Cross Network Topology Design 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 proposed a Contingency Cellular Network (CCN) for emergency communication by connecting disconnected base stations together with wireless links and constructing a multi-hop cellular network. CCN can support existing mobile phone users with reduced capability. Such a system can support a large number of disaster responders in the early hours of a catastrophic natural disaster, thus save many lives. This paper addresses the design of forwarding topology using multiple operator's base stations aiming to maximize the efficiency of disaster response. We take the degree of emergency and population of each stricken area as the priority measure as well as the available resources as the constraint to determine the topology. The CCN Cross Network Topology Design problem is modeled as a K-Maximum Spanning Tree Problem. The problem is proven NP Hard. We also designed a few efficient heuristic algorithms to solve the problem when it is needed in urgent.***

Keywords—Disaster Management, Emergency Communication, Mobile Communication, Ad Hoc Network, Deployment Scheduling

I. Introduction

Frequently occurring large-scale natural disasters in recent years has caused huge property damage and loss of lives. The Haiti Earthquake that occurred in 2010 alone claimed 230,000 lives. The Japan Northeastern 9.0 magnitude Earthquake that happened on March 11, 2011, followed by a 23-meter high tsunami, and a nuclear melt-down disaster together created a complex major natural disaster stunning the whole world. We summarize the common system problems observed in many large-scale natural disasters, such as 921 Chi-Chi Earthquake (Taiwan) [1], 88 Flood (Taiwan), SiChuan (China) [5] and Haiti Earthquakes as follows:

- paralysis of transportation system
- paralysis of communications network
- lack of professional disaster responders
- dysfunctional administrative command system

The impact to the disaster response caused by above mentioned system problems are as follows:

- difficult to transport resources to the disaster areas
- inefficient resource allocation and reallocation resulting in the misplacement of resources
- inefficient coordination among disaster responders lowering the disaster response efficiency

Although plenty of resources may be available from all over the world to assist a large scale natural disaster, due to the above mentioned inefficiency, a disaster may still claim many lives that could have been saved if disaster response operations could be more efficient. A well operated mobile communication system is certainly a key factor to improve the efficiency of a disaster response operation.

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, we found that during 88 Flood and 921 Chi-Chi Earthquake in Taiwan and Hurricane Sandy in the East coast of United States, the 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 a disaster.

Critical hardware equipments were knocked down: due to (1) external power outage; (2) fuel for power generator exhausted; (3) cooling system broken; and (4) switch overheated.

Because every base station must be connected to the controllers or switches through backhaul cables, it can no longer keep in operation as long as its backhaul is disconnected even if its physical structure remains intact in a

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disaster. Unfortunately, the cables of power lines or backhaul links are usually laid along roads and bridges for the convenience of deployment and maintenance. The destruction of roads and bridges, which was a common phenomenon in a disaster, leads to power outage and network disconnection. Although power lines and communication backhauls usually have redundancy for higher availability, they may not necessary improve the survivability significantly in a large scale disaster. For instance, a huge flood over a river may destroy many bridges over the river simultaneously breaking all redundant cables completely. Take 88 Flood as an example, the structure of many base stations remained intact because they were often located at a higher place. However, when the power lines and backhauls that were laid along the roads and bridges were destroyed by the flood, mobile communications system was paralyzed a consequence. Power lines and backhauls become an Achilles' heel of many existing mobile communications networks.

Unfortunately, current emergency communication systems are limited by either small capacity or paralyzed transportation systems [2]. We proposed a Contingency Cellular Network (CCN) [2,3] for emergency communication by connecting disconnected base stations together with wireless links and constructing a multi-hop cellular network. CCN can support existing mobile phone users with reduced capability. Such a system can support a large number of disaster responders in the early hours of a catastrophic natural disaster, thus save many lives.

