

# Bandwidth Allocation of 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 life saving. We propose to build a contingency cellular network (CCN) to support emergency communication in large scale natural disasters by connecting disconnected base stations. This research addresses the bandwidth allocation problem. The advance of mobile communication technologies has brought great convenience to users. Cellular phone becomes the first communication tool most people would use in emergency. However, cellular networks were usually crashed in earthquake, typhoons or other natural disasters due to power outage or backhaul breakage. Unfortunately, the efficiency of communication system is a critical factor to the success of disaster response operation such as resource allocation as well as coordination of rescue and relief operations. We designed a contingency cellular network (CCN) by connecting physically intact but service-disrupted base stations together with wireless links. As the bandwidth resource in CCN is limited, a smart bandwidth allocation to facilitate prioritized bandwidth sharing will maximize the contribution of CCN to the disaster response operation. We model the CCN Bandwidth Allocation Problem into a Nested 0-1 Knapsack Problem aiming to maximize disaster response operation efficiency. The problem is proven to be NP Hard. We also design an efficient heuristic algorithm to solve the problem when it is needed in urgent.

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

## I. INTRODUCTION

### A. The Impact of Large-Scale Natural Disasters

When stricken by a catastrophic natural disaster, many communication systems, including cellular networks, usual crashed. 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 commonest 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.

Coordination among disorganized disaster response workers has become extremely difficult without a functional communications system. The efficiencies of their disaster response operations are severely crippled. Therefore, we designed an emergency communication network for disaster response (ECN-DR), which is called Contingency Cellular Network (CCN) [3,4,5], by connecting disconnected base

stations in the disaster zones with wireless links and portable power generators. CCN can support existing cellular users with limited capability. Such a system will be able to support many voluntary workers and victims in the early hours of catastrophic natural disasters, and thus saving many lives.

### B. Grant Challenges of ECN-DR

TABLE I. 7-ability of ECN-DR

7-ability	<i>Practicability</i>	<ul style="list-style-type: none"><li>• low development cost</li><li>• easily access to the equipment</li><li>• construct rapidly and easily</li></ul>
	<i>Popularity</i>	<ul style="list-style-type: none"><li>• large amount</li><li>• user friendly</li></ul>
	<i>Usability</i>	<ul style="list-style-type: none"><li>• key services to response works</li><li>• support mobility</li><li>• high quality of service</li><li>• long standing time of terminals</li></ul>
	<i>Capacity</i>	<ul style="list-style-type: none"><li>• sufficient number of concurrency users</li><li>• resist the burst of call request</li></ul>
	<i>Sustainability</i>	<ul style="list-style-type: none"><li>• long sustained time</li><li>• quick recover</li></ul>
	<i>Operability</i>	<ul style="list-style-type: none"><li>• have operation and maintain functions</li><li>• can adjust network topology, bandwidth allocation and etc. accord to the requirement of response workers</li></ul>
	<i>Adaptability</i>	<ul style="list-style-type: none"><li>• disaster awareness</li><li>• self-adjustment</li></ul>

An emergency contingency communication system should be constructed rapidly and provides communication services in disaster areas. Due to the highly time demand and extreme environment conditions, there are seven issues which are called 7-ability [3] (see TABLE I.) have to be addressed when constructing and operating a contingency communication system. Especially, practicability, popularity, usability and capacity are the key issues.

## II. RELATED RESEARCHS

### A. Comparison of General ECN-DR

Common communications systems, such as walkie talkie, amateur radio, satellite communication, trunking radio, cell on wheels, MANET, have their own advantages and limitations (see TABLE II.). Apart from the mobile base stations applicable to the general users, the rest can be used by specific target groups, rendering the disaster response communication almost impossible in the disaster areas. However, the mobile base stations make transportation to the afflicted areas difficult and its number is limited. As a result, it can only be used in certain areas, making it difficult to meet the communication needs in the afflicted areas. To accelerate the progress of

disaster response work, new disaster contingency communications systems need to be researched and developed to satisfy the basic needs of the communication in the disaster areas so that disaster response communication can be widely used in the disaster areas [3,4].

