# Deployment Scheduling of Contingency Cellular Network for Disaster Relief Operations

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***Abstract*—When a catastrophic natural disaster occurs, the efficiency of disaster response operation is crucial to life saving. However, communication systems, such as cellular networks, usually crashed due to various causes that make coordination difficult for many disorganized disaster response workers extremely. 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) by connecting disconnected base stations together with wireless links and portable power generators. CCN can support existing mobile phone users with limited capability. Since the transportation capacity may be very limited, scheduling of CCN deployment order according to the demand of disaster operation becomes an important issue. A model of the CCN Deployment Scheduling (CCN-DS) Problem which is aiming to maximize disaster operation efficiency is proposed in this research. Emergency levels of disaster areas, time decreasing profit functions and scheduling constraints are taken into consideration in the CCN-DS model. The problem is proven NP complete. Thus, we design an efficient heuristic algorithm to solve the problem when it is needed in urgent.**

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

## I. INTRODUCTION

### 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 a disaster comes, the destroyed areas will be 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 summarize the impact of large-scale natural disasters, such as 921 Chi-Chi Earthquake (Taiwan) [3], 88 Flood (Taiwan), SiChuan (China) [11] 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 of resources 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.

### 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 the following reasons:

**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 (3) overheated switch.

We notice that the 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.

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Fig. 1. Broken Bridge Cut Off Communications Cables

As clearly shown in Fig. 2, the backhaul of base stations, the basic structure of mobile communication systems, must be connected to controllers or switches. Even if a base station remains intact in a disaster, as long as its backhaul is disconnected, it can no longer be in operation.

Take 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, with the communications network laid along the roads and bridges destroyed, mobile communications system was therefore paralyzed. Power and backhaul has become the disadvantage of mobile communications network.

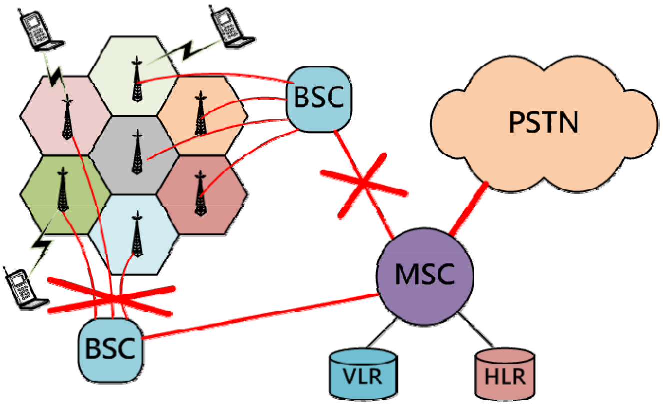


Fig. 2. Vulnerable Points of Cellular Network

It can be confirmed that mobile communications system is actually vulnerable judging from the overall paralysis of mobile communications system in numerous disasters over the years. Encumbered by many external factors, it is still futile to build stronger base stations and switches as it cannot greatly guarantee 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 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 [11].

### *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 them remained out of service 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.

### *D. Contingency Cellular Network*

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 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 the selected base stations via airdrops or helicopter. First, EC Modules are connected to base stations. Second, we use the ICC 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 connect 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.

Challenges, related researches, design philosophy and system architecture of CCN are discussed in paper [1,4,5,6,10].

## II. RELATED RESEARCHES

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) [4,5,6] 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.

Before CCN operates in a disaster area, there are several works needed to be done. One is to determine the topology and to select the base stations out of all disrupted base stations to maximize disaster response efficiency. The second is to determine the deployment schedule to transport the CRPs to the disaster area to resort those selected base stations.

Because the number of those CRPs is limit, only some of base stations would be selected and equipped to form an Ad Hoc network. Network Topology Planning Algorithm [6] was proposed to select base stations and to compute the CCN forwarding tree (CCN FT). A survival base station is chosen as the root. And thus, other stations can connect to the core network by multi-hop through the root. Minimum of a pair of ICC Modules is needed to establish the wireless link between base stations. In order to maintain the connectivity of base stations, the forwarding tree is re-planned immediately, if any of the links in the forwarding tree is broken.

