國立政治大學資訊科學 研究所

Department of Computer Science

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博士學位論文

Doctoral Dissertation

應急行動通訊系統設計

Design of Contingency Cellular Network

指導教授：連耀南 博士

博 士 生：黃智賢 撰

中華民國一百零六年一月

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研 究 生：黃智賢　　Student：Jyh-Shyan Huang

指導教授：連耀南　　Advisor：Yao-Nan Lien

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應急行動通訊系統設計

摘要

當大型災害來臨，通訊系統對救災效益具有不可或缺的重要性。然而，一般公眾通訊系統，如行動通訊網路等，常因各種不同因素導致系統癱瘓。在災變初期，外援常因交通運輸問題無法即時進駐災區，而需仰賴數以萬計甚至數十萬的災區在地志工投入救災工作。而現存多個緊急通訊系統的佈建，需仰賴良好的交通運輸，不幸的是，部分道路和橋樑常因大型災害而斷裂或變型，導致災區對外交通運輸中斷，無法快速的將緊急通訊系統的網路元件，運送至災區佈建。再者，因造價之故，系統容量僅能提供小部分專業救災團隊使用，而無法提供給數量龐大的救災志工使用。

我們提出應急行動通訊系統 (Contingency Cellular Network, CCN) 以提供災區救災工作的緊急通訊。我們在歷年的災害中發現行動通信系統斷訊時大部分基地台的結構是完整的，但因失去與核心網路連線能力或電力供應，而無法提供服務，成為孤立基地台。應急行動通訊網路(CCN)利用這些孤立基地台搭配無線通訊與衛星通訊技術建置一多重跳接無線網路，以恢復孤立基地台與核心網路連線能力；並配備發電機，提供電力，使孤立基地台可提供有限的服務。救災志工和災民無需使用特殊手持設備或額外的訓練，只需使用原有的手機，即可使用 CCN 的應急通訊服務。CCN 可於第一時間，提供大批救災志工和災民通訊服務，以提高救災效益，因而拯救更多寶貴的生命。

本論文主要聚焦在應急行動通訊系統設計所衍生出的相關議題,如 應急網路需求分析、系統架構設計、網路拓樸規劃、網路頻寬規劃、佈署行程規劃等議題。本論文針對網路拓樸規劃、網路頻寬規劃、佈署行程規劃問題以數學模式進行塑模，並證明這些問題為

NP-Hard 問題。因網路拓樸規劃、網路頻寬規劃、佈署行程規劃需緊急完成，我們也提出啟發式演算法快速解決這些規劃問題。實驗結果顯示，這些啟發式演算法均具良好的效能。

關鍵字 — 災難管理、緊急通訊、行動通訊、 Ad Hoc 網路、網路拓樸、佈署行程、頻寬管理

Design of Contingency Cellular Network

Abstract

Communication system is crucial to the efficiency of disaster response operation in the large-scale disaster. 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 to construct a wireless 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.

Our research addresses various design issues of CCN, such as network topology planning, bandwidth management, deployment scheduling, etc. We take the level of emergency and population of each stricken area as the priority measure as well as the available resources as the constraint to maximize disaster response efficiency. Mathematical models of these design issues are proposed and proved as NP-Hard problems. Since the network topology, bandwidth management, deployment scheduling are needed in urgent, we propose heuristic algorithms to solve these problems quickly. Finally, we evaluated the proposed algorithms by simulation. A

significant improvement in resiliency is reached.

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

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Chapter 1. Introduction

1.1. Disaster Response for 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 of people homeless, and causing a huge financial loss. The earthquake that occurred in Haiti in 2010 alone claimed 230,000 people's lives. When a large-scale disaster strikes, the destroyed areas are often sunk into desperation. Take the earthquake that happened on March 11, 2011 in North-Eastern Japan for example, after stricken by a 9.0 magnitude earthquake, followed by 23-meter high tsunami and the combined major disasters (i.e. nuclear crisis, earthquakes and tsunami), the world and the already experienced disaster responders were all stunned by the huge scale of disaster.

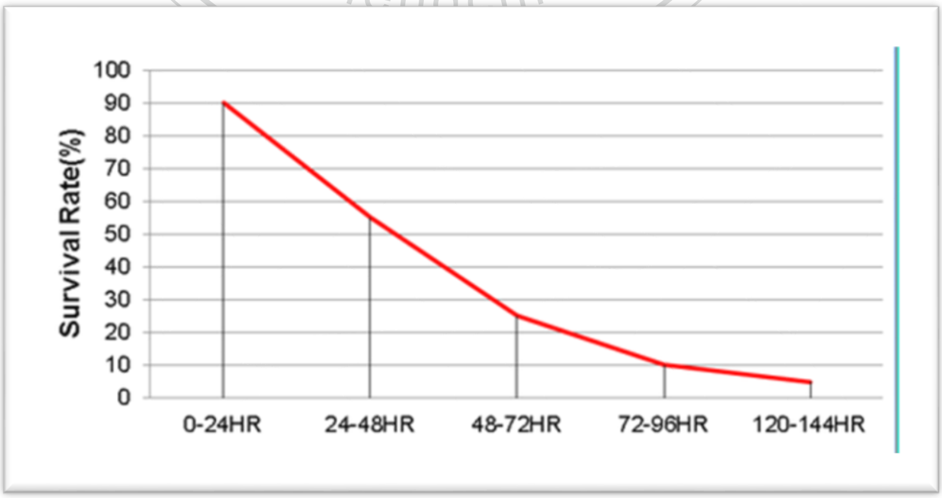


Figure 1.1. Survival rate statistics

One major task for an earthquake response is to rescue victims who are trapped in the rubble of collapsed buildings. The survival rates are highly depended on the time that the victims are rescued. Survival rate statistics is showed in Fig. 1.1. The survival rate may be as high as 90% in the first 24 hours, but may drop to 55% and 25% after 48 and 72 hours, receptivity. To rescue trapped and wounded victims within Golden 72 Hours is a critical task of Disaster Response Operation (DRO).

1.2. Lessons Learn from Haiti and Chi-Chi Earthquake

Haiti Earthquake occurred in January 2010, claimed more than 230,000 lives. Entire government and social infrastructure were completely paralyzed. All utilities such as running water, electricity, communications, food, and medical supplies were all knocked out. Port-au-Prince Airport was forced to shut down because it could not supply fuel for airplanes to take off. Most roads were also destroyed. Therefore, DRO resources and equipment were extremely difficult to deliver to the stricken zones. In the first few days, Haitian people had to help themselves with little external aid. Internet was lucky to survive the quake because most ISPs relied on satellite for their external connections.

Chi-Chi/Taiwan Earthquake occurred in September 1999, claimed 2,415 lives. Communication systems were mostly down or jammed resulting in big impact to DRO [13]. Chunghwa Telecom took 15 days of 7/24 operation to restore its systems. A large number of local volunteers were mobilized to execute DRO and it’s difficult to coordinate large number of voluntary responders without a good communication system.

Figure 1.2. A fell building divided a rescue squad into two parts

Without a good communication system may cause rescue efforts interfere with each other. For instance, in Chi-Chi Earthquake, sound detection operations were interfered by sirens. The collapsed buildings as showed in Fig. 1.2 fell down and blocked the street dividing first responders into two isolated groups. While one group was doing sound-sensitive operation (e.g. using a high sensitive sound detector to detect any human sound under debris), the group on the other side was using heavy machinery to dig the rubbles. It also happened that rescued victims died on the way being transferred from hospital to hospital. It is because Victim Arrangement System (ambulance) couldn't follow up changing status of hospital capacities. Some rescue and relief resources were misplaced because assessment of disaster distribution was blind and inaccurate. Reallocation of misplaced resources may not be possible due to paralyzed transportation systems. Misplacement of rescue and relief resources may lead to catastrophic consequence.

Communication systems are critical in disaster response operations. However, they are not dependable, including cellular networks. Any emergency communication system proposal must consider (1) large number of disorganized voluntary responders and victims, (2) transportation system may be paralyzed, (3) external aids may not be available in Golden 72 Hours.

1.3. Robustness Analysis of Cellular Networks in a Disaster

Figure 1.3. Broken bridge cut off communications cables

Public communication and transportation systems are often completely or partially destroyed after large-scale natural disasters [13,23,45], and thus transporting resources into disaster zones to restore communication systems is difficult. There may be more than ten thousand or one hundred thousand of local volunteers are mobilized to execute DRO. And, it is hard to coordinate these disorganized voluntary responders. Hence, following a disaster, the first responders demand a rapidly deployable network (RDN) to provide connectivity.

Communication systems are known to be crucial to disaster response; however, apparently stable public communication networks frequently do not survive natural disasters. Notably, cell phone networks were vulnerable during the 88 Flood and 921 Chi-Chi Earthquake [13] in Taiwan. When Hurricane Sandy hit the East Coast of the United States, one quarter of base stations in the East Coast were disrupted. The following reasons for the vulnerability were later identified: [23]

Common causes for service disruption of base stations are: (1) power outage (the backup batteries usually can only last several hours), (2) broken backhaul, and (3) physical destruction by disasters. Critical hardware was knocked out resulting from (1) external power outage, (2) exhausted power generator fuel, (3) broken cooling systems, or (4) overheated switches caused by the loss of cooling systems.

Because base stations must be connected to controllers or switches through backhaul cables, they cannot remain in operation when their backhaul is disconnected, even if their physical structure remains intact. Typically, power lines and backhaul links are laid along roads and bridges for the convenience of deployment and maintenance. The destruction of roads and bridges is a common phenomenon in disasters and leads to power outages and network disconnection (see Fig. 1.3, 1.4). Although power lines and communication backhauls usually have inbuilt redundancy to increase availability, they do not necessarily improve survivability significantly in large-scale disasters. For instance, a substantial flood may destroy many bridges over a river, and thus completely break all of the redundant cables. In the 88 Flood, the structure of many base stations remained intact because they were located in higher places. However, when the power lines and backhauls that were laid along the roads and bridges were destroyed by the flood, mobile communications systems were paralyzed. In short, power lines and backhauls are an Achilles' heel for many existing mobile communication networks.

Because of the aforementioned problems, building stronger mobile communication networks has been proposed. However, such robust networks are prohibitively expensive for large-scale deployment. For instance, although the National Communications Commission of Taiwan selected a small number of locations in which to build strengthened base stations with satellite communication for backhauls, the number of such base stations is limited due to funding constraints.

Long Term Evolution (LTE) is a network technology that will be used for emergency communications in the future. Currently, Canadian public safety agencies are attempting to clear up new spectrum bands, leverage commercial services, and reuse existing spectrum assets. On June 11, 2012, Trans-European Trunked Radio (TETRA) and Critical Communications Association (TCCA) and National Public Safety Telecommunications Council (NPSTC) announced that they had signed a Memorandum of Agreement to underscore their joint commitment to developing mission-critical public safety communication standards for LTE-based technology [14,18,19,54]. However, key features must still be implemented in LTE before it can satisfy public safety requirements. Before the LTE is applied in disaster response, a rapidly deployable network (RDN) is necessary to assist first responders.

A RDN is an adaptive, mobile communications network that can be easily accessed. Its purpose is to temporarily replace damaged public networks after a disaster, thereby providing emergency communications among the first responders and, if possible, the victims. As the permanent communications for the affected population are gradually restored, the RDN is withdrawn.

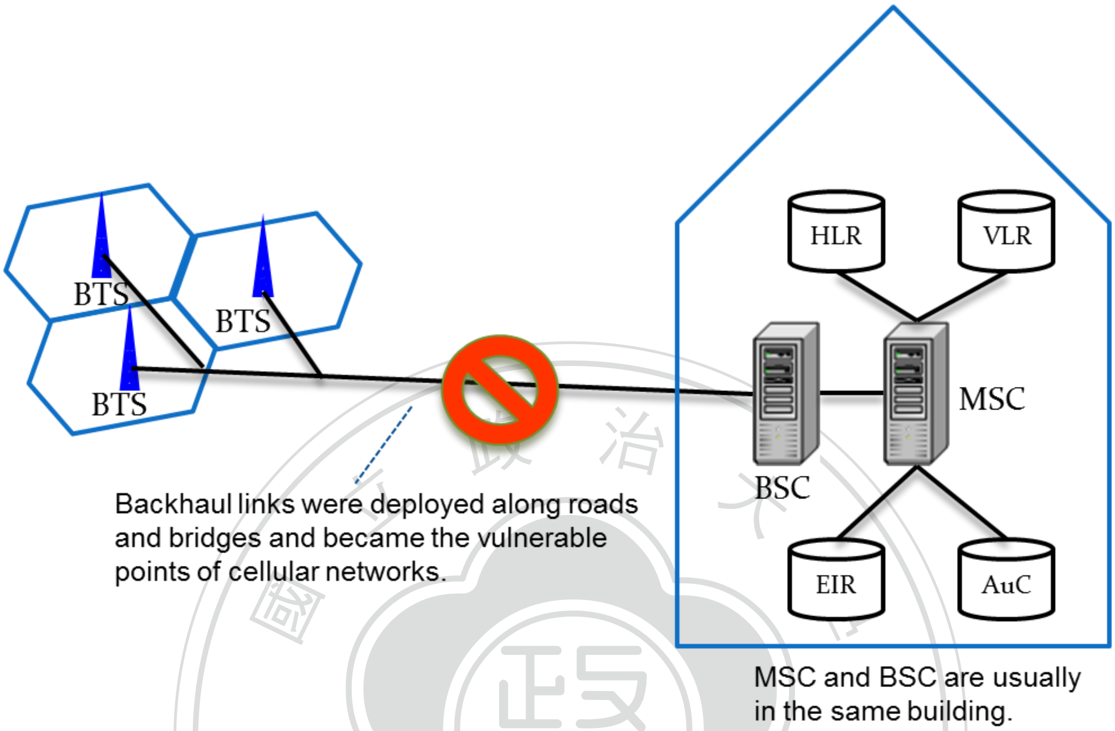


Figure 1.4. Vulnerable points of cellular network

1.4. System Requirements for RDN

On the basis of our firsthand experience obtained in the 921 Chi-Chi Earthquake and extensive research over the past decade [14,13,17,23,42]. We summarized the environmental constraints in the disaster areas are described as follows, (1) large number of disorganized non-professional voluntary responders and victims, (2) transportation system paralyzed, (3) time is running out, (4) hectic/chaotic usage environment, and (5) very limited deployment funding due to little commercial incentive.

