network by multi-hop through the root. A pair of ICC Modules is needed to establish the link between base stations. Since the number of ICC Modules is limited. In order to maintain the connectivity of base stations, the forwarding tree is re-planned immediately, if any of the links of the forwarding tree is missing.

Although tree topology is vulnerable for its suffering of single point of failure, we choose to use tree topology for the following reasons. First of all, tree topology is easy to deploy and maintain, which is very critical in a hectic disaster environment. More importantly, each base station require ONLY three antennas. Multi-path topologies require more than three antennas, which may increase the difficulty of CCN deployment. Nevertheless, we will design multi-path topologies in the future based on the experiences we obtained on tree topology.

Furthermore, if there are more than one survival base stations available to act as the root of a forwarding tree, we can easily convert the multi-root topology planning problem into a single root problem by adding a virtual root and one link from the virtual root to each of the real roots to the graph.

C. Optimization models

We propose two optimization models for building forwarding tree. The first model is K-Maximum Profit Spanning Tree with Bounded Depth (K-MaxSTBD). The goal of K-MaxSTBD is to find K out of N base stations to form the forwarding tree which has maximum benefits of disaster-saving and the depth of the tree is no more than D. K is equal or less than N. The depth of the forwarding tree is limited due to two reasons. One is to balance the network traffic and the other is to avoid too much hop from the leaf to the root. Too much hops will cause long delay time and decline the quality of voice communication. The second model is K-maximum Profit Spanning Tree with Hop Concern, K-MaxSTHC, in which, the profit of recovering a base station is decreasing as its hop distance to the root is increasing. Other conditions of K-MaxSTHC are the same as K-MaxSTBD.

D. K-MaxSTBD

The model of K-MaxSTBD is described as follow:

Given a graph *G(V,E)*, where
$V = \{v_i | i = 0, 1, \ldots, n\}$ is the set of survival base stations.
v_o is the root node that has an external link.
Degree of $v_i \leq 6$.
$E = \{e_{ij} | v_i, v_j \in V\}$ is the set of links to be constructed if selected, and a wireless connection between v_i and v_j can be established on e_{ij}.
$P = \{p(v_i) | p(v_i) \in \mathbb{Z}^+, v_i \in V\}$, $p(v_i)$ is the profit of v_i.
$\mathcal{K} \in \mathbb{Z}^+$ is the total number of resources(CRP).
$\mathcal{B} \in \mathbb{Z}^+$ is an upper bound of CCN forwarding tree's depth.
In CCN forwarding tree, "Forwarding Path of v_i" is the path from v_i to v_o through path $\langle v_i, \ldots, v_o \rangle$.

Our problem is to find a CCN forwarding tree $T(V_T, E_T)$, $T(V_T, E_T) \subseteq G(V, E)$, where v_o is the root of $T(V_T, E_T)$, such that $\sum_{v_i \in V_T} p(v_i)$ is maximized, subject to $|V_T| = \mathcal{K}$ and The depth of $T(V_T, E_T) \leq \mathcal{B}$.

E. K- MaxSTBD is NP Hard

K-Maximum Spanning Tree (K-MaxST) problem has been proved NP-Hard [12], which is to find a maximum total profit spanning tree whose number of nodes is an integer K, and K-MaxSTBD is actually to find a K-MaxST and the depth of K-MaxST is no more than an integer $\mathcal{D}$. Thus, K-MaxSTBD can be easily proved as NP Hard.

As a decision problem, we ask simply whether a K-spanning tree with bounded depth (K-STBD) of a given total profit $\mathcal{P}$ exists in the graph. The formal definition is

$$\mathrm{K-MaxSTBD} = \{\langle G, \mathcal{P} \rangle : \text{G is a graph with a K} - \text{STBD of total profit } \mathcal{P}\}$$

(A) K-MaxSTBD is in NP

Suppose we are given a graph $G\{V, E\}$, and a integer $\mathcal{P}$. The certificate we choose is the K-MaxSTBD$\subseteq G\{V, E\}$ itself. The verification algorithm affirms that the total profit of K-MaxSTBD$= \mathcal{P}$, and then it checks, whether the tree depth $\leq$ B. This verification can be performed straightforwardly in polynomial time.

(B) K-MaxSTBD is NP-Hardness

To prove that K-MaxSTBD is NP-hard, we show that $\mathrm{K-MaxST} \leq_p \mathrm{K-MaxSTBD}$.

Let $G\{V, E\}$ be an instance of K-MaxST. We construct an instance of K-MaxSTBD as follows. We form the graph $G'(V', E')$, where $V' = V$, $E' = E$, $K' = K$, and $\mathcal{D} = K$.