Since the transportation capacity may be very limited, it may need several rounds of deployments. Unfortunately, the benefit of saving a station is gradually attenuated with time. The deployment sequence will largely determine the disaster response efficiency. A good sequence may save more lives than a bad one. The transport sequence has not only to consider the emergency level of base stations but also to follow the scheduling constraint that ancestor nodes have to be resorted before their child. That's because a child node cannot connect to the core network without the forwarding of its ancestors.

CCN deployment scheduling problem is similar to fleet routing and scheduling problems [7] which aim to find an optimal rout of one or more vehicles through a graph and assign vehicles to ideal routes at particular time. Formulations of flee routing and scheduling problems are usually based on multi-commodity network flow problem or vehicle routing problem. Objectives of these formulas are minimizing the unsatisfied demand or maximizing the demand satisfied. Formulas and solutions are proposed in [2,7,9]. Objectives of these researches aim to minimize the transport time and the number of vehicles under the limitations of transport capacity.

Researches of fleet routing and scheduling problems mainly consider the problem of how to transport resource to disaster points with shortest time and minimum cost. Beside transport time and cost, there have more issues needed to be addressed in CCN deployment scheduling problem. First, the emergency levels of disaster areas are different, the profits of delivering materials to disaster areas to resorting base stations are also different. The disaster area which has higher emergency level should have higher priority. Second, the profits are not constant but decreasing with time. Third, the deployment sequence has to follow the scheduling constraint. In order to solve these issues, a CCN deployment scheduling (CCN-DS) formulation is proposed in this research. And, a CCN-DS algorithm is used to find a heuristic deployment scheduling to approximately maximum the efficiency of disaster response operation.

The rest of this paper is organized as follows. Section III presents the CCN deployment scheduling problem. Experiments are provided in sections IV. Discussion of concluding remark and future work is in section V.

## III. CCN Deployment Scheduling

### A. Definition of Profit

The emergency level of the area covered by a base station is represented by a time-variant profit parameter, which has to be defined by the disaster response authority because they have not only the necessary knowledge for disaster response, but also the official situation statistics. A typical example of profit definition is the estimated time dependent survival rate. Fig. 3 is a sketch map of the survival rate when an emergency communication system is available.

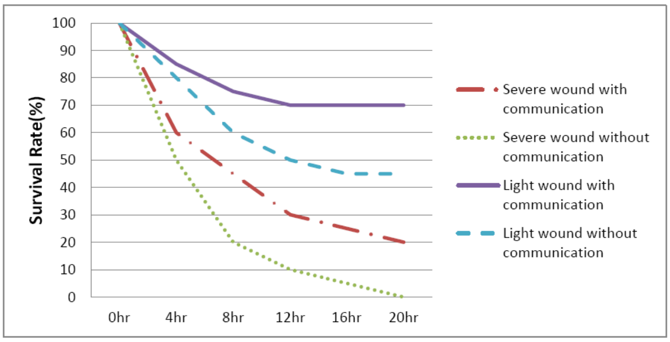


Fig. 3. Time Dependent Survival Rate.

### B. CCN Deployment Scheduling Problems

The CCN Deployment Scheduling Problem (CCN-DS) is formulated into two optimization models, one for single deployment team and the other for multiple deployment team. We assume one or more forwarding tree is calculated in advance. However, multiple forwarding tree problem can be easily converted into a single forwarding tree problem by adding an extra root connecting all forwarding tree together. The CCN-DS is similar to the conventional single and multiple machine scheduling (SMS) problems. The non-preemptive CCN deployment scheduling problem is as follows. There is a set of nodes organized in a tree structure has to be fixed by work teams. Each node must be fixed before its descendants. The construction sequence is called CCN deployment scheduling.