TABLE II. Comparison of General ECN-DR

	Practicability			Popularity		Usability		Capacity
	Cost	Construction	Access of Equipment	Number of Terminals	User Friendly	Mobility	Quality	Concurrency users limited
Walkie-Talkie	Low	No need	Easy	Regards the area	Easy	High	Middle	Number of handsets
Amateur Radio	Middle	Need professionals	Easy	Few	Profession-als only	Low	Middle	Number of handsets
Satellite communication	Extreme High	Existing system	Easy	Few	Easy	High	Middle	Number of handsets
Trunking Radio	High (devices are few)	Easy	Hard (Land transport)	Few	Learning is needed	High	High	Number of handsets
Cell on wheels	High (devices are few)	Easy	Hard (Land transport)	Many	Easy	High	High	Number of cell on wheels
MANET	Low	Need professionals	Easy (devices on hand)	Middle	Easy	Middle	Low	Bandwidth of MANET
CCN	Low	Middle	Middle (Air/Land transport)	Many	Easy	High	High	Number of BS

### B. Related Researches of ECN-DR

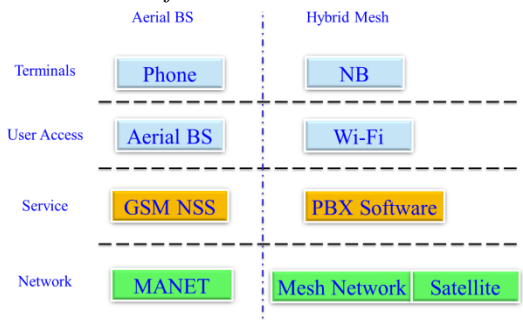


Figure 1. Aerial BS and Hybrid Mobile Ad Hoc Network

In aerial wireless emergency communication system [7], 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 Fig. 1.

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 [6], which can, but is limited, provide a small portion of disaster response workers. First, it supports 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.

### 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 created with low cost; (d) low-barrier of use, which are mostly needed in current 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 comes. Therefore, reconnecting disconnected base stations in the disaster area to provide a large-scale emergency communication service is a good option.

Based on the first-hand experiences we learned from Chi-Chi Earthquake [2] and 88 Flood that occurred in Taiwan, power outage and backhaul link breakage were the two most popular problems that crumpled base stations though most of their structures were intact.

*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. Devise 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**

Contingency Cellular Network (CCN) is constructed by reusing the disconnected base stations in the disaster area. The high level system architecture of CCN is showed in Fig. 2 and Fig. 3. Modules of CCN are described as follows. Functions of these modules are illustrated in [4].

**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.

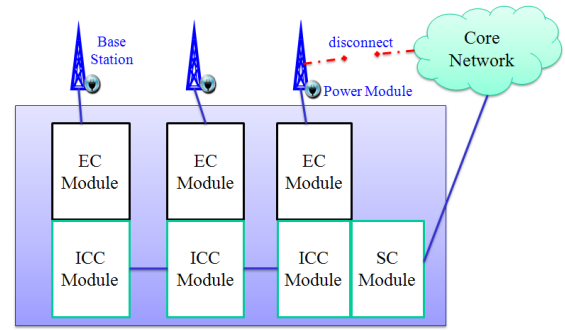


Figure 2. System Architecture of CCN- Level 0

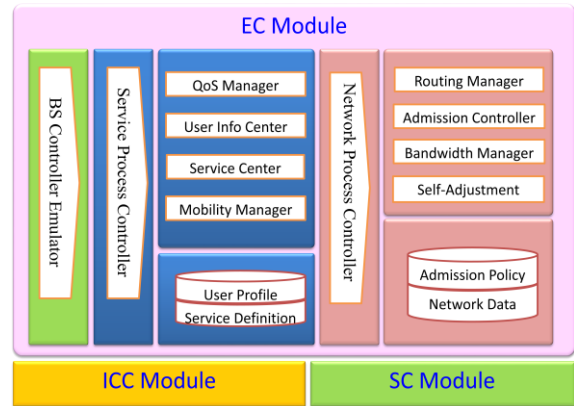


Figure 3. System Architecture of CCN- Level 1

**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. Because the wireless bandwidth of CCN is rare, EC Module provides communication without using wireless resources to increase concurrent users.