The instance of K-MaxSTBD is easily formed in polynomial time. We now should show the graph G has a K-MST if and only if graph G' has a K-MaxSTBD whose bound constraint = K. The process is very straightforward. If we simply found a K-MaxST for graph G with no other constraint, the depth $\mathcal{D}$ of the K-MaxST is always between 1 and (K-1), that is $1 \leq \mathcal{D} \leq K - 1$, which is always smaller than the depth bound constraint K. Conversely, suppose the G' has a K-MaxSTBD whose depth bound constraint $\mathcal{D} = K$. The K-MaxST with bounded depth $\mathcal{D} = K$ is always the K-MaxST in G, just like no depth bound existing.

F. Bounded Depth Tree Building Algorithm (BDTBA)

We solve the K-MaxSTBD by a heuristic algorithm BDTBA as follows.

```
BDTBA(G, p, r, K, B)
  Set T = {}        /* bounded depth tree */
  Set U = {r}       /* r is the root of  T, belong to G*/
  while elements in U has at least one adjacent node
     while size of T < K do
          let v be a highest profit adjacent node of u such that
          v ∈ V(G) − U, u ∈ U and depth of u ≤ B − 1
          add v to U
          add link(u, v) to T
          delete v from V-U
     end while
  end while
```

G. K-MaxSTHC

The model of K-MaxSTHC is described as follow:

Given a graph *G(V,E)*, where
$V = \{v_i | i = 0, 1, \dots, n\}$ is the set of survival base stations.
v_o is the root node that has an external link.
Degree of $v_i \le 6$.
$E = \{e_{ij} | v_i,\ v_j \in V\}$ is the set of links to be constructed if selected, and a wireless connection between v_i and v_j can be established on e_{ij}.
$P = \{p(v_i) | p(v_i) \in \mathbb{Z}^+,\ v_i \in V\}$, $p(v_i)$ is the profit of v_i.
$\mathcal{K} \in \mathbb{Z}^+$ is the total number of resources(CRP).

Our problem is to find a CCN forwarding tree $T(V_T, E_T)$, $T(V_T, E_T) \subseteq G(V, E)$, where v_o is the root of $T(V_T, E_T)$, and $h(v_i)$ is the number of hops from root to v_i, such that maximize $\sum_{v_i \in V_T} \left(\frac{p(v_i)}{h(v_i)}\right)$, subject to $|V_T| = \mathcal{K}$.

H. Hop Concern Tree Building Algorithm (HCTBA)

The K-MaxSTHC can also be proved NP-Hard. It is not presented here for space saving. We design a heuristic algorithm HCTBA as follow.

HCTBA(G, p, r, K,)
Set T = {} /* hop-concern tree */
Set U = {r} /* r is the root of T, belong to G*/
while elements in U has at least one adjacent node
while size of T < K do
let v be a highest (profit/hop) adjacent node of u such that $v \in V(G) - U, u \in U$
/ hop= the number of relay hops from root to v*/*
add link(u, v) to T
delete v from V-U
end while
end while

V. PERFORMANCE EVALUATION

A. Objective and Enviroment of Experiments

We use a desktop PC to evaluate proposed algorithms by simulation. 10 random graphs are generated in each specified in Table I. Heuristic algorithms for K-MaxSTBD (BDTBA) and K-MaxSTHC (HCTBA) were evaluated against optimal solutions (by brute force).

TABLE I. EXPERIENCE PARAMETERS

	Graph		K (CCN FT size)	B (depth bound)
	N(size)	E(edges)		
1(a)	10	15-20	5	3
1(b)	20	30-45	10	4
1(c)	30	46-70	15	5

B. Experiment Results

From Fig.6, we can see that the total profits of BDTBA are similar to optimum solutions in most cases. The total profits of HCBTA are less than optimum solutions in half of cases. From Fig7, we can see that the depth of HCTBA is shallower than BDTBA's and optimum solutions. In other words, the hop count of HCTBA is less than BDTBA's and optimum solutions. Although optimal solution can be solved by using brute force, brute force cannot find the optimal forwarding trees in reasonable time when the size of group excess 10 in our experiments. Therefore, when size is more than 10, only BDTBA and HCTBA were evaluated.