We also summarized a set of communication requirements that must be addressed when constructing and operating a communication network for first responders. These requirements are categorized into two sets: user end and operator end.

User End Requirements

Popularity: In large-scale disasters, numerous volunteers must be mobilized to work on rescue and relief operations. In addition, people in the disaster area—including victims—may have extensive communication requirements. Therefore, several user terminals are necessary for a RDN. Because of the rareness of terminals, most common emergency communication networks, such as satellite systems, trunking radios, and amateur radios, can only be used by specific groups; most victims and volunteer disaster responders cannot access these communication networks. Moreover, users must be trained before using the terminals for trunking radio and amateur radio; hence, these systems can only be employed by professional disaster response squads.

Usability: A RDN should provide task-oriented communication services and support mobility, as well as have adequate service quality. Furthermore, RDN handsets should be user-friendly, durable, and not require a long training period, and task-oriented communication services should include both ordinary and group communication services. Finally, because disaster responders may have to move frequently, the mobility of user terminals is crucial.

Operator End Requirements

Practicality: Practicality is the essential operator end requirement, and includes low deployment costs, easy acquisition of equipment, and rapid deployment. Although RDNs are essential to disaster response operation, they do not generate profit and the occasions for their use are limited. A commercial cell phone operator may not be justified in making a large investment in the design and development of a large-scale RDN; therefore, a RDN must have low development costs to be practical.

Because of obstacles created by terrain and paralyzed transportation systems, transporting external aid to disaster areas is usually difficult. In many cases, helicopters may be the only vehicle that can access disaster areas in the early hours or days of a large-scale disaster. Hence, the size and weight of RDN equipment should be suitable for air transportation. For instance, mobile base stations (called “cells-on-wheels”), which have a base station with satellite backhaul and are carried by a truck, may be too heavy to be carried by a helicopter; hence, this equipment may be useless.

Finally, survival rates are highly dependent on rescue speed. If trapped victims are rescued quickly, their chances of survival are considerably higher; thus, RDNs should be deployed as swiftly as possible. Furthermore, cell phone operators must work at full capacity to restore their systems. The value of a “band-aid” style RDN is substantially lower once any cell phone is recovered. Therefore, a RDN must be rapidly deployable.

Capacity: A RDN must have sufficient capacity to satisfy the communication demands of large numbers of victims and disaster responders—both professional and voluntary—within stricken areas, as well as limited incoming and outgoing calls to external institutions. Furthermore, a RDN should have the ability to resist the burst of call requests, to prevent it from crashing.

Sustainability: A RDN should not only be deployed as quickly as possible but should also continuously operate until the public communication network is recovered, which may take several days or even weeks. If nonstop operation is impossible, it should be rapidly recoverable once it has crashed.

Practicability	• low development cost • easily access to the equipment • construct rapidly and easily
Popularity	• large amount of terminals • user friendly
Usability	• key services to responders • support mobility • high quality of service • long standby time of terminal
Capacity	• support sufficient number of concurrent users • resist the burst of call requests
Reliability	• long sustained time
Operability	• have operation and maintain functions • can adjust network topology, bandwidth allocation and etc., according to the requirement of responders
Adaptability	• disaster awareness • self-adjustment

Figure 1.5. 7-Ability of rapidly deployable network

Adaptability: Similar to a battle field, the situation in a disaster area may constantly change due to factors such as aftershocks, fires, and the progress of disaster response. Therefore, a RDN must be able to adapt to the changing environment either manually or automatically.

Operability: Similar to any production system, a RDN must have an operation, administration, and maintenance function to remain in operation.

The system requirements are summarized as 7-ability of rapidly deployable network and showed in Fig. 1.5.

The layout of this dissertation is as follows. Chapter 2 introduces the traditional communication systems for disaster response and current available solutions with a comparative evaluation against the 7-ability requirement. We design a large-scale, low cost and rapidly deployable communication system called Contingency Cellular Network (CCN) to support large number of disorganized users. Chapter 3 discusses the design philosophy, system architecture and research issues of CCN. Chapter 4 formulates the network design problems of CCN with a comprehensive mathematic model. A binary linear algorithm and a topology design heuristic algorithm are proposed to solve the problem. Effectiveness and efficiency of the algorithms are verified by simulation. Chapter 5 formulates the deployment scheduling problem. Two heuristic algorithms are proposed and discussed. Chapter 6 formulates the bandwidth allocation problem and proposes a solution. Finally, Chapter 7 concludes this dissertation with a discussion of the contribution of our research works.

Chapter 2. Related Works

2.1. Traditional Communication System for Disaster Response

Conventional communication systems 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***) has been studied by many researchers. A MANET based system uses mobile computing devices such as laptop PC, tablet PCs and smartphones to construct an emergency communication network. Some may have satellite connection to the external Internet. Users can use a mobile device running a VoIP application to access the communication service [34]. A brief comparison of these technologies using the 7-ability requirement presented in Chapter 1 is shown in Table 2.1. 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 user terminals. They have high usability and practicality, but low popularity. Except a few countries such as the 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 approximately 1000 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 a 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.

TABLE 2.1. Comparisons of emergency communication solutions for disaster response

	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	Profession al 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-Whe els

2.2. Wireless Network Approaches

Numerous researchers have focused on the approach to RDNs [17,42]. Several approaches to RDNs, including examples, are introduced in this section. An essential set of challenges must be conquered when deploying a network under critical conditions [23,42].

First, the RDN must be deployed with limited prior knowledge of the environment and as efficiently as possible to replace the damaged portion of the public communication network. However, because traffic movement is paralyzed in most scenarios, transporting professionals and network components into the disaster zone is difficult. The RDN must reuse the network components in the disaster zone and be deployed with minimum human intervention. Second, the network must be adaptive, self-reconfigurable, flexible, scalable, and energy efficient to cope with unknown dynamic environments and battery-powered wireless devices. In other words, the network must be set up on demand in accordance with the location and current needs.

The ***mobile ad hoc network approach*** uses on-hand mobile devices to construct a mobile ad hoc network (MANET) and provide connectivity among the first responders in the absence of external network devices [34]. This approach uses the mobile devices of participants, such as smartphones and notebooks, to construct a MANET. These participant nodes build interconnections by using wireless technologies, such as IEEE 802.11x and Bluetooth, and cooperatively routes packages. Some participant nodes may have satellite connections, enabling a MANET to connect to the Internet. In the case of failure, the packages can be sent by selecting an alternating forwarding path.

MANET is flexible and rapidly deployable, its distribution requirements are simple, and it can rely entirely on first responders' mobile devices without external network devices; hence, it can be applied in most disaster zones. However, its coverage area and support for real time communications are limited. MANET is most suitable for small scale areas, and helping the first responders share text messages, pictures, and videos for rescue purposes. Examples of

MANET are described in the following section.

Lien [36] used notebooks to construct a MANET and developed a Voice over Internet Protocol (VoIP) application to provide a walkie-talkie-like communication service. Notably, the audio quality decreases as the number of hops increases, and the experimental results indicated that this is because the delay time and distortion become longer and more unstable when the number of hops increases. When the number of hops exceeds four, the audio is entirely blurred. In other words, the coverage range is limited when using a MANET to provide a voice communication service.

Bruno [8] proposed the use of wireless mesh networks, in which a set of nodes is dedicated to forwarding the traffic of the other nodes. These dedicated nodes form a multi-hop wireless backhaul to extend coverage and enhance network performance.

MANET based systems can support laptop and smartphone users. They are easy to construct in terms of physical connections 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 the lack of commercial incentive.

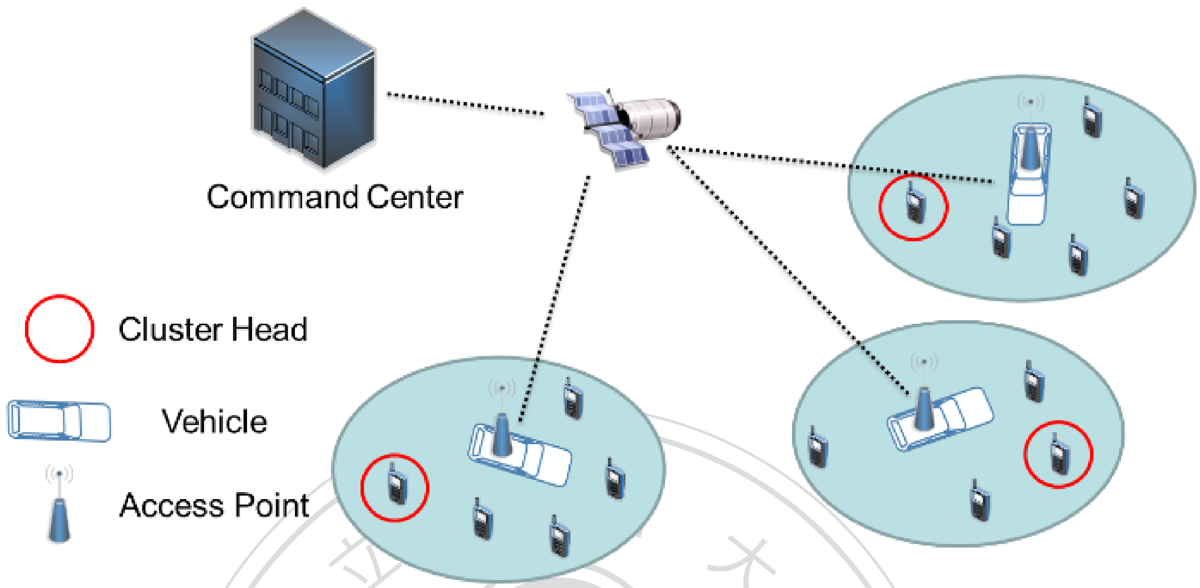


Figure 2.1. System architecture scheme of the metropolitan area approach

The ***metropolitan area approach*** aims to deploy network components to cover large incident areas. System architecture scheme of the metropolitan area approach are showed in Fig. 2.1. This approach applies a layer infrastructure to form a wireless mesh backbone. The first responders connect to base stations or access points that are mostly carried by vehicles, which connect to the Internet through an aerial or aerospace node. The systems of the metropolitan area approach cover a larger area and provide superior network performance to those of MANET approach; their ability to support real time services is also better. However, the network components of these systems require adequate transportation to be transferred into an incident area and transportation systems are usually paralyzed after large-scale nature disasters. In addition, the system architecture is more complicated and requires professionals to be deployed. Examples of metropolitan area systems are described in the remainder of this section.

Aerospace Communications for Emergency Applications [7] adopts a layered composition. The first responders connect to base stations or access points that are mostly carried by vehicles, such as ambulances, police cars, or fire trucks. Base stations are connected to an aerial or aerospace node, and the access points use virtual cell layout (VCL) resources to create an overlaid real cell that moves over the virtual cells. Man-pack radios (MPRs) form small cells, each of which has a node that plays the role of an MPR cluster head, and are grouped into a larger cell through radio access points. Finally, all cells are connected through a satellite or an unmanned aerial vehicle. The VCL approach focuses on adapting 3G technologies to tactical systems.

The CHORIST Broadband and Wideband Rapidly Deployable Systems [1] involve forming a mesh network using wireless routers carried by emergency vehicles. The vehicles are automatically connected in a peer-to-peer fashion and form a self-configuring intervehicular core. At the edges, the mobile radios carried by the first responders are connected to the closest router via WiFi and create local cells; the remote connection to the command center is established through an IP backbone.

Advanced Wireless Ad-Hoc Networks for Public Safety [2] is a cross-layer approach coupled with a cluster-based architecture that provides a high bitrate service using ad hoc hot spots, and includes PHY, MAC, and network levels. The physical layer relies on reconfigurable Orthogonal Frequency-Division Multiple Access with multi-antenna capability (multiple input and multiple output) to provide data transport services. In addition, this approach includes a MAC layer organized in clusters wherein, in a given set of nodes, the cluster head is the optimally located node. Relay nodes are used to ensure interconnectivity between clusters, and gateway nodes are used to connect the created network to other networks. The cornerstone of this proposal is the terminode concept, for which each node in the network is able to perform the functions of a cluster head, relay, router, or gateway, depending on its location and service requirements.

The application of 3G PCS Technologies to Rapidly Deployable Mobile Networks [9] was proposed for military communications. According to the cluster-based organization in a layered architecture, this approach provides a cluster head for each group of first responders. The cluster head acts as a bridge between the first responders and the access points carried by the vehicles, and there is at least one cluster head connecting the remainder of the nodes to an upper layer, such as a satellite acting as a gateway.

The Satellite-Assisted Localization and Communication Systems for Emergency Services [46] involves an integrated navigation/communication (NAV/COM) reconfigurable system architecture for emergency scenarios. In this architecture, rescuers within the incident area network are organized into teams or clusters. The main topics of the project are localization techniques, software-defined radio, cognitive radio NAV/COM devices, the integration of satellites and high-altitude platforms into rescue services, and the adoption of heterogeneous solutions in the intervention area.