II. System Requirements for Emergency Communication Network

Based on our firsthand experience obtained in 921 Chi-Chi Earthquake and extensive researches in past decade [1,2,3,5], we summarized a set of system requirements for Emergency Communication Network dedicated to Disaster Responses (ECN-DR), which have to be addressed in constructing and operating an emergency communication network. These requirements are categorized into two different sets: User End and Operator End.

A. User End Requirements

Popularity: In a large scale disaster, a large number of volunteers must be mobilized to work on rescue and relief operations. In addition, the people, including victims, in the disaster area may have extensive communication needs. Therefore, a large number of user terminals are needed for an ECN-DR. Due to the rareness of terminals, most common emergency communication networks, such as satellite communication, trunking radio and amateur radio can only be used by specific groups. Most victims and volunteer disaster responders cannot access to these communication networks. Besides, users need to be trained to use special designed terminals for trunking radio and amateur radio, hence these systems can only be used by professional disaster response squads.

Usability: ECN-DR should provide task oriented communication services, support mobility, and have adequate QoS. Furthermore, the handset of ECN-DR should be user friendly that doesn't require a long training time as well as long standing time. Task oriented communication services should include ordinary and group communication services. Finally, disaster responders might have to move frequently, the mobility of the user terminal is also important.

B. Operator End Requirements

Practicality: Practicality is the most important operator end requirement**,** which includes low deployment cost, easy acquisition of equipment, and rapid deployment, etc.

Although ECN-DR is critically important to disaster response operation, it does not engage in making profit and the opportunity of use is only occasional. It may not be justifiable for a commercial cell phone operator to put in a huge investment on the design and development of a large scale ECN-DR. Therefore, an ECN-DR must have low development cost in order to be practical.

Due to the hindrance of the terrain and the paralyzed transportation system, external aid is usually difficult to transport to the disaster areas. In many cases, helicopter may be the only vehicle that can access to the disaster area in the early hours or even days of a large scale disaster. Hence, the size and weight of ECN-DR equipments should fit to air transport. For instance, mobile base stations, called "Cell-on-Wheel", which has a base station with satellite backhaul and is carried by a truck, may be too heavy to be carrier by a helicopter, and hence may be useless.

Survival rate is highly dependent on the rescue speed. The earlier a trapped victim is rescued, the higher the chance he/she will survive. Thus, to save more lives, ECN-DR should be deployed as quickly as possible. Furthermore, cell phone operators will work in full capacity to restore their systems. The value of a Band-Aid style ECN-DR will be much lower once any base station is recovered back to work. Therefore, an ECN-DR must be rapidly deployable.

Capacity: An ECN-DR must have sufficient capacity to satisfy the communication demand among large number of victims and disaster responders, both professional and voluntary, as well as limited incoming and outgoing calls to communicate with external aids. Furthermore, ECN-DR should have ability to resist the burst of call requests, to prevent itself from being crashed by the massive phone calls.

Sustainability: An ECN-DR has to keep operating until the public communication network is recovered, which may take several days or even weeks. If non-stop operation is impossible, it should be recovered quickly once it is crashed.

Adaptability: The situation in a disaster area may change constantly due to aftershocks, fires, and the progress of disaster response, etc. Therefore, an ECN-DR must be able to adapt to the changing environment either manually or automatically.

Operability: Similar to any production system, an ECN-DR must have OAM (Operation, Administration, and Maintenance) function to keep in operation.

TABLE I. COMPARSIONS OF ECN-DRS

	Practicality		Usability		Popularity			Capacity
	Terminal Popularity	Terminal Usability	Terminal Mobility	Quality	Per User Cost	Deployment Difficulty	Transportation Demand	Concurrent User Limit
Walkie-Talkie	Low to Moderate	Low learning cost	High	Moderate	Low	None	Low	No. of handsets
Amateur Radio	Low	Professional skill required	Low	Moderate	Moderate	Professional skill required	Low	No. of handsets
Satellite Mobile Phone	Low	Easy	High	Moderate	Very High	None	Low	No. of handsets
Trunking Radio	Low	Low learning cost	High	High	High	Easy	High	No. of handsets
Cell-On-Wheel	High	Easy	High	High	High	Easy	High	No. of Cell-on-Wheels
MANET	Moderate	Easy	Moderate	Low	Low	Professional skill required	Can use local resource	Bandwidth of MANET