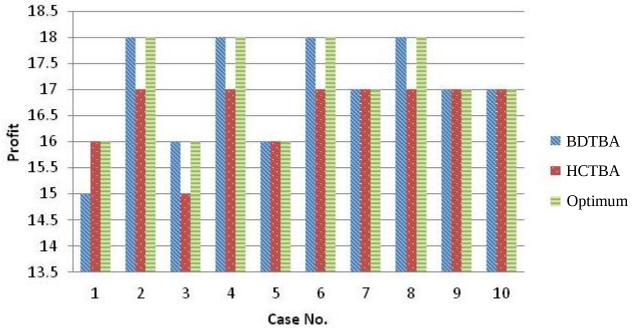

Figure 6. Experiment (a): Total Profit

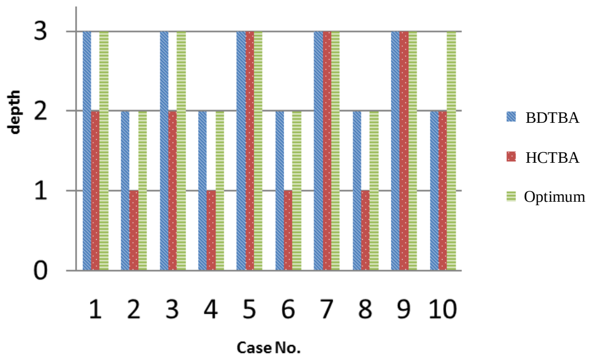

Figure 7. Experiment (a): Depth of forwarding trees

We can see that from Fig. 8 and 9, the forwarding trees which have deeper depths have higher total profits. Since the depth of BDTBA is bounded by ***B***, HCTBA tends to build deeper forwarding trees.

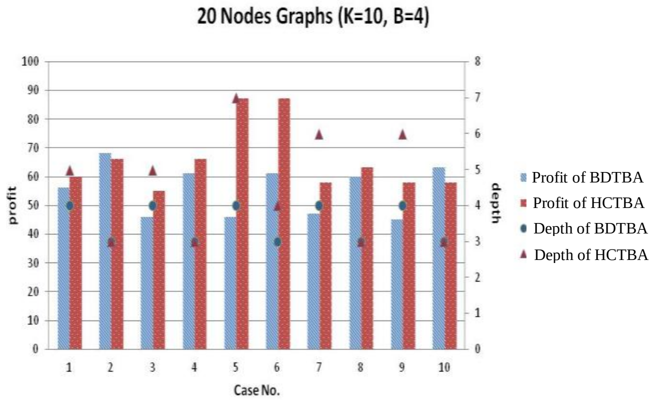

Figure 8. Experiment (b): Total Profit and depth of forwarding trees

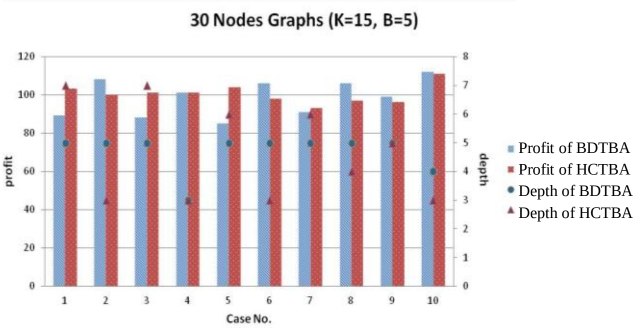

Figure 9. Experiment (c): Total Profit and depth of forwarding trees

VI. Concluding Remarks

When stricken by a catastrophic natural disaster, many communication systems crashed, including cellular networks. The loss of communication system may have a catastrophic consequence. From Chi-Chi Earthquake and 88 Flood, we learn that power outage and backhaul link breakage were the two common problems that crushed base stations. It is difficult to enhance the availability of power lines and backhauls since they are highly dependent on the robustness of roads and bridges. Unfortunately, due to the paralysis of transportation system, the disaster response operation in the Golden 72 Hours may have to rely on many disorganized local voluntary workers. Rapid deployment of many existing emergency communication systems relies on a good transportation system, which is usually not available in a catastrophic natural disaster. Coordination among these disorganized disaster response workers has become extremely difficult without the support of the communications system. The efficiencies of their disaster response operations are severely crippled.

In this paper we introduce our CCN architecture connecting physically intact but service-disrupted base stations together with wireless links. The design strategies of network topology must maximize the relief efficacy and balance network traffic distribution to increase the stability of CCN. We model the CCN topology design problem into two maximum spanning tree problems of graph theory aiming to maximize the total profit of recovered base stations and limit the tree depth in the same time. The problems are proven NP-hard and we designed two efficient heuristic algorithms (BDTBA and HCTBA) to solve them. From the experiment results, we found that the total profit of BDTBA is less than HCTBA's in most cases. Further, the depth of HCTBA solutions is likely deeper than BDTBA solutions. If a CCN network is delay sensitive, the CCN operator can use BDTBA with a tolerable depth bound to find the forwarding tree. Otherwise, the operator can use HCTBA to find the forwarding tree that may have higher total profit and deeper depth.

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