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 the high cost of satellite communications equipment. Others connected to core network through 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.

## IV. CCN BANDWIDTH ALLOCATION

### A. Design Philosophy of CCN Bandwidth Allocation

In our CCN, all base stations are equipped with an Inter-Cell Communication Module (ICC Module) [4] to form an Ad Hoc network. Goal of network topology planning is finding a CCN forwarding tree (CCN FT) of the Ad Hoc network [5]. A survival base station is chosen as the root. And thus, other stations can connect to core network by multiple hops through the root. A pair of ICC Modules is needed to establish the link between base stations. 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.

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 response demands regarding the number of communications channels of each base station to avoid allocation disequilibrium. Take SiChuan Earthquake [8] 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. Obviously, the number of calls is much exceeding the capacity of CCN. 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.

### B. CCN Bandwidth Allocation Problem

Assuming a CCN forwarding tree is given, each node has  $m$  channel classes to choose. When a channel is assigned to a node, the disaster response profit is earned. Different combinations of channels and nodes will earn different profits.

The channels assigned to the node cannot exceed the capacity of the node. And, an ancestor node has to forward the traffic of its descendant nodes. The channels assigned to it and its descendant cannot exceed the bandwidth capacity of it. This makes CCN bandwidth allocation (CCN-BA) problem become a nested 0-1 knapsack problem.

### C. Mathematical Model of CCN-BA

Given a CCN forwarding tree  $T=(V,E)$ , where

- $V = [v_i]_{n \times 1}$ , where  $i = 1, 2, \dots, n-1$ .  $v_i$  is the disaster operation efficiency of node  $i$ .  $v_1$  is the node that has an external link.  $v_0$  is a virtual node that represents the core network.
- $E = [e_{ij}]_{n \times n}$ .  $e_{ij}$  is the edge between  $v_i$  and  $v_j$ . The value of  $e_{ij}$  represents the bandwidth capacity between  $v_i$  and  $v_j$ .  $e_{0,1}$  and

$e_{1,0}$  are the external downlink and uplink bandwidth.

- $B = [b_k]_{m \times 1}$  is the set of channel class.  $b_k$  is the bandwidth required of channel class  $k$ .
- $P = [p_{ij}]_{n \times n}$ .  $p_{ij}$  is the path from  $v_i$  to  $v_j$ .
- $A = [a_{i,j,k}]_{n \times n \times m}$ .  $a_{i,j,k}$  represents the amount of channel class  $k$  assigned to path  $p_{ij}$ .
- $F = [f_{i,j,k}]_{n \times n \times m}$ .  $f_{i,j,k}(a_{i,j,k})$  is the profit of channel class  $k$  assigned to path  $p_{ij}$ .

Objective of the CCN bandwidth allocation (CCN-BA) problem is to find a matrix  $A$ , such that