III. COMPARISONS OF ECN-DRS

Conventional Emergency Communication Network dedicated to Disaster Responses (ECN-DRs) that have been widely used in disaster responses are Walkie-Talkie, amateur radio, trunking radio, mobile satellite phone, and Cell-on-Wheel (mobile base station), etc. Recently, WiFi based Ad Hoc network (***MANET***) for ECN-DR has been studied by many researchers. A MANET based system uses mobile computing devices such as laptop PC, tablet PCs and smart phones to construct an ECN-DR. Some may have satellite connection to the external Internet. Users can use a mobile device running a VoIP application to access the communication service. A brief comparison of these technologies using part of the requirements presented above is shown in Table I. Each of them has its own advantages and limitations.

Walkie-Talkie, amateur radio, satellite communication and Trucking radio are often used in disaster response. All of them need special terminals. They have high usability and practicality, but low popularity. Except a few countries such as United States, Walkie-Talkie is not very popular among ordinary people. According to our experience in 88 Flood, it took Taiwanese government more than two weeks to borrow approximately1000 Walkie-Talkie sets from vendors to support disaster response. Nowadays, the popularity of Walkie-Talkie even in the United States is much lower than that of cell phone.

Cell-on-Wheel can be deployed rapidly to the disaster area to support cell phone users. However, due to its high cost, local cell phone operators may not have sufficient number of such equipment ready for a large scale natural disaster. Furthermore, a Cell-on-Wheel system is usually built on a truck such that it may have difficulty to be transported to the afflicted areas from either local or foreign areas. MANET based systems can support laptop and smart phone users. They are easy to construct and can use user's own equipment such that it doesn't count on pre-allocated funding to acquire user end devices. However, their quality is skeptical for one critical reason: a GEO satellite link and VoIP over MANET may cause a long delay time which may severely hurt the quality of a phone conversation. Finally, MANET is not a commercially mature product and may not be able to obtain sufficient financial support for further research and development due to its lack of commercial incentive.

IV. CONTINGENCY CELLULAR NETWORK (CCN)

In our long time study in the past decade, we discovered that most base stations were crashed in a disaster due to the breakage of power source or their backhaul links. Based on this fact, we designed a new ECN-DR, called Contingency Cellular Network (CCN), by connecting service disrupted but physically intact base stations using wireless links to form a multi-hop cellular network. The main design philosophy of CCN is to reuse existing disconnected base stations to save cost and deployment time as well as to support a large number of existing users. 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 use. 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.

Contingency Recover Package (*CRP*) consists of a power module, a number of 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 the selected base stations via 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 core network. Anyone who has a cell phone can access service through these base stations. If there is no way to connect to the core network, some CRP may equip with a satellite modem to establish a connection to the core network.The system architecture of CCN is illustrated in Fig. 1. All required equipment to rescue a base station is packaged in a *Contingency Recovery Package* (CRP), which is described as follows.

Power module: consists of a portable power generator and required fuel that is sufficient to provide electricity to a base station for a few days.

Inter-Cell Communications Module (ICC Module): is used to establish connections between base stations. (There is usually no wired connection between base stations.) Major components are a wireless transceiver and an antenna.

Emulated Controller Module (EC Module): is the core controlling component of CCN. Its main functionalities are establishing connections between base stations and transferring telecommunication signaling as well as acting as a PBX to provide intra-CCN communication services. Because the external bandwidth of CCN will be shared by all base stations, there must be many radio channels remaining idle. EC Module uses these idle channels to provide intra-CCN communication services.

There are many low-cost solutions to implement EC Module. A powerful laptop equipped with interfaces to the ICC module and the target base station (most likely an Ethernet interface) running Linux operating system will be sufficient.