Mathematical model of CCN-DS is introduced as follows. Given a forwarding tree, T(V,E) , where

- V = $\{v_i \mid i=0,1,2,\ldots,n\}$ is the set of survival base stations. $v_0$ is the root which has an external link.
- E = $\{e_{i,j} \mid e_{i,j}$ is the link of $(v_i,v_j)$ and $v_i,v_j$ □ V$\}$
- R = $\{r_i \mid i=1,2,\ldots,n$ and $r_i > 0\}$, $r_i$ is the construction time of the isolated station $v_i$.
- $\pi=\{\pi_a \mid \pi_a = (\pi_a(1),\ldots,\pi_a(n))$ , $a$ is a positive interger$\}$ is the set of CCN deployment schedulings. $\pi_a(i)$ is the construction sequence of $v_i$.
- $C(\pi_a,i) = \{\sum r_{\pi a(k)} \mid$ for all $\pi_a(k)>\pi_a(i)$ and $k=1,2,\ldots,n\}$ is the deployed time of $v_i$ of the deployment scheduling $\pi_a$.
- $P_i(t)$ is the profit of $v_i$ when it is constrcted at time $t$. $t$ =

$C(\pi_a,i)$, for all $\pi_a \in \pi$.

The objective of CCN deployment scheduling problem is finding a deployment scheduling $\pi_a$ from $\pi$, such that

Maximize

$$\sum P_i(t) = \sum P_i(C(\pi_a,i)), \quad i=1,2,\ldots,n$$

Subject to

$$\pi_a(i) > \pi_a(j),\ v_j \text{ is the descendant of } v_i \text{ for all } v_i,v_j \in V.$$

### C. Complexity Analysis

Similar to the conventional machine scheduling problem, CCN-DS can be easily proven being a NP-hard problem.

**CCN-DS is in NP：**

We first show that CCN-DS $\in$ NP. Assuming that we are given a forwarding tree T(V,E), as well as a schedule, we can use a double loop to verify that a parent node must be fixed before its child nodes in T. The verification algorithm can affirm the schedule is a valid CCN-DS schedule within $O(n^2)$ time.

**CCN-DS is NP-Hard：**

We now prove that CCN-DS problem can be reduced to SMS problem straightforwardly. Given an instance A:[J,P,W] in SMS, we can find an instance B:[N,L,W,E,n] in CCN-DS such that an optimal solution $\pi_b$ for B is also an optimal solution for A. Let N=J, L=P, W'=W, $E=\{e_{root,i}|v_{root},v_i \in V\}$, n(work teams)=1. The verification can be performed in polynomial time. Let total weighted completion time of SMS for $\pi$ is TWC($\pi$), total weighted profit of CCN-DS for $\pi$ is TWP($\pi$). We prove the following 3 Lemmas first：

**Lemma 1**: Any valid schedule $\pi_b$ for B(CCN-DS) is a valid solution for A(SMS).

**Proof:** Any permutation of J is a valid schedule for A, and $\pi_b$ is a permutation of N, which is J. Therefore $\pi_b$ is a valid solution for A. Q.E.D.

**Lemma 2**: Any valid schedule $\pi_a$ for A is also a valid schedule for B.

**Proof:** A valid schedule $\pi_a$ for A is a permutation of J. Since each node in B can directly connect to the root of B, therefore any permutation of N, which is J, is a valid schedule of B. Thus $\pi_a$ is also a valid schedule for B. Q.E.D.

**Lemma 3**: If $TWC(\pi_a) < TWC(\pi_b)$ then $TWP(\pi_a) > TWP(\pi_b)$

**Proof:** If $\sum_{i \in J}(w_i * C_i(\pi_a)) < \sum_{i \in J}(w_i * C_i(\pi_b))$, by Equal Division Theorem, we can get $\sum_{i \in N}(w_i / C_i(\pi_a)) > \sum_{i \in N}(w_i / C_i(\pi_b))$. Q.E.D.