The ***local area approach*** aims to deploy a network to a target area using small, inexpensive, and light-weight wireless relay nodes. An on-demand multi-hop wireless forwarding network is created that allows the first responders to communicate as soon as the relay nodes are deployed. The primary problem with this approach is identifying an appropriate deployment decision algorithm to maximize network performance. On the basis of the deployment strategies of the relay nodes, this approach is divided into two categories, namely the static relay nodes approach and the automobile relay nodes approach.

In the ***static relay nodes approach***, the relay nodes are mainly deployed by the first responders. The first responders are notified to drop the relay nodes at a certain distance to maintain the connectivity of the relay nodes. The connectivity quality can be measured using a received signal strength indicator (RSSI) [5], the signal-to-noise ratio (SNR) [49] or bandwidth [53]. Moreover, there are two types of deployment decision strategies. Souryal [49] proposed a deployment decision strategy based on the connectivity quality measured by the relay node. A relay node constantly sends signals to measure the SNRs of neighboring nodes, and once the SNR exceeds a predefined threshold, the relay node sends a deployment request to the closest first responder. Bao [5] proposed a similar deployment decision strategy based on the connectivity quality measured by the devices of the first responders. In this approach, the first responder or the closest neighbor receives a deployment request if the RSSI between his device and the relay node crosses a predefined threshold.

Relay nodes are inexpensive and deployed easily. Hence, the coverage area can be simply extended by dropping more relay nodes into an incident area. However, these relay nodes remain static after deployment and cannot be adjusted according to environmental changes. Moreover, the deployment of relay nodes is reliant on first responders. Once the first responders have entered an incident area, deploying relay nodes is not their primary task, and they may be unable to drop a relay node after receiving a deployment request. This may cause the degradation of network performance or partition of the coverage area.

The ***automobile relay nodes approach*** overcomes the weakness of the static relay nodes approach by reducing the degree of human intervention. Here, the deployment of relay nodes is not reliant on the first responders, because the relay nodes are automobiles that can self-spread across the target area following deployment. There are two types of deployment strategies. The first one involves guiding the automobile relay nodes to form a chain formation [31,43,44], thereby restoring the connectivity between the APs of the mesh network or creating connectivity between the command center and the rescue team. The second [47,50] attempts to cover the target area thoroughly, to connect as many rescue workers and victims as possible.

Chapter 3. Contingency Cellular Network

3.1. Design Philosophy

After a decade of study, we have discovered that most base stations crash during disasters because of the damage to their power source or backhaul links. Therefore, we designed a new RDN called the Contingency Cellular Network (CCN) [23,24]. In this approach, isolated base stations that have had their service disrupted but remain physically intact are connected using wireless links to form a multi-hop cellular network. Traffic can be forwarded hop by hop from any isolated base station to a survival base station. A base station which has external link to core network is called survival network. The main design concept of the CCN was to reuse existing disconnected base stations to minimize cost and deployment time, and to support a large number of existing users. The rationale for this system was that (a) mobile communication networks provide wide coverage; (b) cell phone use is widespread; (c) only a low-cost add-on module is required to repair a disconnected base station; and (d) there is a low barrier of use, which is necessary in current disaster response communication. Furthermore, cell phones are likely to be carried by affected people in a disaster area (a crucial, although nontechnical justification for this approach). Therefore, reconnecting disconnected base stations in a disaster area to provide a low-cost large-scale emergency communication service is a favorable option.

The Contingency Recovery Package (CRP) consists of a power module, several Intercell Communication (ICC) modules, and an add-on processing module, which is referred to as an Emulated Controller (EC) module. The CRP can be stored in national disaster response centers or with cellular network operators and delivered to base stations using airdrops or helicopters. In the first step, an EC module is connected to a base station. ICC modules are then used to connect the base station to its neighbors using long range wireless links; notably, at least one pair of ICC modules is necessary for each base station. A multi-hop wireless network overlapped on top of the selected base stations is subsequently formed, which provides the connectivity between the base stations and the 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 CRPs may be equipped with a satellite modem to establish a connection.

3.2. System Architecture of CCN

The system architecture is showed in Fig. 3.1. The details of power, ICC, and EC modules are as follows.

Power module: This module consists of a portable power generator and required fuel that is sufficient to provide electricity to a base station for at least a few days. Note that although most base stations have backup power, it usually can last only a few hours.

Inter-Cell Communications Module (ICC Module): Its main function is 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): 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 (from base stations to cell phones) 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 an interface to the ICC module and the target base station (most likely an Ethernet interface) running Linux operating system will be sufficient. Note that the majority of traffic, which is intra base station traffic, will be handled by base station itself, but not EC Module. Inter base station traffic will be low because it is regulated by the bottlenecks, the external and inter base station links.

Satellite Modem: This optional module provides the connection between CCN and the core network once the connections to the core network are all broken. Satellite communications, which is not confined by the geographical boundaries, can connect to the core network directly. However, only a few base stations can be installed due to its high cost. Others will be connected to the core network through the multi-hop connectivity.

CRP can be stored in national disaster response centers or cellular operators and delivered to the selected base stations via any transportation means even airdrops or helicopters. The EC-Module is connected to a base station in the first step. Then, ICC Modules are used to connect the base station to its neighbors in the second step via long range wireless links. At lease a pair of ICC Modules is needed for each base station. A multi-hop wireless network overlapped on top of the selected base stations is finally formed. The overlapped network provides the connectivity between base stations and the core network. Anyone who has a cell phone can access the contingency communication service from these base stations.

If the constructed CCN is completely isolated from the core network, some CRP may include a Satellite Communication Module (SC Module) to establish a connection to the core network.

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.

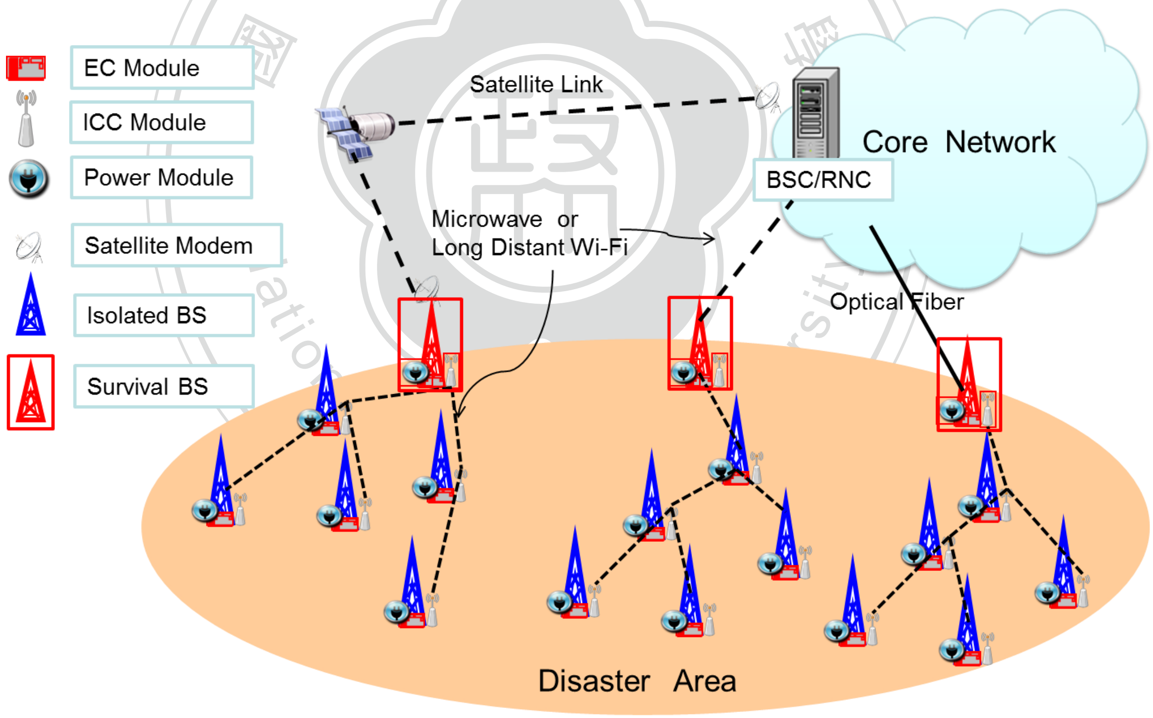


Figure 3.1. System architecture of CCN

The use scenarios of CCN are illustrated in Fig. 3.2. In Scenario 1, some base stations are out of service, a result of losing connections with the core network; however, their structures are intact. These base stations are called **isolated base stations**. The CCN recovers the functionality of these isolated base stations by reconnecting them to the core network. ICC modules are used to construct wireless links among the base stations and reuse the undamaged backhaul links to form a multi-hop wireless network that recovers connectivity between the isolated base stations and the cellular network.

In Scenario 2, the command center is located in an area that requires more bandwidth and higher reliability. The CCN satisfies the requirements by constructing multiple disjointed paths between the command center and the core network.

In Scenario 3, when an isolated base station cannot connect to the core network through other base stations, the CCN recovers the backhaul link of this isolated base station by using satellite and satellite modem to reconnect to the core network.

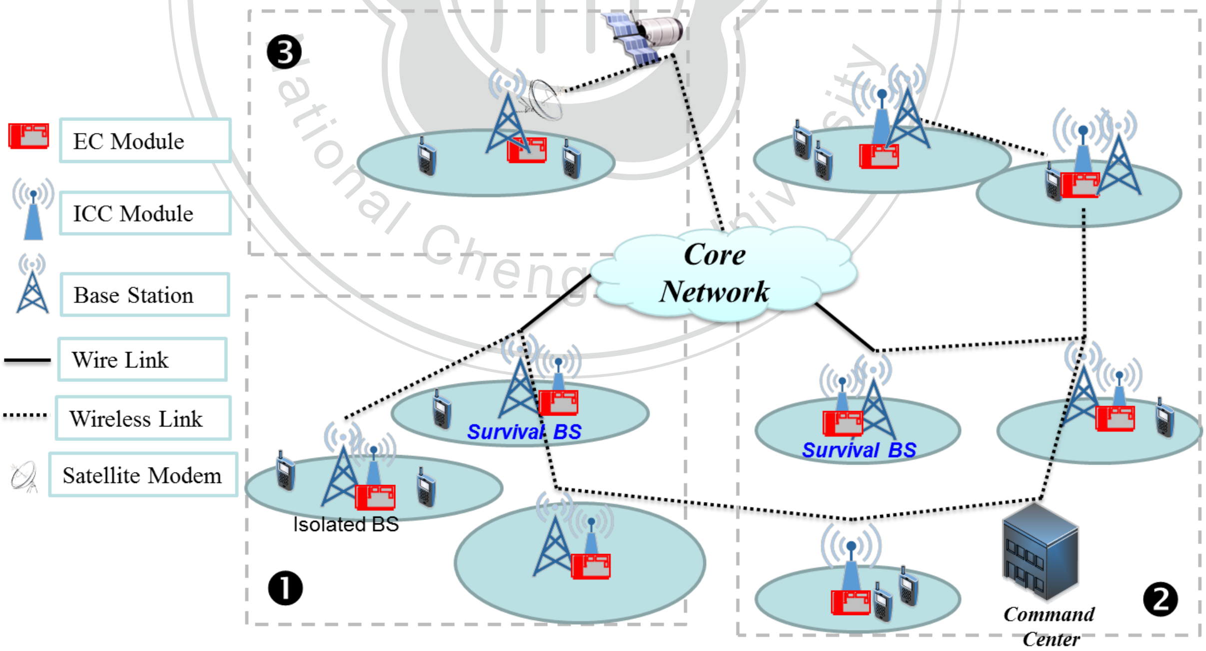


Figure 3.2. Use scenarios of CCN

3.3. Software Architecture of EC Module

Software architecture of EC Module is showed in Fig. 3.3. Components of EC Module are illustrated as follows:

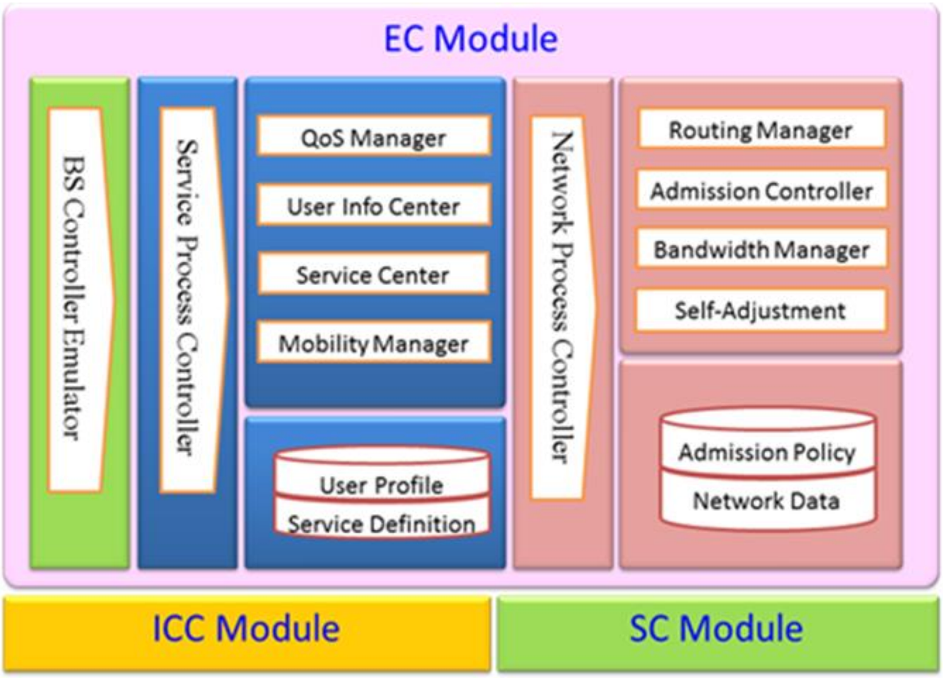


Figure 3.3. Software architecture of EC Module

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), 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 supports 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 SLV.