Satellite Modem: provides the connection between CCN and the core network. Only a few base stations can be installed due to its high cost. Others connected to core network through those base stations embedded with satellite modem through the multi-hop connectivity. Thus, the external bandwidth can be shared by all recovered BS of CCN.

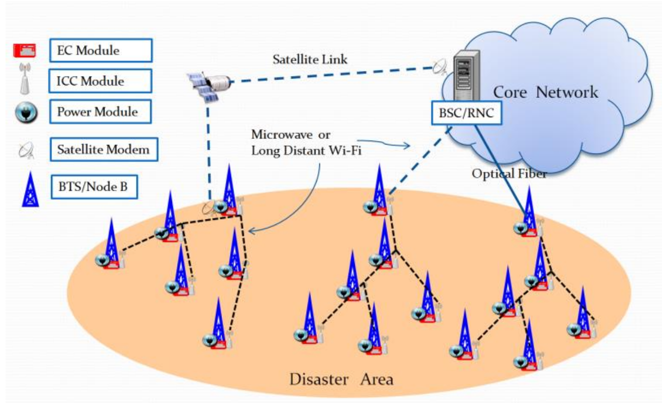

Fig. 1. System Architecture of CCN

Fig. 2.

V. CROSS NETWORK TOPOLOGY DESIGN

The number of available CRP may be far less than the number of disrupted base stations. Therefore, the first issue in deploying a CCN is to select a limited number of disrupted base stations according to the available CRPs to form a multi-hop forwarding topology with an objective aiming to maximize its efficiency as well as the stability. The priority measures include the emergency level and population of the afflicted areas, as well as the number of committed disaster responders. In our previous study, the base stations in concern all belong to a single operator. Under this assumption, the topology of a CCN may be constrained by the broken backhauls. To improve CCN topology, we propose to use the base stations from multiple operators assuming that disaster response authority has the privilege to expropriate any operator’s base stations in emergency. The problem is formulated into three different optimization models. The first model is Depth Bounded Mutually Exclusive K-Maximum Profit Spanning Tree (DBME K-MaxST). DBME K-MaxST has two constrains. First one is the depth constraint to avoid too much forwarding traffic as well as to avoid long hop connections. The second constraint is the mutual exclusive constraint that only one base station in each covered area can be included into CCN to avoid redundancy. This model is simple, but may discard a seriously damaged area that is too far from the root. The second model is Depth Controlled Mutually Exclusive K-Maximum Profit Spanning Tree (DCME K-MaxST). DCME K-MaxST dynamically adjusts the tree depth so that the serious damage areas would not be discarded by the depth constraint. The first two models allow only one base station being selected into CCN. However, the damage of a disaster may not evenly distribute such that some afflicted areas may be much more serious than others. It may be more beneficial to relax mutual exclusive constrain. The third model is Depth Controlled K-Maximum Profit Spanning Tree (DC K-MaxST). Enlarging the concurrent users of some critical areas, such as headquarter area, may increase the disaster response efficiency, the mutual exclusive constraint in DC K-MaxST is relaxed such that the base stations from more than one operator in the same covered area can be included into CCN. These three optimization models are all NP-Hard that require extensive time to solve. Due to highly stringent time constraint, only simple an fast solutions are affordable. Therefore, we developed a few fast heuristic algorithms to solve them. Technical details are skipped and can be found in [5].

VI. CONCLUGIND REMARK AND FUTIRE WORKS

In this paper, the analysis of an emergency communication system for large scale national disaster based on our first hand experiences is presented. We also introduce CCN architecture that connects physically intact but service-disrupted base stations together with wireless links as well as the cross network topology design. The objective of topology design is to maximize the efficacy of disaster response and to balance network traffic for stability. CCN topology design problem were modeled as three maximum spanning tree problems aiming to maximize the total profit with various constraints. These problems are proven NP-hard.

In the future, we will develop a prototype using wireless access points as ICC Module to verify the CCN design concept.

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