Next, we prove by contradiction that an optimal solution $\pi_b$ to B must be an optimal solution to A. By Lemma 1, we know $\pi_b$ is also a valid schedule for A, whose total weight completion time is T.W.C($\pi_b$). Assume $\pi_b$ is not an optimal schedule for A, there must be another schedule $\pi_a$, whose total weight completion time T.W.C($\pi_a$) is smaller than T.W.C($\pi_b$). By Lemma 2, $\pi_a$ is also a valid schedule for B, whose total profit is T.W.P($\pi_a$). By Lemma 3, we can obtain T.W.P($\pi_a$) is bigger than T.W.P($\pi_b$). This contradicts to the fact that $\pi_b$ is an optimal solution for B. Therefore, $\pi_b$ must be an optimal solution for A. Q.E.D.

### D. Heuristic CCN-DS Algorithm

Sine CCN-DS is an NP-hard problem, we designed a heuristic approximated algorithm to solve both single team and multiple team CCN-DS problem. The algorithm consists of two phases. A greedy algorithm is used to calculate an initial solution in phase I. In phase II, we adjust the construction sequence of the initial solution to gain more profit iteratively. The flow charts of phase I and II are shown in Fig 4. The time complexity of phase I and II are $O(n^2)$.

In the phase I, a forwarding tree T(V,E), a set of nodes $\pi_a$ , an integer variable $k$ and deployment time $t$ are given at the first step. In the following steps, the CCN-DS algorithm finds out the base station which is the neighbor nodes of $\pi_a$ and has maximum profit and adds this base station into $\pi_a$ iteratively until all base stations are added. Treating the added sequence of base stations as the deployment schedule, the initial solution $\pi_a$ is obtained.

In the phase II, the construction sequence of a base station will be rescheduled forward if this move could increase the profit and follow the schedule constraint. The rescheduling to gain more profit are repeated from the tail of the schedule to the head. Then, the final solution $\pi_b$ is obtained.

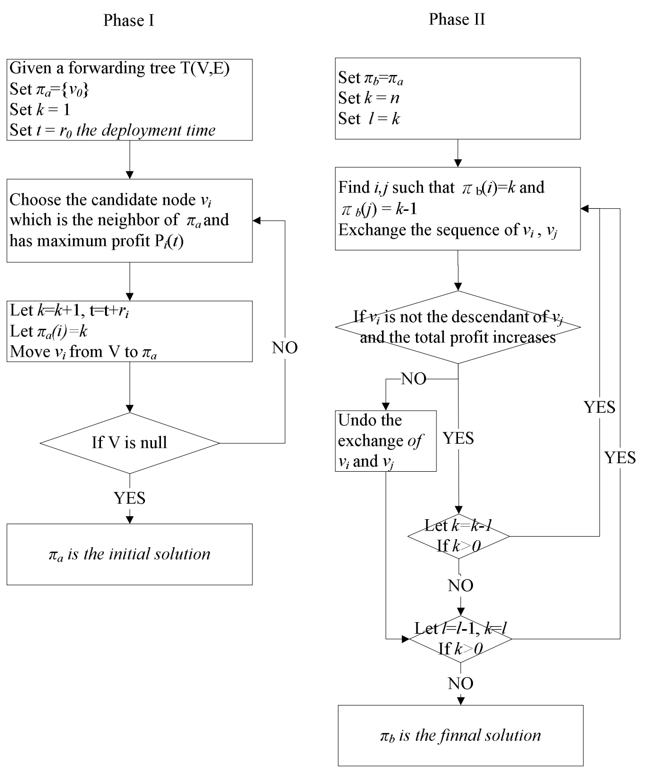


Fig. 4. Flow Charts of Phase I and II.

## IV. Performance Evaluation

### A. Profit Function

The profit function of a base station is assumed as shown in Fig. 5. The initial profit is *x* at disaster time and decreases with time. The slope from disaster time to P is s1 and becomes s2 after time P. P is called the turning point of profit.