Maximize

$$\sum f_{i,j,k}(a_{i,j,k}), \text{ for all } 0 \leq i, j < n, 1 \leq k \leq m$$

Subject to

$$e_{i,j} \geq \sum a_{q,r,k} b_k, \text{ for all } e_{i,j} \in p_{q,r}$$

### D. Complexity Analysis

Given an instance  $X:[C,W,P]$  in 0-1 knapsack problem, we can find an instance  $Y:[V,T,C',B,F,D,G]$  in CCN-BA such that an optimal solution  $a_y$  for  $Y$  is also an optimal solution for  $X$ . Let instance  $Y$  be a one level tree, where  $V=T=\{v_1\}$ ,  $C'=\{C\}$ ,  $B=W$ ,  $F=P$ ,  $D=\{0\}$ , and  $G=\{1\}$ . Denote the total profit of a solution  $a$  for  $X$  and  $Y$  to be  $p_x(a)$  and  $p_y(a)$ , respectively. Because  $F=P$ , we can easily prove  $p_x(a)$  and  $p_y(a)$  are equal. For simplicity, both  $p_x(a)$  and  $p_y(a)$  are denoted as  $p(a)$ .

First, we prove  $a_y$  is a valid allocation for  $X$ . Since  $B=W$ ,  $F=P$ , and  $C'=\{C\}$ , any solution of  $Y$  whose total bandwidth must less than or equal to the given limit  $C$  so that  $a_y$  must be a valid allocation for  $X$ .

Since instance  $Y$  is a one level tree, for a similar argument, we can prove that any valid allocation  $a_x$  for  $X$  is also a valid allocation for  $Y$ .

Next, we prove that an optimal solution  $a_y$  for  $Y$  is also an optimal solution for  $X$  by contradiction. As we have proved,  $a_y$  is also a valid allocation for  $X$ , whose total profit is  $p(a_y)$ . Assume  $a_y$  is not an optimal allocation for  $X$ , there must be another allocation  $a_x$ , whose total profit  $p(a_x)$  is greater than  $p(a_y)$ . And any valid  $a_x$  is also a valid allocation for  $Y$ , whose total profit is  $p(a_x)$ , which is greater than  $p(a_y)$ . This contradicts to the assumption that  $a_y$  is an optimal solution for  $Y$ . As a result,  $a_y$  must be an optimal solution for  $X$ . The reduction of CCN-BA to 0-1 Knapsack Problem is done. The proof of NP-hardness of CCN-BA is straightforward. Q.E.D.

### E. CCN-BA Heuristic Algorithm

Since CCN-BA is a NP hard problem, the optimal solution of CCN-BA is difficult to find in limit time when the number of base stations or the number of channels grows. Since disaster response operations are racing with time, we

proposed a heuristic algorithm, called Bandwidth Allocation Greedy (BAG), to find suboptimal solutions in seconds.

The flow chart of BAG is showed in Fig. 4. A forwarding tree  $T(V,E)$  and matrix  $B, F$  and  $P$  are given, firstly. Then, the base stations are selected as candidate node sequentially according to their disaster operation efficiency in descending order. The channels are assigned iteratively until the paths from the candidate node to others are crammed with channels. The heuristic solution, three dimensional matrix  $A$ , is got when all base stations are selected as candidate and assigned channels.

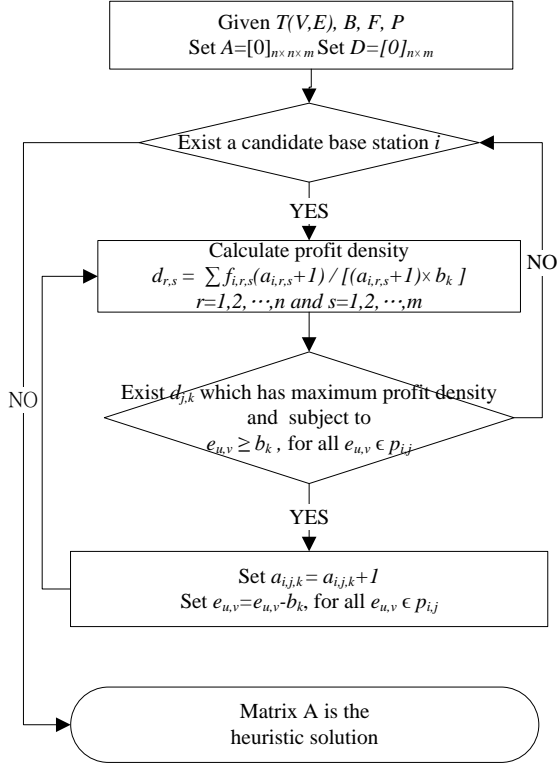


Figure 4. Flow chart of BAG algorithm

## V. PERFORMANCE EVALUATION

In CCN, only the survival base station has the external bandwidth which is shared by all nodes. The external bandwidth is rarer than internals. In order to understand the external bandwidth allocation performance of BAG algorithm, we only selecting  $v_0$  as the candidate node in the follow experiments.