QoS manager: is responsible for deciding the QoS of incoming calls. Incoming calls have different level of emergency. Based on the emergency level of a phone call, appropriate QoS will be provided. The more urgent one will be allocated with higher bandwidth to provide better service quality, and vice versa. The emergency level of a phone call is determined by the agency groups registered by both caller and callee. If neither the caller or the callee is registered, the priority will be given to those who have registered. The main purpose of bandwidth differentiation according to the urgency of the phone calls is to answer as many phone calls as possible without affecting the disaster response efficiency.

Mobility Manager: is responsible for the interrogation of callee locations.

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

Disaster Situation Data: records the situation data of disaster areas, such as population distribution, numbers of victims and responses workers. In order to efficiently support responders, CCN collects the disaster situation data and allocates network resources accordingly.

Network Data: records the network related information such as network topology, bandwidth allocation, bandwidth utilization, etc.

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

Admission Controller: prioritizes urgent phone calls and admits phone calls. The capacity of CCN is much smaller than usual public network, making it difficult to handle massive phone calls. Also, the level of urgency varies, ranging from regular phone calls to urgent calls for victim rescue. Since CCN capacity cannot provide service to all phone calls, every possible means should be made to prioritize urgent phone calls for them to access the telephone service in CCN.

Routing Manager: is 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 efficiency of disaster response.

Bandwidth Manager: is responsible for wireless bandwidth allocation and management. Because the information needs to be forwarded to and by the neighbor stations, which will consume 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. 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 response efficiency, it is necessary to allocate appropriate amount of communications channels to each base station.

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

3.4. Deployment and Operation Procedures

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

Stage 1: Damage Assessment Phase

The disaster response headquarter, 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, identify the routing path to a survival 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, scheduling for the deployment of the topology, 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 one of the core functionality of this phase.

3.5. Basic CCN Services

Three communication services were designed to support disaster response: the ordinary phone, walkie-talkie-like, and agency communication services.

Ordinary Phone Service: a regular telephone service similar to the Plain Old Telephone Service (POTS) with priority-based admission control.

Walkie-Talkie-Like Service: a push-to-talk, or walkie-talkie, group communication service. In a disaster response operation, people—especially trapped victims—may not know each other; thus, anonymous group communication (which does not require a caller to dial the 9- or 10-digit cell phone number of the recipient) is the most useful communication mode and constitutes the majority of CCN traffic. The CCN designates a 3-digit special number that should fit the national dialing plan to enable users to turn their cell phones into walkie-talkies. This instruction can also be automatically sent to all cell phones within the CNN covered area by Short Message Service, thereby enabling even trapped victims to receive it. Notably, the scope of this service is confined to each base station to prevent the excessive consumption of resources.

Agency Communication Service: Each group of users with the same functional specialty can form an agency group with a dedicated, easy-to-remember phone number. Thus, every user can make a request to a specific functional agent by dialing the corresponding phone number. Examples of agency groups are the headquarters, surgical doctors, blood suppliers, medical suppliers, power cutters, and excavators. When a user makes a request by dialing the special phone number, the CCN rings a set number of members of the corresponding group near the caller. Any paged recipient can answer the phone, and the agency database can be preloaded or registered in real time. However, the original phone number of a cell phone may be lost if a CCN does not establish its connection to the core network; thus, the CCN must have its own dialing plan and phone number designation process.

3.6. Design Issues of the CCN

During a real disaster, a CCN may proceed with a phased deployment: disaster assessment, planning, deployment, and operation. Each of these phases presents design concerns, and thus several critical planning and deployment challenges are discussed in this section.

- **Definition of Resource Profit**

Resource allocation and scheduling problems are usually modeled as combinatorial optimization problems for which plenty of solutions are available. Some profit is earned when one unit of resource is allocated to a base station, where the objective is to maximize the total profit earned with limited resources. In a CCN design, profit should be measured by the efficiency with which it improves disaster response operations. Moreover, the definition of profit must be defined by a specific disaster response authority, because they possess the relevant real time disaster situation statistics as well as the priority determination authority. A typical profit definition when allocating a CRP to a base station is a linear or nonlinear combination of the emergency level and the user population covered by the base station. The profit definition of allocating a communication channel to a pair of base stations is a major challenge yet to be tackled. In the future, social scientists must formulate improved profit definitions and optimization models.

- **Network Topology Design**

According to the statistics we collected, more than 3300 base stations crashed during the 88 Flood, which was only a moderate scale disaster affecting a small number of counties in southern Taiwan. However, larger scale system crashes can be anticipated to occur in larger natural disasters. Therefore, the first concern when deploying a CCN is the selection of a limited number of crashed base stations based on the available CRPs as well as the topology for their connectivity; a simple tree-type or a resilient non-tree-type topology can then be formed with the objective of maximizing its efficiency and stability. In our study, the topology design [22,55] was formulated into different combinatorial optimization problems and solved using typical algorithmic methodologies [5]. To maintain the integrity of a CCN and adapt to the constant changing conditions of a disaster, the forwarding topology must be replanted frequently. A system that has self-healing capabilities would be preferable, but requires further research.

Tree topology is simple, but also vulnerable to a single link or node failure. In response, Charnrsriponyo [10,11] improved network reliability by maximizing the number of chains, and Elshqeirat [15,16] used a dynamic programming scheme to generate a topology comprising a selected sequence of spanning trees, thereby satisfying a predefined reliability. All nodes in the methodologies of Charnrsriponyo [10,11] and Elshqeirat [15,16] are identical. However, some pivot nodes such as command centers require higher bandwidth and reliability than others. Hence, we proposed a better optimization model with differentiated reliability demands together with a Disjoint K-Path Max-Profit Mesh algorithm [22] to satisfy bandwidth and reliability requirements by providing multiple path to the pivot nodes; thus, every pivot node can reach the core network through two or more disjointed paths.

- **Deployment Scheduling**

Some number of CRPs can be previously stored in the national disaster response center and be transported via some transportation vehicle such as helicopter to the selected stations to construct a CCN rapidly. The deployment sequence may have a big impact on the disaster response efficiency since the profit of restoring a base station keeps decreasing over time. The time variant survival rate, the difficulty of accessing, the delivery time, the topology constraints, and many other parameters all together makes the deployment scheduling a highly complex problem.

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 recovered 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 [17] which aim to find an optimal route of one or more vehicles through a graph and assign vehicles to ideal routes at the 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 [2,17,22]. Objectives of these researches aim to minimize the transport time and the number of vehicles under the limitations of transportation capacity.

Researches of fleet routing and scheduling problems mainly consider the problem of how to transport resource to disaster points with the 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 recover base stations are also different. Hence, 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 [27]. And, a CCN-DS algorithm is used to find a heuristic deployment scheduling to approximately maximize the efficiency of disaster response operation.

- **Priority Based Bandwidth Allocation and Admission Control**

The system capability of a CCN is mainly limited by the bandwidths of the external link from the CCN to the core network, the inter-base-station links, and the radio channels from the base stations to cell phones. The bandwidth demand from users in a disaster typically far exceeds capacity. Therefore, some priority-based admission control must be implemented, in addition to a precise allocation plan that rationally distributes available bandwidth to base stations and maximizes CCN efficiency. Similar to the previous two problems, bandwidth allocation challenges were modeled into combinatorial optimization problems and solved using heuristic algorithms [25].

Chapter 4. Network Topology Design

4.1. Considerations of Network Topology Design

In CCN, most disconnected base stations require multiple hops to connect to the core network. The network topology of CCN may have a great impact on the efficiency of CCN, which is the efficiency of disaster response operation and its stability. The objective of network topology design is to find a network topology to maximum the disaster response efficiency. The evaluation factors of disaster response efficiency include the emergency level of the afflicted areas or the level of the disaster and the number of disaster responders and victims. Referring to Fig. 4.1., the CCN network topology should deploy to those incident areas that have large population or high emergency level to maximum the disaster response efficiency. However, some important areas, such as command centers, require higher reliability and network bandwidth. These two requirements, maximization of the disaster response efficiency and reliability, are dependent to each other. A good network topology design algorithm of CCN should compromise these two requirements.

Besides, there are some constraints needed to be considered. The number of CRPs and the number of antennas in each CRP are fixed. Hence, the number of selected BSs is constrained by the number of CRPs; the number of selected links of each selected BS cannot exceed the number of antennas in each CRP. The packages are forwarded through multi-hop, too many hops may cause long delay time and consume too much intra-BS bandwidth. Therefore, the number of hops from some important areas to the core network should be limited to maintain appropriate quality of network service.

Except these basic constraints mentioned above, CCN topology design need to be considerate of more complicated problems. These problems are discussed as fellows.

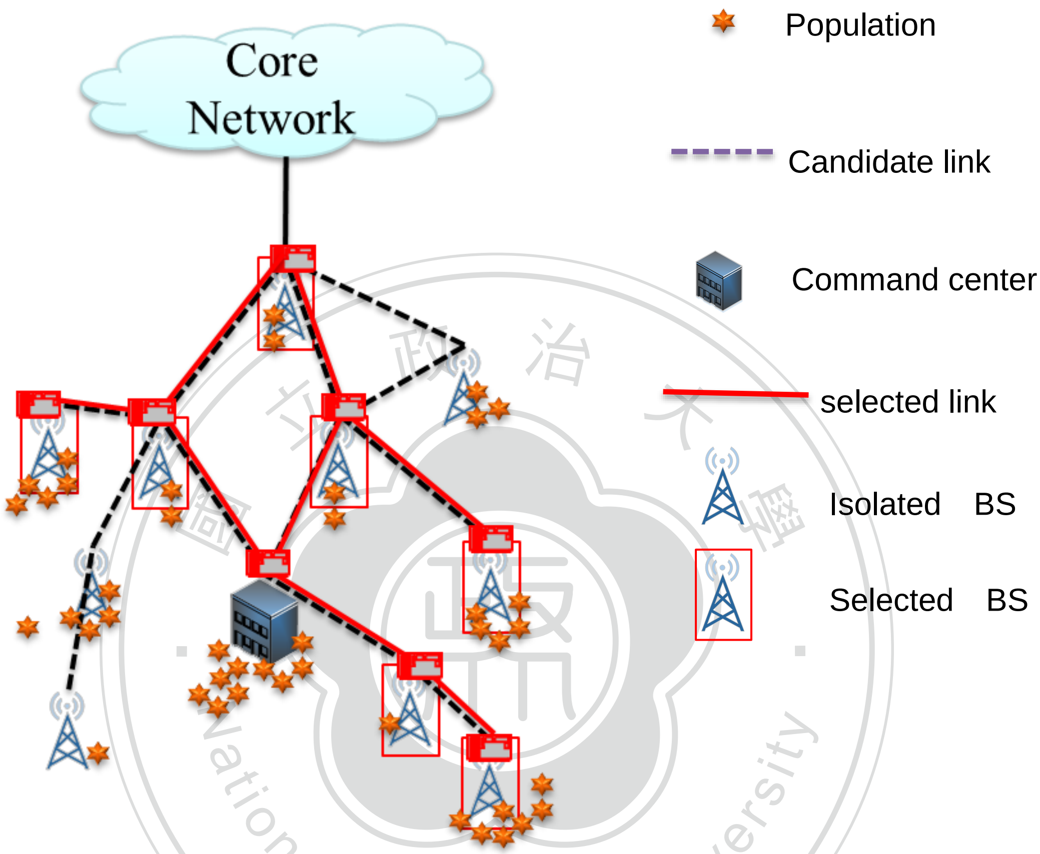


Figure 4.1. Considerations of topoloy design

Tree-type Topology vs. Mesh Network Topology

Strengths of the tree-type network topology are easy to construct and maintain, and thus tree-type network topology is wildly applied. But, it is vulnerable to a single link or node failure. The mesh network topology increases the network availability by using multiple path to connect the core network and critical areas, such as command centers, such that every critical areas can reach the core network via two or more disjointed paths. However, it will have a side effect to the total profit when using multiple path. Hence, it needs to balance the network availability and total profit when employing multiple path.

Single Operator vs. Multiple Operators

In general, the coverage areas of base stations are well planned and mutual exclusive. Therefore, it's simpler to construct CCN network by using base stations from one operator than multiple operators. Nevertheless, enlarging the concurrent users of some critical areas may increase the disaster response efficiency. This can be achieved by including the base stations from multiple operators in the same covered area into CCN. However, the profit function of the base stations that cover the same area is a decreasing function of the number of base stations in service. The marginal benefit of profits will gradually decease when multiple base stations covering the same area are selected into CCN.

Depth Bound vs. Depth Weight

The base stations connect to the core network by multi-hops in CCN. In order to avoid long hop connection and too much forwarding traffic, the number of hops has to be controlled. Depth bound constrains the number of hops by setting an upper bound of the number of hops. This model is simple, but may discard a seriously damaged area that is too far from the root. Depth weight dynamically adjusts the tree depth so that the serious damage areas would not be discarded by the depth constraint.