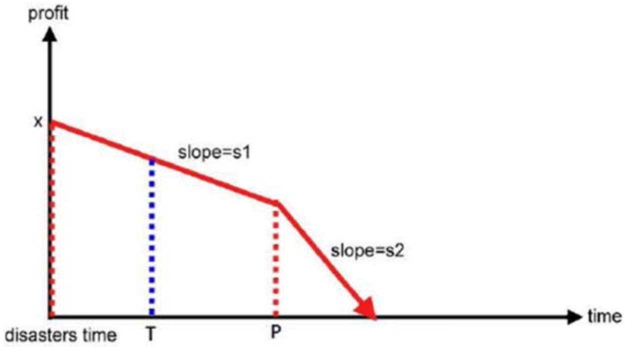


Fig. 5. Profit Function Model

TABLE I. Parameters of test instances

| **Parameters** | **Range of values** |
|---|---|
| **Initial Profit** | x ~ Uniform(30, 100) |
| **Turning point** | P ~ Uniform (0, 168) hr |
| **Slope1** | s1 ~ Uniform (0, 0.5) |
| **Slope2** | s2 ~ Uniform (0, 0.5) |
| **Construction Time** | $r_i$ ~ Uniform (5, 15) hr |

In all test instances, the values of parameters are generated by uniform random functions. The ranges of values are shown in TABLE I.

### B. Experimental Results

The CCN-DS is evaluated by simulation on a regular PC. Large numbers of random cases were generated to evaluate the proposed algorithm against optimal solutions.

TABLE II. List of Experimetns

| Condition / Experiment | Construction Time | Number of work teams | Number of base stations |
|---|---|---|---|
| I | Identical | 1 | 10~14 |
| II | Different | 1 | 10~14 |
| III | Different | 2 | 10~14 |
| IV | Repeat Experiment I, II, III | | 100 |

Four sets of experiments were carried out. Construction time, the number of work teams and the number of base stations of these experiments are showed in TABLE II. In Experiments I, II and III only small scale (10 to 14 nodes) instances were evaluated, the solution was compared with optimum solutions. In experiment IV, Experiments I to III were repeated with large instances (100 nodes). The best solutions obtained within time limit were taken as optimal solutions for comparison and is defined as pseudo optimum solution.

From the Fig 6 to 8, we can see that the average ratios of final solutions to optimum solutions are 96.6%, 96% and 98%, respectively. The CCN-DS algorithm performs well when the number of nodes is 10 to 14. In many cases, even the first phase greedy algorithm is sufficiently good such that the second phase calculation becomes unnecessary, which is very demanding since disaster response cannot afford long calculation time.

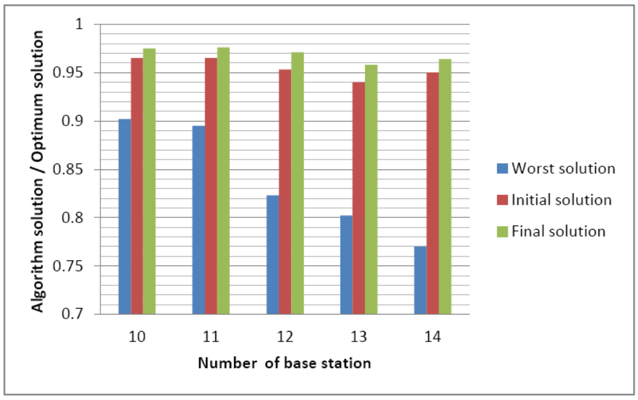


Fig. 6. Performance of CCN-DS in Experiment I

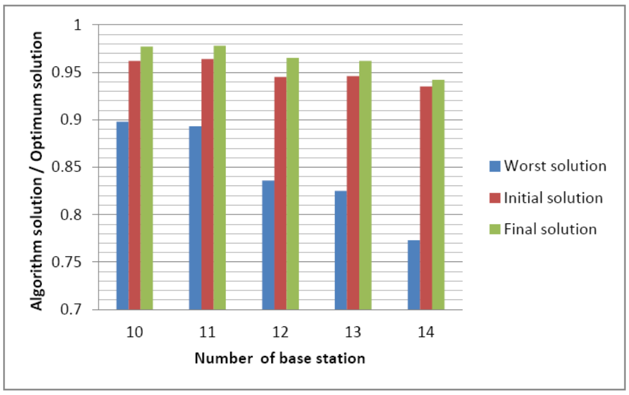


Fig. 7. Performance of CCN-DS in Experiment II

Compare with the experiment I and II which are showed in Fig. 6 and 7, the results of Experiment I is similar to Experiment II. Performance of CCN-DS algorithm is not affect with the construction time is identical or different.