### A. Profit Function and Evaluated Indices

TABLE III. THREE SETS OF EXPERIMENTS

Parameters Experiment	Profit Function $f_{i,j,k}$	Number of base stations $n$
I	$(v_i+v_j) \cdot \frac{1}{\sqrt{k}}$	6~10
II	$(v_i+v_j) \cdot \frac{1}{k}$	6~10
III	$(v_i+v_j) \cdot \frac{1}{\sqrt{k}}$	100

Due to high complexity, the BAG algorithm is evaluated by simulation on a regular PC. Large numbers of random cases were generated to evaluate the proposed algorithms against optimal solutions. Three sets of experiments were carried out. The profit functions and numbers of base stations of experiments I, II and III are shown in TABLE III. In experiments I and II, the size of the forwarding tree is between 6 and 10. The profit function  $f_{i,j,k}$  is defined as  $(v_i+v_j) \cdot g(k)$ . The attenuation functions  $g(k)$  of experiment I and II are  $\frac{1}{\sqrt{k}}$  and  $\frac{1}{k}$ , respectively. In experiment III, the size of forwarding tree is 100 and the profit attenuation function is  $\frac{1}{\sqrt{k}}$ .

Because the instances of experiments were generated randomly, these instances are independent and cannot compare directly. We use two indices to evaluate them. One is the deviation from optimum solution and the other is the optimal accomplish ratio. Formulas of the two indices are listed as follow.

$$\text{Deviations} = \frac{\text{optimal solution} - \text{algorithm best solution}}{\text{optimal solution} - \text{worst solution}} \dots (1)$$

$$\text{Optimal accomplish ratio} = \frac{\text{algorithm best solution}}{\text{optimal solution}} \dots (2)$$

Experiment I and II were repeated in Experiment III with 10 instances (100 nodes). The optimal and worst solutions are difficult to find within limit time. Instead, we generated 100,000 solutions randomly and took the best solution as pseudo optimal solution and worst solution as pseudo worst solution.

### B. Experimental Results

Disaster operation efficiency, bandwidth capacities of edges and channel class of test instances are shown in TABLE IV. Values of these given parameters are generated from uniform random functions.

TABLE IV. PARAMETERS FOR TEST INSTANCES

Parameters	Range of values
$V=[v_i]_{n \times 1}$	$v_i \sim \text{Uniform}(30, 100)$
$E[e_{i,j}]_{n \times n}$	$e_{i,j} \sim \text{Uniform}(32, 100)$
$B[b_k]_{3 \times 1}$	$b_k \sim \text{Uniform}(16, 32)$

Deviations and optimal accomplish ratios of experiment I and II are shown in Fig. 5 and Fig. 6, respectively. In experiment I, the best deviation is 2.5% and the best accomplish ratio is 98.21%. In experiment II, the best deviation is 3.14 and the best accomplish ratio is 97.58.

The result of experiment II is similar to experiment I. The deviation increases as the number of base stations increases too. It is because BAG algorithm is only a suboptimal solution. As the number of base stations increases, the number of solutions increases. The deviation increases, too.

In experiment III which are showed in Fig.7 and Fig. 8, the average pseudo deviation is 32.71% and the average pseudo accomplish ratio is 133.58%.