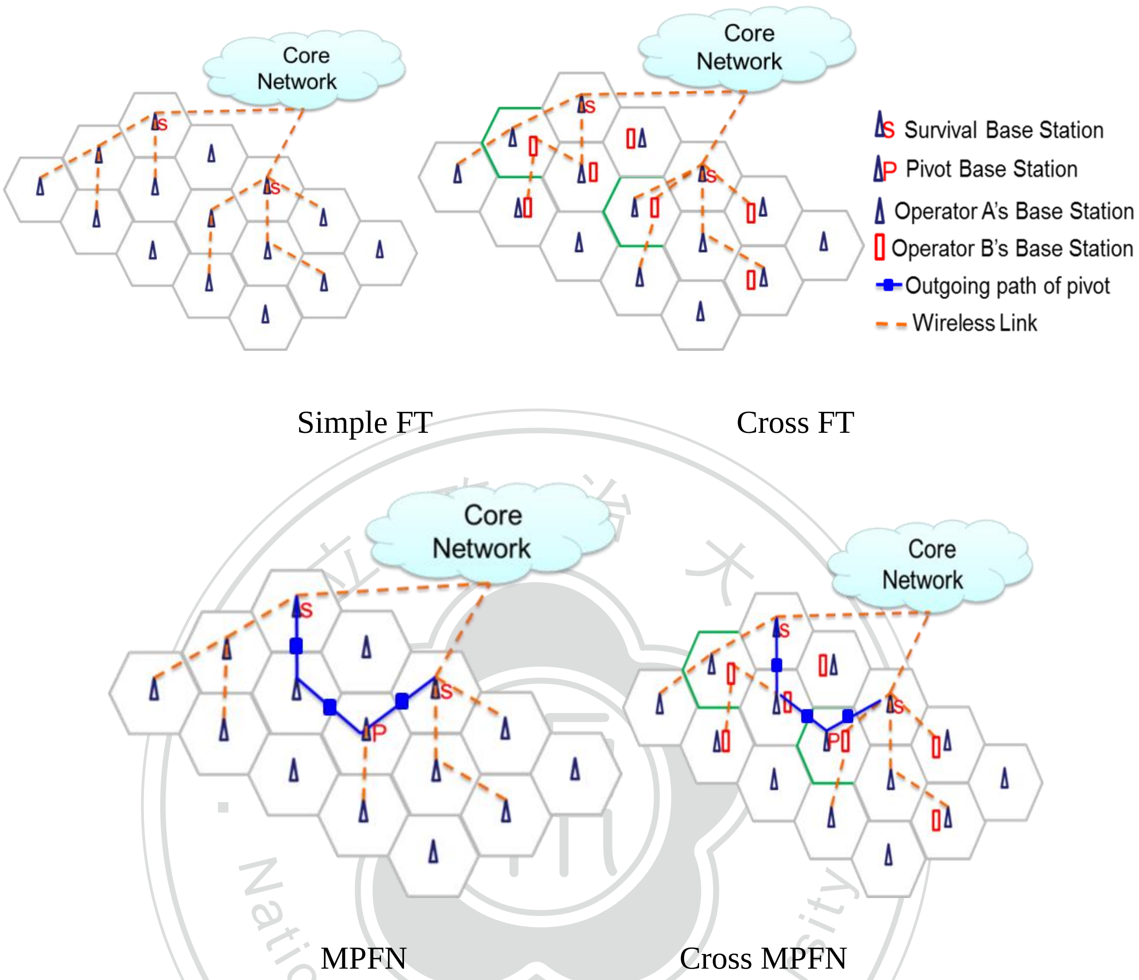


Figure 4.2. Four types of CCN network topology design problems

Combinations of these considerations discussed above are simple forwarding tree (Simple FT), cross-forwarding tree (Cross FT), multiple path forwarding network (MPFN) and Cross multiple path forwarding network (Cross MPFN), are proposed and discussed in this dissertation. Examples of these topologies are showed in Fig. 4.2.

Simple FT design problem is to find a K-maximum spanning tree with degree bound. The original base stations of Simple FT belong to one operator. Dash lines denote the selected wireless links. Cross FT is also a tree-type topology. But, the original base stations of Cross FT are from multiple operators. Triangle and rectangle denote the base stations of different operator. Cross FT assumes that disaster response authority has the privilege to expropriate any operator's base stations in an emergency.

MPFN design problem is to find a mesh network topology with degree bound to maximize the disaster response efficiency. Moreover, critical areas must have multiple outgoing paths which represented by the lines with squares to core network. Besides, the lengths of these multiple outgoing paths are limited with a fixed number of hops. The base stations of MPFN are from one operator. Cross MPFN is a mesh network topology, too. Cross MPFN use the base stations from multiple operators.

4.2. Related Works

Most topology design researches aim to find a minimum cost network with reliability constraint. In this section, we will present two models of network topology design problems. The first model adopt a two-phase methodology to find a mesh network with minimum cost while stratifying reliability; the second model formulates the network topology design problem as a minimum cost mesh network with reliability constraint.

Charnsripinyo [10] proposed a network topology design model that aims to finds a mesh network with minimum constructing cost while meeting reliability. Charnsripinyo adopt a two-phase design methodology. In the first phase, Charnsripinyo models the problem as a minimum cost spanning tree problem and provides a minimum cost network. The problem in the phase two is formulated into a Knapsack problem which aims to maximize the number of rings by augmenting edges to the network topology from the phase one to satisfy the reliability requirement. The experiment results show that this approach can greatly enhance the network reliability and quality of services. However, his model does not clear define the relationship between the number of rings and reliability. Therefore, the reliability of the network topology is unpredictable.

Elshqeirat [16] modeled the topology design problem as topology design with minimal cost subject to network reliability constraint. The reliability of the network topology is the probability that at least one spanning tree in the network topology is functional. Elshqeirat also proposed a dynamic programming (DP) scheme and three greedy heuristics algorithms to solve this problem. In Elshqeirat's model, reliabilities of each nodes is unified that is inapplicable to CCN. CCN topology design aims to find a tree-type or mesh network topology with maximum disaster response efficiency. The reliability requirements of different nodes are variant. Some critical areas request multiple outgoing paths, but some are not.

4.3. Comprehensive Mathematical Model for Network Topology Design

In our previous researches [22,26,27], we had proposed mathematical models and heuristic algorithms for Simple FT, Cross FT, MPFN and Cross MPFN problems. However, each model and heuristic algorithm is dedicated to solve one type of topology design problem. In this section, we will propose a comprehensive mathematical model to take all four types of topology design problems that are generally called CCN Comprehensive Network Topology Design (CNTD) problem into considerations.

The input parameters are *G=(V, E), S, Φ, R, W, C, D, U and Q* that are defined as follows.

- $V=\{ v_i | i=1, 2, \ldots, n\}$ *is the set of nodes represent the* disconnected base stations in the *disaster area.*

- $E=\{ e_{ij}| v_i, v_j \in V \}$ *is the set of links represent candidate wireless links between adjacency base stations, where* e_{ij} *denotes the wireless link between* v_i *and v.;*

- $S=\{ s_i|i=1, 2, \ldots, m\}$ *is the set of outgoing nodes denote the base stations that have external links to the core network, where* $S \subseteq V$.

- $\Phi=\{ \varphi_i|i=1, 2, \ldots\}$ *is the set of pivot nodes representing critical areas, where* $\Phi \subseteq V$.

- $R=\{ r_i|i=1,2,\ldots,n\}$ *is the set of profits, where* r_i *is the profit of* v_i*, if* v_i *is recovered.*

- $W=\{ w_{ij}|v_i, v_j \in V \}$ *is the weight of the edge* e_{ij} *representing the noise level of the edge, where the lower the level is, the better the quality is.*

- $C \in Z+$ *is the total number of available resources (CRPs).*

- $D \in Z+$ *is the number of antennas in a CRP.*

- *Q is a positive integer representing a lower bound of the number of pivot paths which are disjoint outgoing paths from the pivot node to the core network.*

- $U \in Z^+$ *is the upper length bound of pivot paths.*

- $g(m_i)$ *is a decreasing function which represents the profit earned by the* m_i*-th selected* *node in the same covered area, where m_i denotes the sequence order of v_i.*

- *Sum(X) is the summation of the values of the elements that belong to X, where X can be represented as a set of nodes, edges or paths.*

- *| X | is the number elements that belong to X.*

Two types of optimization models, based on two different depth control approaches, are proposed to formulate CCN CNTD problem: depth bound based and depth weight based.

Depth Bound Based Network Topology Design

CCN network topology design with depth bound is to find a network topology *G'(V', E')* from *G(V, E)* to maximize the total profit. m_i denotes the selected sequence of v_i in a covered area, for all v_i in *V'*. Optimization model of Depth Bound Based Network Topology Design (DBBNTD) is shown as follows.

Maximize

$$f(G') = \sum_{v_i \in V'} r_i \times g(m_i)$$

Subject to

$|V'| \leq C$ ------ (4.1)

$|E'| = |V'| - 1$ *,where G'(V', E') is a tree-type topology* ------ (4.2)

G' *is a connected graph* ------ (4.3)

$Degree(v_i) \leq D$, *for all* $v_i \in V'$ ------ (4.4)

$\sum_{v_j \in S} num\_of\_path(v_i, v_j) \geq Q$, *for all* $v_i \in \Phi$ ------ (4.5)

Length of pivot paths $(v_i) \leq U$, *for all* $v_i \in \Phi$ ------ (4.6)

$V' = \{ v'_i | i=1,2,\ldots,C\}$ is the set of nodes represents the selected base stations that are equipment with CRPs; $E' = \{ e'_{ij} | v'_i, v'_j \in V' \}$ is the set of links that represent the wireless links constructed by using the antennas in CRPs.

The object function, $f(G')$, is equal to the summation of profit multiply by $g(m_i)$ in G'. The comprehensive optimization model can be easily degenerated into Simple FT design problem, by setting $g(m_i)$ to 1 for all nodes and the set of pivot nodes into a null set. Cross FT's optimization model is similar to Simple FT, except that $g(m_i)$ is equal or smaller than 1 due to the decreasing marginal profit earned by recovering more than one base station in the same covered area.

Degenerating the comprehensive optimization model into MPFN design problem, the constraint 1.2 will not take effect since G' is a mesh network topology. $g(m_i)$ is equal to 1 for all selected nodes. Unlike the tree-type topology, the set of pivot nodes is not a null set. Cross MPFN's optimization model is similar to MPFN, expect that $g(m_i)$ is equal or smaller than 1.

Constraint 4.1 represents that the number of nodes in V' is less than or equal to the number of CRPs. Constraint 4.2 becomes effective when G' is a tree-type topology. Constraint 4.4

represents that the degree of v_i is less than or equal to the number of antennas in a CRP for all v_i in V'. Constraint 4.5 represents that the number of disjoint outgoing paths from the pivot node to the outgoing nodes is larger or equal to Q. Constraint 4.6 represents that the lengths of pivot paths are smaller than or equal to hop count limit, U.

Depth Weight Based Network Topology Design

Let SP_m denotes the shortest path from root to v_m *in* G' and $c_m = \sum_{e_{ij} \in SP_m} w_{ij}$, optimal objective function of Depth Weight Network Topology Design (DWBNTD) is listed as follow.

Maximize

$$f(G') = \sum_{v_i \in V'} \frac{r_i}{c_i} \times g(m_i)$$

The constraints of the depth weight based network topology are constraint 4.1 to 4.6. Instead of setting an upper bound on the hop count, depth weight based model controls the depth of the topology by lowering the weight of the profit earned by deeper nodes. Hence, constraint 4.7 is relaxed in the model and the objective function is redefined. The methods of degenerating the comprehensive optimization model of depth weight based model into Simple FT, Cross FT, MPFN and Cross MPFN are the same as the methods of depth bound based model.

4.4. Complexity Analysis

K-Maximum Spanning Tree (K-MaxST) problem is to find a maximum total profit spanning tree whose number of nodes is an integer K. K-MaxST problem is a NP Hard problem. Simple FT problem is to find a maximum total profit spanning tree whose upper bound of the number of nodes is C and degree bound is D. Definitions of C and D can be referred to Section 4.3. In this section, we will prove that the time complexity of Simple FT problem is NP Hard.

Some variables are added in order to prove the time complexity of Simple FT problem. The definitions of these variables are as follows.

- $A(N(V,E),K)$ is a problem instance of K-MaxST problem representing to find a maximum K-spanning tree from graph $N(V,E)$.
- $B(G(V, E), C, D)$ is a problem instance of Simple FT problem representing to find a maximum profit spanning tree whose upper bound of the number of nodes is C and degree bound is D, hop count limit is U and the number of pivot paths is Q from graph $G(V,E)$.

(A) Lemma 1: For any K-MaxST problem instance, *A(N(V,E),K)*, there exist a Simple FT problem instance, *B(G(V, E), C, D)*, that can be transformed into the problem *A* in polynomial time.

Proof: Given any K-MaxST problem instance, $A(N(V,E),K)$, we can find *a* dedicated Simple FT problem instance $B(G(V, E),C,D)$ with the given graph $G(V, E)$ and the constraints of the network topology. The network topology's upper bound of the number of nodes is C and degree bound is D, in which, $G(V,E) = N(V,E)$, $C = K$.

Let $D=\infty$, the degree bound constraint are relaxed. The Simple FT problem instance, *B(G(V, E), C, ∞)*, is transformed into a K-MaxST problem instance, *A(G(V,E),C)*. Let *G(V,E) = N(V,E) and C = K*, *A(G(V,E),C)* is equal to *A(N(V,E),K)*.

Therefore, for any problem *A(N(V,E),K)*, there exist a dedicated Simple FT problem instance *B(G(V, E), C, ∞)* that can be transformed into *A*. Obviously, the time complexity of the transformation is polynomial time. Q.E.D.

(B) Lemma 2: For any K-MaxST problem instance, *A(N(V,E),K)*, with optimal solution S_a, there exists a Simple FT problem instance, *B(G(V, E),C,D)*, where S_a is also an optimal solution of *B*.

Proof: From Lemma1, for any *A(N(V,E),K)*, there exist a CNTD problem instance, *B(G(V, E), C, ∞)*, where *G(V,E) = N(V,E) and C=K*.