The ratio of worst solution to optimum solution is 84% in Experiment II (refer to Fig. 7) and increase to 94% in Experiments III (refer to Fig. 8). It shows that adding work teams will have great impact to the worst solution.

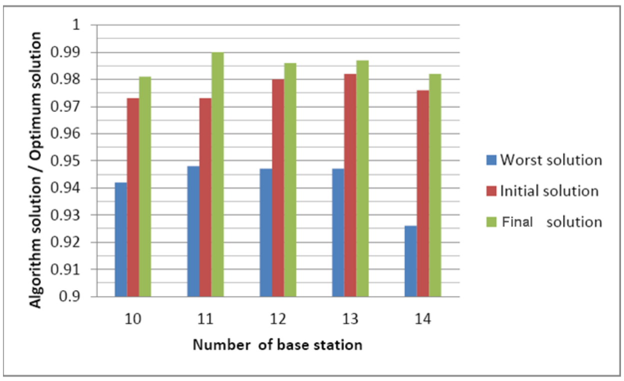


Fig. 8. Performance of CCN-DS in Experiment III

The results of Experiment I, II, III shown in Fig.9 are similar to the results shown in Fig. 6 to 8 except that the ratio of the final solution to the pseudo optimum solution of Experiment III (102%) is less than the result of Experiment II (110%). This is because the deployment times of base stations are closer when the work teams increase from one to two. And then, the range of total profits of Experiment III become narrower than that of Experiment II. The ratio of worst solutions to pseudo optimum solutions of Experiment II and III is increase from 65% to 89%. The increase range becomes larger as the number of base stations increase to 100.

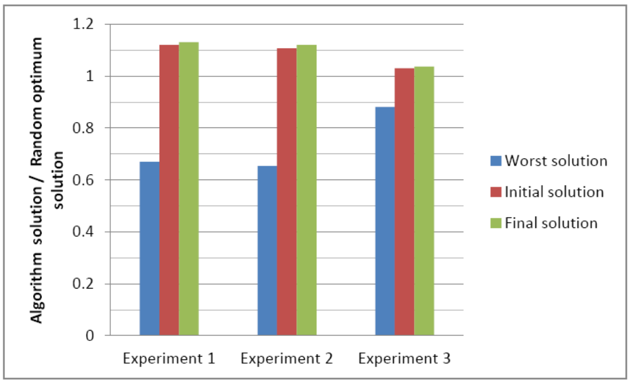


Fig. 9. Performance of CCN-DS in Experiment IV

## V. CONCLUGIND REMARK AND FUTIRE WORKS

Efficiency disaster response operation relies on a good communication system and is crucial to life saving. However, communication systems, such as cellular networks, usually crashed due to various causes that make coordination difficult for many disorganized disaster response workers extremely. 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) by connecting disconnected base stations together with wireless links and portable power generators. CCN can support existing mobile phone users with limited capability. Since the transportation capacity may be very limited, scheduling of CCN deployment order according to the demand of disaster operation becomes an important issue.

The CCN deployment scheduling problem is proved a NP complete problem and hard to find an optimum solution in a limit time. Instead, we proposed a heuristic CCN-DS algorithm to find a good solution. The algorithm consists of two phases. A greedy algorithm is used to calculate an initial solution in phase I. In phase II, we adjust the construction sequence of the initial solution to gain more profit iteratively. Time complexity of CCN-DS algorithm is $O(n^2)$.

From our experiments, we can see that CCN-DS algorithm performs very well in our experiment environment. In many cases, even the first phase greedy algorithm is sufficiently good such that the second phase calculation becomes unnecessary, which is very demanding since disaster response cannot afford long calculation time.

Some components of service part of EC Module, such as Service Center and User Info Center, and an Android application were developed and could provide base communication service. In the future, we will develop the components of network part of EC Module and use wireless access points as ICC Module to build the simulation environment of CCN network to verify that the design concept of CCN is practicable.

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