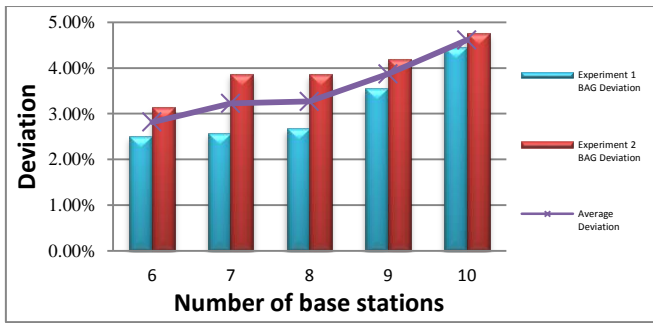


Figure 5. Deviations of Experiment I, II.

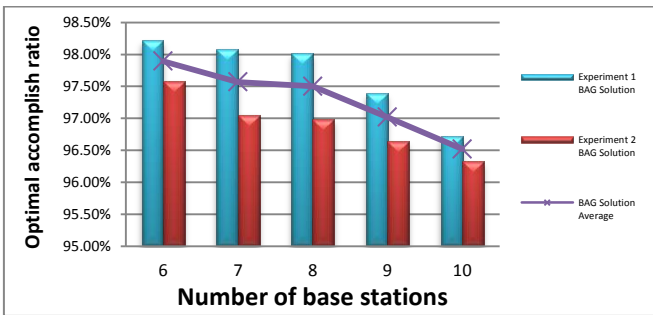


Figure 6. Optimal accomplish ratio of Experiment I, II.

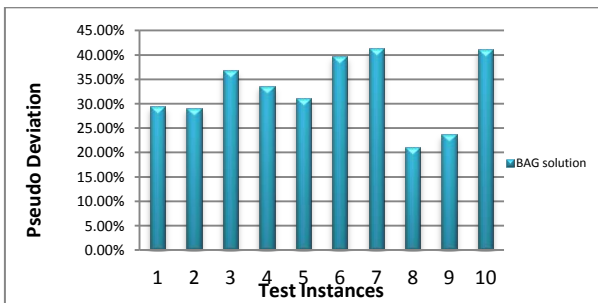


Figure 7. Pseudo Deviations of Experiment III.

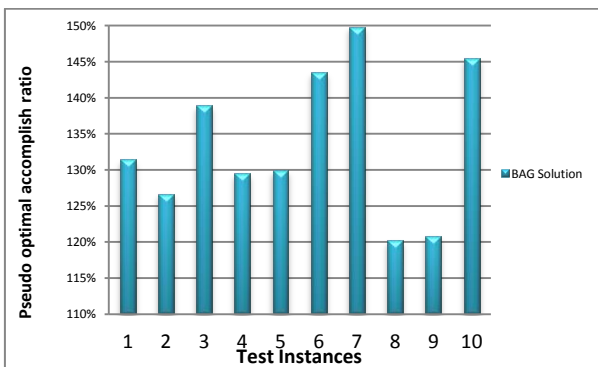


Figure 8. Pseudo Optimal Accomplish Ratio of Experiment III.

The BAG solution is better than the pseudo optimal solution, so the pseudo deviation and the pseudo accomplish ratio grow up. The experiment results show that the BAG algorithm performance good in our experiment environments.

## VI. CONCLUDING REMARKS AND FUTURE WORK

Since the network bandwidth may be very limited, bandwidth allocation according to the demand of disaster operation becomes an important issue. We model the CCN Bandwidth Allocation Problem into a 0-1 Knapsack Problem (0-1 KP) aiming to maximize disaster operation efficiency. The problem is proven NP-Hard. We design an efficient heuristic algorithm which is called BAG algorithm to solve the problem when it is needed in urgent. Our experiments show that the performance of our heuristic algorithm BAG is good. It can fulfill the demand of disaster response operation.

Some components of EC Module, such as Service Center and User Info Center, and an android VoIP application were developed and could provide base communication service. In the future, we will build up the simulation environment of CCN network to testimony the design concept of CCN.

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