Since S_a is the optimal solution of *A* and *G(V,E) = N(V,E)*, S_a is the spanning tree with maximum profit in *G(V,E)*, also. Because the number of nodes in S_a is equal to *K* and *C=K*, S_a satisfies the number of CRPs constraint. Clearly, S_a satisfies degree bound constraint when *D* is infinite. Therefore, S_a is an optimal solution of *B*. Q.E.D.

(C) Lemma 3: If S_b is an optimal solution of *B(G(V, E),C, D)*, then S_b is also an optimal solution of *A*.

Proof: Let *G(V,E) = N(V,E), C=K and D=∞*, S_b is a solution of *A*, obviously.

Let $P_A(X)$ be the total profit of solution *X* in *A* and $P_B(X)$ be the total profit of solution *X* in *B.* Since *G(V,E) = N(V,E)*, the total profit of *X* in *A* and *B* are equal, $P_A(X)= P_B(X)$.

Now, we prove by contradiction. Assume that S_b is an optimal of B, but not an optimal solution in A. Since S_b is an optimal of B, the total profit of S_b in B is $P_B(S_b)$. S_b is also a solution of A and the total profit of S_b in A is $P_A(S_b)$. $P_A(S_b) = P_B(S_b)$.

Let S_a be an optimal solution of A, S_a is also an optimal solution in B by Lemma 2. $P_A(S_a) = P_B(S_a) = P_B(S_b)$. Because $P_A(S_b) = P_B(S_b)$ and $P_A(S_a) = P_B(S_b)$, it implies that $P_A(S_b) = P_A(S_a)$. This contradicts to the assumption that S_b is not an optimal solution of A, $P_A(S_b) < P_A(S_a)$.

Therefore, S_b must be an optimal solution of A. Q.E.D.

Let S_a be the optimal solution of A, $TC_{\mathrm{A}}(S_a)$ be the time complexity of obtaining solution S_a in A. From Lemma 1, for any K-MaxST problem instance, A, there exist a *Simple FT* problem instance, B, that can be transformed into the problem A in polynomial time. Assume that the transformation time is $T_{B,A}$ and $TC_{\mathrm{B}}(S_a)$ be the time complexity of obtaining the optimal solution S_a in B. $TC_{\mathrm{A}}(S_a) = TC_{\mathrm{B}}(S_a) - T_{B,A}$. Because $T_{B,A}$ is polynomial and $TC_{\mathrm{A}}(S_a)$ is NP Hard, $TC_{\mathrm{B}}(S_a)$ is NP Hard.

Since S_a is an optimal solution of B which is proved in Lemma 2, $TC_{\mathrm{B}}(S_a)$ is the time complexity of Simple FT and had proved as NP Hard. Therefore, Simple FT problem is NP Hard. Q.E.D.

Since Simple FT is NP Hard, Cross FT, MPFN and Cross MPFN can be degenerating into Simple FT and thus they are NP Hard problems, also.

In this dissertation, we propose a transformation methodology that transforms the CCN

CNTD problem into a Binary Integer Linear Programming (BILP) problem. The transformation methodology is illustrated in section 4.6.

Since the network topology of CCN is needed in urgent, we also propose a heuristic algorithm, which is called Topology Design Heuristic Algorithm (TDHA), to solve the problem quickly. The detail of TDHA will be introduced in section 4.5. Finally, the performance of the TDHA is examined against BILP.

4.5. Topology Design Heuristic Algorithm

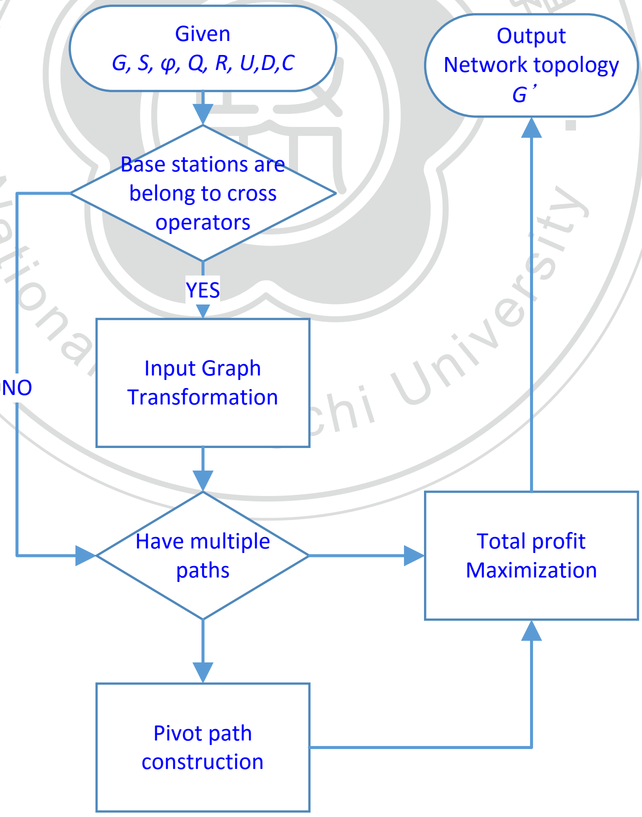


Figure 4.3. Main flow of Topology Design Heuristic Algorithm

Referring to Fig. 4.3, there are two key factors to determine the process flow of Topology

Design Heuristic Algorithm (TDHA). First, whether the base stations belong to a single operator or not? Second, whether the network topologies require multiple paths from pivot nodes to outgoing nodes or not? The mapping table of the two key factors and types of network topologies is showed in Table 4.1.

TABLE 4.1. Mapping table of two key factors and network topologies

Single or Multiple operators	Tree-type or mesh network	Network Topologies (G')
Multiple operators	Mesh network	Cross MPFN
Multiple operators	Tree-type	Cross FT
Single operator	Mesh network	MPFN
Single operator	Tree-type	Simple FT

Four major sub-processes of TDHA, input graph transformation, pivot path construction and total profit maximization, are illustrated as follows.

Input graph transformation takes two steps to transform the input graph that has base stations from multiple operators into a single graph. First, it decides the selected sequence m_i of base station v_i, in which, v_i denotes the base stations that have same covered area. Second, it generates the constraints that if v_i has smaller selected sequence than v_j and v_i, v_j cover the same area, then v_i should be selected before v_j. These constraints are called *cross network constrains*.

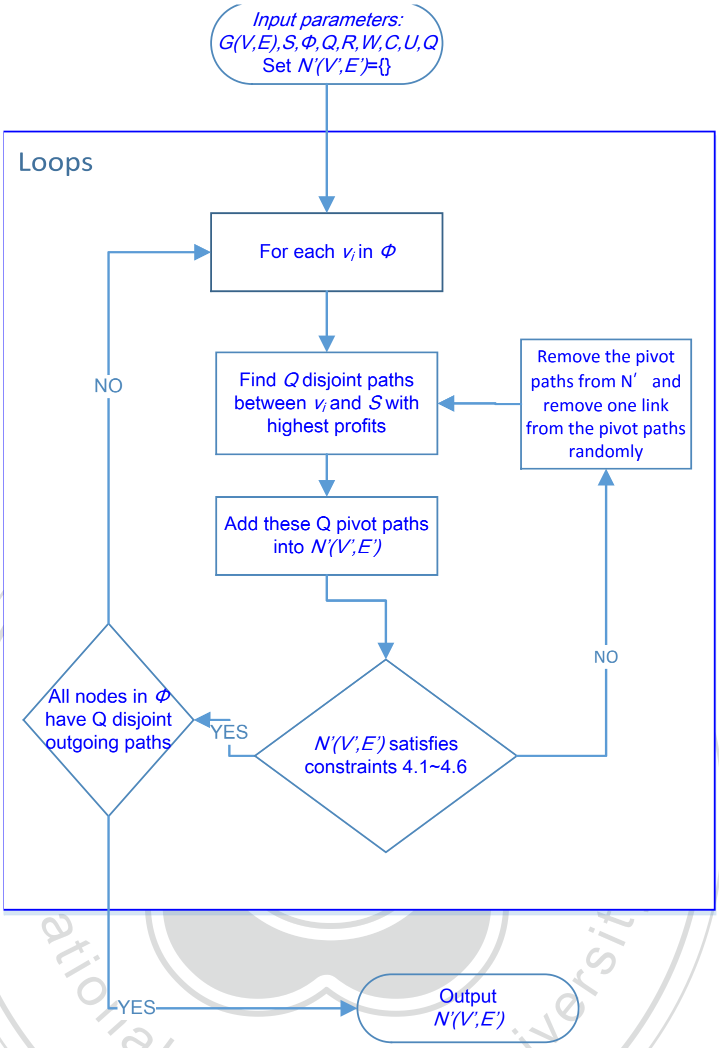


Figure 4.4. Flow chart of pivot path construction

Fig. 4.4 shows the flow chart of pivot path construction. The input parameters of pivot path construction are *G(V,E), S, Φ, Q, R, W, C, U and Q* defined in Section 4.3. Output of this process is *N'(V',E')* representing the mesh graph that contains all pivot paths. This process aims to construct Q disjoint paths for each v_i belonging to *Φ* with maximum total profits. In Step 1, it finds the pivot path of v_i which has highest profit performance ratio and adds this pivot path into *N'(V',E')*. The profit performance ratio is defined as $\frac{\textit{the total profit of the pivot path}}{\textit{the number of nodes in the pivot path}}$. In Step 2, it checks *N'(V',E')* whether it satisfies all constraints or not. If *N'(V',E')* satisfies all constraints, then the process goes back to Step 1 to find another pivot path. Otherwise, it ignores the pivot path and goes back to Step 1. This process will be repeated until all pivot paths are constructed.

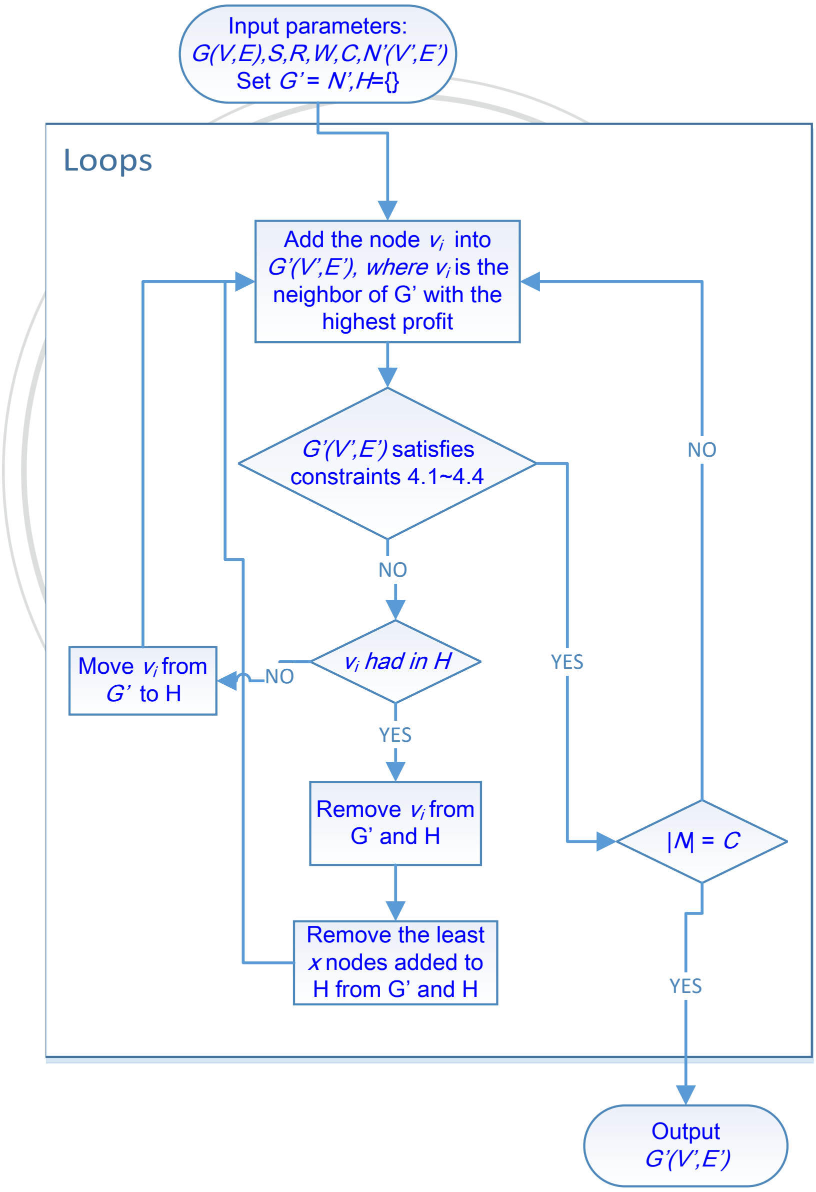


Figure 4.5. Flow chart of total profit maximization

Fig. 4.5 shows the flow chart of profit maximization. The input parameters are *G(V,E), S, R, W, C, and N'(V',E'). N'(V',E')'* is set as the initial solution. H records the nodes that are probed and is set as null, initially. The output parameter is the network topology, *G'(V',E')*. The purpose of total profit maximization is to maximize the total profit of *G'(V',E')* by adding the node which has the highest profit to *G'*, iteratively.

Let v_i represents the neighbor node of G' that has the highest profit and has not been included into *H*. In Step1, the process selects v_i to include into *H* and *G'*.

In Step 2, if *G'* satisfies all constraints after including v_i into *G'*, then goes back to Step 1 when $|V'| < C$. Otherwise, *G'* is not a valid solution, then removing v_i from *G'* and goes back to Step 1.

If all neighbor nodes of *G'* are included into *H* and $|V'| < C$, it means that the process is caught into a local optimal. In order to obtained better solutions by trying another probing sequence, the process randomly removes some nodes from *G'* and *H* and goes back to Step 1. The process will be repeated until $|V'| = C$. *G'*(*V'*,*E'*) is the solution of TDHA. Pseudo code of total profit maximization process is listed in Appendix I.

4.6. Binary Integer Linear Programming Transformation Methodology

To evaluate our heuristic algorithm, we use Binary Integer Linear Programming (BILP) to obtain optimal solutions, although optimal algorithms are not practical in real DRO. In order to translate CCN CNTD problem into BILP problem, some new variables are introduced.

The objective function and the constraints listed in section 4.3 are rewritten as follows.

- *bv_i is a binary variable, where i=1,2,…,n. bv_i =1 represents that v_i is selected;*
- *$be_{i,j}$ is a binary variable, where i,j=1,2,…,n. $be_{i,j}$ =1 represents that $e_{i,j}$ is selected;*
- *$A^{div}(i)$ denotes the set of links diverge from node v_i ;*
- *$A^{conv}(i)$ denotes the set of links converge to node v_i;*
- *$Sum(A^{div}(i))=\sum_{j=0,1,2,\ldots,n} be_{i,j}$ denotes the number of edges diverge from node v_i;*
- *$Sum(A^{conv}(i))=\sum_{j=0,1,2,\ldots,n} be_{j,i}$ denotes the number of edges converge to node v_i;*
- *$DG(v_i) = Sum(A^{div}(i))+ Sum(A^{conv}(i))$ denotes the degree of v_i;*
- *$P_{i,j} = \{p^z_{i,j}| z =1,2,3,\ldots,| P_{i,j} |\}$ denotes the set of paths from v_i to v_j* and *$p^z_{i,j}$ represents the z-th path from node i to j;*
- *$bP_{i,j} = \{bp^z_{i,j}| z =1,2,3,\ldots,| P_{i,j} |\}$ denotes the set of binary variables of the paths from v_i to v_j* and *$bp^z_{i,j}$ represents the binary variable of path $p^z_{i,j}$;*

(1) Transformation of the relationship between nodes and edges

Because the network topology *G'* is a connected graph, the nodes and edges have the following relationship. If v_i is not selected, then neither a converge nor a diverge edge of v_i can be selected. If any converge edge of v_i is selected, v_i must be selected.

Binary linear equations that express the relationship between nodes and edges are listed as follows.

$be_{i,j} - bv_i \leq 0$,*for all* $v_i \in V$; $e_{i,j} \in A^{div}(i)$ ------ (4.7)

$be_{j,i} - bv_i \leq 0$,*for all* $v_i \in V$; $e_{j,i} \in A^{conv}(i)$ ------ (4.8)

$vi - Sum(A^{conv}(i)) \leq 0$,*for all* $v_i \in V$ ------ (4.9)

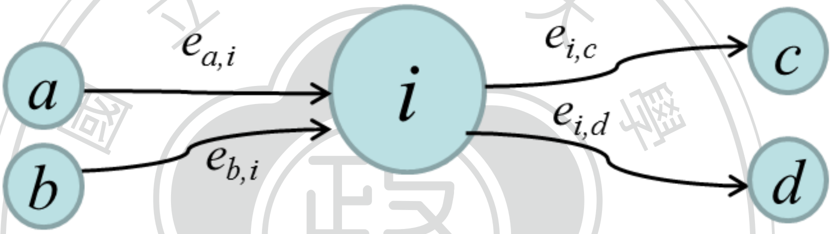


Figure 4.6. Example of relationship between nodes and edges

Fig. 4.6 shows an example of the relationship between nodes and edges, in which, $A^{conv}(i) = \{e_{a,i}, e_{b,i}\}$ and $A^{div}(i) = \{e_{i,c}, e_{i,d}\}$. If v_i is not selected (bv_i=0), then $e_{a,i}$, $e_{b,i}$, $e_{i,c}$ and $e_{i,d}$ must not be selected ($be_{a,i} = be_{b,i} = be_{i,c} = be_{i,d} = 0$). On the other hand, if v_i is selected (bv_i=1), then $e_{a,i}$, $e_{b,i}$, $e_{i,c}$ and $e_{i,d}$ can be either selected or not selected ($0 \leq be_{a,i}, be_{b,i}, be_{i,c}, be_{i,d} \leq 1$). These relationship are expressed in formula 4.7 and 4.8.

Furthermore, if v_i is not selected (bv_i=0), then all converge edges of v_i cannot be selected ($A^{conv}(i)=0$). If v_i is selected (bv_i=1), then at least one converge edge of v_i must be selected ($bv_i = 1, A^{conv}(i) = be_{a,i} + be_{b,i} \rightarrow bv_i \leq A^{conv}(i)$). This relationship is expressed in formula 4.9.

(2) Transformation the relationship between edges and paths

Paths are composed by edges. Relationship between a path and its edges are expressed in formula 4.11 and 4.12. Formula 4.11 shows that if a path, $p^z_{x,y}$, is not selected ($bp^z_{x,y}=0$), then there exist an edge that belongs to path $p^z_{x,y}$ is not be selected. Formula 4.12 shows that if a path, $p^z_{x,y}$, is selected ($bp^z_{x,y}=1$), then all edges that belongs to path $p^z_{x,y}$ must be selected.

$$Sum(p^z_{x,y}) - bp^z_{x,y} \leq |\, p^z_{x,y} \,| - 1 \quad ,for\ all\ v_x, v_y \in V;\ p^z_{x,y} \in P_{x,y} \quad \text{------ (4.10)}$$

$$bp^z_{x,y} - be_{i,j} \leq 0 \quad ,for\ all\ v_x, v_y \in V;\ p^z_{x,y} \in P_{x,y};\ e_{i,j} \in p^z_{x,y} \quad \text{------ (4.11)}$$

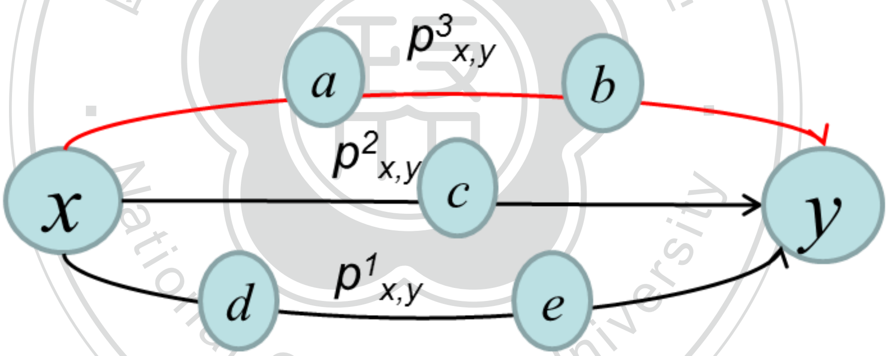


Figure 4.7. Example of relationship between paths and edges

Fig. 4.7 shows an example of the relationship between paths and edges, in which, $p^1_{x,y}=\{e_{x,d}, e_{d,e}, e_{e,y}\}$, $p^2_{x,y}=\{e_{x,c}, e_{c,y}\}$, $p^3_{x,y}=\{e_{x,a}, e_{a,b}, e_{b,y}\}$, Sum($p^3_{x,y}$) = $be_{x,a} + be_{a,b} + be_{b,y}$ and $|\, p^3_{x,y} \,| = 3$. Referring to formula 4.10, if path, $p^3_{x,y}$, is not selected ($bp^3_{x,y}=0$), then $Sum(p^3_{x,y}) - bp^3_{x,y} \leq |\, p^3_{x,y} \,| - 1$. It implies that $be_{x,a} + be_{a,b} + be_{b,y} \leq 2$. The equation means that at least one edge belonging to $p^3_{x,y}$ cannot be selected.

Referring to formula 4.11, if path, $p^3_{x,y}$, is selected ($bp^3_{x,y}=1$), then $bp^3_{x,y} - be_{i,j} \leq 0$, *for all* $e_{i,j}$ *belongs to* $p^3_{x,y}$. *It implies* $1 \leq be_{i,j}$. *All* edges belong to $p^3_{x,y}$ must be selected.

(3) Transformation of hop count limit

Let $P_{x,y}(h) = \{p^z_{x,y} | p^z_{x,y} \in P_{x,y} \text{ and } |p^z_{x,y}| \leq h\}$. $P_{x,y}(h)$ is the set of paths from v_x to v_y whose length is less than or equal to h. When a pivot nodes v_y is selected, then there exist a paths from root the v_y, $p^z_{x,y}$, whose length is less than or equal to hop count limit, U. The hop count limit is showed in formula 4.12.

$$bv_y - Sum(P_{root,y}(U)) \leq 0 \qquad , \text{for all } v_y \in \Phi; p^z_{root,y} \in P_{root,y}; \; |p^z_{root,y}| \leq U \qquad \text{------ (4.12)}$$

(4) Transformation of resource constraints

The constraint that the number of selected nodes is equal or less than the number of CRPs and this constraint is expressed in formula 4.13. Formula 4.14 represents that the degree of v_i is equal or less than the number of antennas, D, in each CRP. The degree of v_i is equal to $Sum(A^{conv}(i))+ Sum(A^{div}(i))$. Because $e_{i,j}$ and $e_{j,i}$ denotes the same wireless link, $e_{i,j}$ and $e_{j,i}$ cannot be selected simultaneously to avoid double count of wireless links (refers to formula 4.15).

$$Sum(V) = C \qquad \text{------ (4.13)}$$

$$Sum(A^{conv}(i))+ Sum(A^{div}(i)) \leq D \qquad , \text{for all } v_i \in V \qquad \text{------ (4.14)}$$

$$be_{i,j} + be_{j,i} \leq 1 \qquad , \text{for all } v_i, v_j \in V \qquad \text{------ (4.15)}$$

(5) Transformation of minimum disjoint path constraints

Each pivot node requires a minimum of Q disjoint paths to meet the reliability constraint. $P_{root,y}(e_{i,j})$ denotes the set of paths from root to v_y that have common edge $e_{i,j}$. Formula 4.16 represents that at most one of paths belonging to $P_{root,y}(e_{i,j})$ can be selected due to the disjoint path constraint. Formula 4.17 represents that a minimum of Q paths from root to v_y must be selected.

$$Sum(P_{root,y}(e_{i,j})) \leq 1 \qquad \text{for all } v_y \in \Phi;\ e_{i,j} \in E;\ |P_{root,y}(e_{i,j})|>1 \qquad \text{------ (4.16)}$$

$$Q - Sum(P_{root,y}) \leq 0 \qquad \text{for all } v_y \in \Phi \qquad \text{------ (4.17)}$$

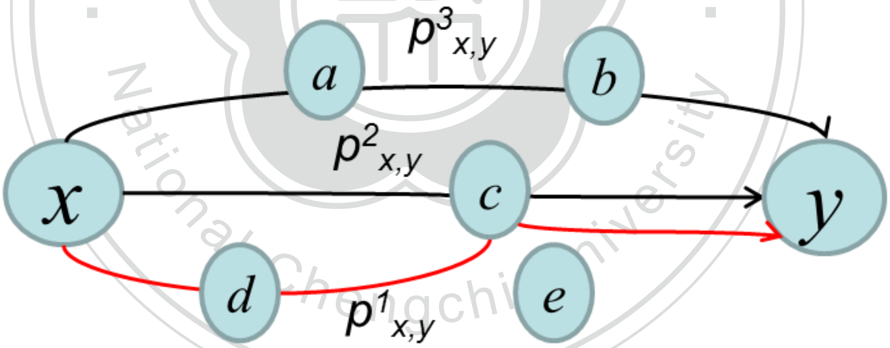


Figure 4.8. Example of multiple disjoint paths

Referring to Fig. 4.8, $p^1_{x,y}=\{e_{x,d}, e_{d,c}, e_{c,y}\}$, $p^2_{x,y}=\{e_{x,c}, e_{c,y}\}$ *and* $p^3_{x,y}=\{e_{x,a}, e_{a,b}, e_{b,y}\}$. $p^1_{x,y}$ and $p^2_{x,y}$ have common edge $e_{c,y}$, $P_{x,y}(e_{c,y})$ = $\{p^1_{x,y}, p^2_{x,y}\}$. Therefore, they cannot be selected simultaneously. If the number of outgoing paths, Q, is 2, then the feasible solutions are either $\{p^1_{x,y}, p^3_{x,y}\}$ or $\{p^2_{x,y}, p^3_{x,y}\}$. If Q = 3, then no feasible solution can be found.

(6) Transformation of path reliability constraints

If the path reliabilities of pivot nodes are given, then the number of disjoint paths can be computed. Let the path reliabilities of pivot nodes be greater than $1-\alpha$. Let *Rel(X)* denotes the reliability of *X* and Fail*(X)* denotes the failure probability of *X* where Fail$(X)=1-Rel(X)$.

The path reliability from root to v_y, Rel($p^z_{root,y}$), is the probability that all edges belonging to $p^z_{root,y}$ are functional. Rel($p^z_{root,y}$) is equal to the multiplication of the reliabilities of the edges that belong to $p^z_{root,y}$.

$Rel(p^z_{root,y}) = \prod Rel(e_{i,j})$, for all $e_{i,j} \in p^z_{root,y}$

$Fail(p^z_{root,y}) = 1 - Rel(p^z_{root,y})$

Failure probability of pivot v_y, $Fail(v_y)$, is equal to the multiplication of the failure probability of the paths that belong to $P_{root,y} \cap G'$.

$Fail(v_y) = \prod Fail(p^z_{root,y})$, for all $p^z_{root,y} \in P_{root,y} \cap G'$

Transferring the equation of $Fail(v_y)$ to a binary linear equation by adding logarithm and binary variables of paths, $bp^z_{root,y}$, for all $p^z_{root,y}$ belong to $P_{root,y}$.

⇨ $\log Fail(v_y) = \log \prod Fail(p^z_{root,y})$, for all $p^z_{root,y} \in P_{root,y} \cap G'$

⇨ $\log Fail(v_y) = \Sigma \log Fail(p^z_{root,y})$, for all $p^z_{root,y} \in P_{root,y} \cap G'$

⇨ $\log Fail(v_y) = \Sigma[\log Fail(p^z_{root,y})] \times bp^z_{root,y}$, for all $p^z_{root,y} \in P_{root,y}$

Since $Fail(v_y)$ is less than or equal to α.

⇨ $\Sigma[\log Fail(p^z_{root,y})] \times bp^z_{root,y} \leq \log \alpha$, for all $p^z_{root,y} \in P_{root,y}$

Referring to formula 4.18, the binary linear equation of computed number of disjoint paths is showed.

$$\Sigma[\log Fail(p^z_{root,y})] \times bp^z_{root} \leq \log\alpha \qquad for\ all\ v_y \in \Phi; \qquad \text{------ (4.18)}$$

$$\text{and } p^z_{root,y} \in P_{root,y}$$

Take Fig. 4.7 as an example, assuming the reliability of each edge is 0.9, then the failure probabilities of paths, $p^1_{root,y}$, $p^2_{root,y}$ and $p^3_{root,y}$ can be computed as follow.

$Fail(p^1_{root,y}) = 1\text{-}\ Rel(p^1_{root,y}) = 1 - Rel(e_{x,d}) \times Rel(e_{d,c}) \times Rel(e_{c,y}) = 1\text{-}0.9^3=0.27;$

$Fail(p^2_{root,y}) = 1\text{-}\ Rel(p^2_{root,y}) = 1 - Rel(e_{x,c}) \times Rel(e_{c,y}) = 1\text{-}0.9^2=0.19;$

$Fail(p^3_{root,y}) = 1\text{-}\ Rel(p^3_{root,y}) = 1 - Rel(e_{x,a}) \times Rel(e_{a,b}) \times Rel(e_{b,y}) = 1\text{-}0.9^3= 0.27;$

The relaibility of pivot node, v_y, is computed as follow.

$\log Fail(v_y) = \Sigma[\log Fail(p^z_{root,y})] \times bp^z_{root} \quad , z=1,2,3$

- ⇨ $\log Fail(v_y)=bp^1_{root,y} \times \log Fail(p^1_{root,y}) + bp^2_{root,y} \times \log Fail(p^2_{root,y}) + bp^3_{root,y} \times \log Fail(p^3_{root,y})$
- ⇨ $\log Fail(v_y)= bp^1_{root,y} \times \log 0.27 + bp^2_{root,y} \times \log 0.19 + bp^3_{root,y} \times \log 0.27$
- ⇨ $\log Fail(v_y) = (-0.569)\ bp^1_{root,y} + (-0.721)\ bp^2_{root,y} + (-0.569)\ bp^3_{root,y}$

When applying path $\{bp^1_{root,y}, bp^3_{root,y}\}$ as outgoing paths, then $Rel(v_y)=92.71\%$

- ⇨ $\log Fail(v_y) = -1.137$
- ⇨ $Fail(v_y) = 7.29\%$
- ⇨ $Rel(v_y) =1\text{-}\ Fail(v_y) = 92.71\%$

When applying path $\{bp^2_{root,y}, bp^3_{root,y}\}$ as outgoing paths, then $Rel(v_y)=94.87\%$

- ⇨ $\log Fail(v_y) = -1.29$
- ⇨ $Fail(v_y) = 5.13\%$

⇨ $Rel(v_y) = 1 - Fail(v_y) = 94.87\%$

(7) Transformation of cross network constraints

Let $cover_x = \{v_i, v_j, v_k, \ldots\}$ denotes the set of BSs that cover the same area x with corresponding selection sequence 1,2,3,…. The order of v_i in the selection sequence precedes that of v_j. Formula 4.19 indicates that v_i must be selected before v_j.

$$bv_j - bv_i \leq 0 \qquad \text{for all } v_i, v_j \in cover_x;\ m_i < m_j \qquad \text{------ (4.19)}$$

(8) Transformation of topology type constraints

If G' is a tree-type topology then, $|V'|-1 = |E'|$, since $|V'|=Sum(V)$ and $|E'|= Sum(E)$. Referring to formula 4.20, the tree type topology constraint is that the number of node of G' minus one must be equal to the number of edges of G'. If G' is a mesh network, then no constraint is necessary.

$$Sum(V) - Sum(E) = 1 \qquad \text{------ (4.20)}$$

Let x denotes the solution of binary linear programming. x is a binary vector.

$x = \{\ldots, bv_i, \ldots, be_{i,j}, \ldots, bp^z_{root,y}, \ldots\}$, for all $v_i \in V$, $e_{i,j} \in E$, $v_y \in \Phi$ and $p^z_{root,y} \in P_{root,y}$

The objective function of BILP is expressed as follows.

Maximize

$$f(x) = \sum bv_i \times r_i \times g(m_i), \text{ for all } v_i \in V$$

Subject to

$$be_{i,j} - bv_i \leq 0 \quad , \text{for all } v_i \in V;\ e_{i,j} \in A^{div}(i) \quad \text{------ (4.21)}$$

$$be_{j,i} - bv_i \leq 0 \quad , \text{for all } v_i \in V;\ e_{j,i} \in A^{conv}(i) \quad \text{------ (4.22)}$$

$$vi - Sum(A^{conv}(i)) \leq 0 \quad , \text{for all } v_i \in V \quad \text{------ (4.23)}$$

$$Sum(p^z_{root,y}) - bp^z_{root,y} \leq |\, p^z_{root,y} \,| - 1 \quad , \text{for all } v_y \in \Phi;\ p^z_{root,y} \in P_{root,y} \quad \text{------ (4.24)}$$

$$bp^z_{root,y} - be_{i,j} \leq 0 \quad , \text{for all } v_y \in \Phi;\ p^z_{root,y} \in P_{root,y};\ e_{i,j} \in p^z_{root,y} \quad \text{------ (4.25)}$$

$$bv_y - Sum(P_{root,y}(U)) \leq 0 \quad , \text{for all } v_y \in \Phi;\ p^z_{root,y} \in P_{root,y};\ |p^z_{root,y}| \leq U \quad \text{------ (4.26)}$$

$$Sum(V) = C \quad \text{------ (4.27)}$$

$$Sum(A^{conv}(i)) + Sum(A^{div}(i)) \leq D \quad , \text{for all } v_i \in V \quad \text{------ (4.28)}$$

$$be_{i,j} + be_{j,i} \leq 1 \quad , \text{for all } v_i, v_j \in V \quad \text{------ (4.29)}$$

$$Sum(P_{root,y}(e_{i,j})) \leq 1 \quad , \text{for all } v_y \in \Phi;\ e_{i,j} \in E;\ |\, P_{root,y}(e_{i,j})| > 1 \quad \text{------ (4.30)}$$

$$Q - Sum(P_{root,y}) \leq 0 \quad , \text{for all } v_y \in \Phi \quad \text{------ (4.31)}$$

$$bv_j - bv_i \leq 0 \quad , \text{for all } v_i, v_j \in cover_x;\ m_i < m_j \quad \text{------ (4.32)}$$

$$Sum(V) - Sum(E) = 1 \quad , \text{If } G' \text{ is tree-type} \quad \text{------ (4.33)}$$

f(x) denotes the profit function. Constraints 4.21, 4.22 and 4.23 represent the relationship between nodes and edges. Constraints 4.24 and 4.25 represent the relationship between the outgoing paths of pivot nodes and edges. Constraint 4.26 excludes those paths violating the hop count limit constraints. Constraints 4.27, 4.28 and 4.29 represent the limits of the number of CRPs and the number of antennas in each CRP. Constraints 4.30 and 4.31 indicate that the pivots nodes should have Q disjoint outgoing paths. Constraint 4.32 indicates the cross network constraint. Constraint 4.33 becomes effective when *G'* is a tree-type topology.

In this section, we propose a transformation methodology that transforms the CCN CNTD problem to a BILP problem which can be solved using any binary linear programming algorithm. This transformation methodology is not only applicable to CCN network topology design, but also applicable to other optimization problems. One major benefit of this methodology is that there exists some commercial software such as MatLab such that even non-professional programmers can easily solve the problems. Pseudo code of binary integer linear programming algorithm is listed in Appendix II.

4.7. Performance Evaluation

We conduct several simulation based experiments to evaluate our TDHA against optimal solutions obtained from BILP. The experiment objectives are (1) to analyze the characteristics of CCN topology design problems, (2) the performance of TDHA, (3) the availabilities of multiple path network topologies and (4) depth bound vs. depth weight analysis. Three experimental results analysis, characteristics of CCN network topology problems, the performance of THDA and availabilities of multiple path network topologies, are proposed in this section.

Table 4.2 shows input parameters for test case generation and evaluation metrics. Testing graphs *G(V, E)* were generated randomly. The profits of nodes are generated by a uniform random function ranging from *0* to *100*. Algorithm TDHA is applied to solve Simple FT, Cross FT, MPFN and Cross MPFN problems to generate heuristic solutions. Algorithm BILP is applied to solve Simple FT and Cross FT problems to generate optimal solutions. Since BILP needs excessive long computing times to solve MPFN and Cross MPFN problems when the size, of given graph, G, is greater than 100, we used the Topology Random Search Algorithm (TRSA) [22] to find the pseudo-optimal solutions of them. TRSA generates one million solutions randomly and chooses the maximum solution as the pseudo-optimal solution. The pseudo-optimal solutions are used to analyze the chrateristic of CCN CNTD problem and to evaluate the performance of TDHA when optimal solutions are not available.

TABLE 4.2. Parameters for experiment setup

<table>
<tr><th colspan="6">Input parameters</th><th colspan="4">Evaluation metrics</th></tr>
<tr><th>Network Topology</th><th>G(V,E)</th><th>|S|</th><th>|Φ|</th><th>|Q|</th><th>|U|</th><th>Total Profits</th><th>Unit profit gain</th><th>Deviation of profit</th><th>Reliability of pivot nodes</th></tr>
<tr><td>Simple FT</td><td rowspan="4">G(50,200)
G(100,400)
(200,800)</td><td rowspan="4">2, 3</td><td rowspan="2">0</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="4">TDHA
BILP/TRSA</td><td rowspan="4">$\frac{total\ profits}{number\ of\ CRPs}$</td><td rowspan="2">Deviation of optimal profit</td><td rowspan="2"></td></tr>
<tr><td>Cross FT</td></tr>
<tr><td>MPFN</td><td rowspan="2">1 - 8</td><td rowspan="2">1 - 3</td><td rowspan="2">4, 6</td><td rowspan="2">Deviation of pseudo-optimal profit</td><td rowspan="2">Rel(Φ)</td></tr>
<tr><td>Cross MPFN</td></tr>
</table>

Definitions of unit profit gain, deviation of optimal profit and deviation of pseudo optimal profit and reliability of pivot nodes are showed in Table 4.3. Unit profit gain is a normalized metric used to examine the characteristics of generated topologies. Deviations of optimal and pseudo-optimal profits are applied to evaluate the performance of TDHA against the optimal and pseudo-optimal solutions, respectively.

TABLE 4.3. Evaluation metrics

Metrics	**Definition**
Unit profit gain	$\frac{\text{the total disaster response profit}}{\text{the number of CRPs}}$
Deviation of optimal profit	$1 - \frac{\text{heuristic solution}}{\text{optimal solution}}$
Deviation of pseudo-optimal profit	$1 - \frac{\text{heuristic solution}}{\text{pseudo optimal solution}}$
Reliability of pivot nodes, $Rel(\Phi)$	$Rel(\Phi) = Rel(\varphi_1 \cap \varphi_2 \cap \varphi_3 \cap \ldots)$ -----(4.34)

The reliability of pivot nodes, $Rel(\Phi)$, is the probability that all pivot nodes are funtional. $Rel(\Phi)$ is equal to $Rel(\varphi_1 \cap \varphi_2 \cap \varphi_3 \cap \ldots)$ for all pivot nodes φ_i and applied to evaluated the reliability of the network topology.

TABLE 4.4. Environments of experiments

Software	
MATLAB R2012a	
Hardware	
CPU	Intel® Core™ i3 2.93GHz
RAM	4 GB
OS	Windows 7

The specifications of hardware and software are showed in Table 4.4. The test cases are evaluated by simulation using MATLAB on a regular PC.

(a) Experiment 1: Characteristics analysis of CCN network topology problems.

The characteristics of generated topologies are examined by observing the influence of the number of survival nodes |*S*|, pivot nodes |*Φ*|, pivot paths |*Q*| and length bound of pivot paths |U| on the unit profit gain, which is the profit gain per CRP, of both optimal and pseudo-optimal solutions.

The characteristics of Simple FT and Cross FT are showed in Fig.4.9. The x-axis is the number of survival nodes/number of nodes/solutions and pivot nodes and the y-axis is the unit profit gain. The maximum unit profit gain is 86.2 when |S|=3, |V|=5 and network topology type is Cross FT. The minimum unit profit gain is 76.2 when |S|=2, |V|=200 and network topology type is Simple FT. The unit profit gains of Cross FT are better than Simple FT's. The unit profit gains of Cross FT and Simple FT are 81.1 to 79.5, respectively. The unit profit gains are 79.4 and 81 when the numbers of survival stations, |S|, are 2 and 3, respectively. Besides, the profit gain decrease as the value of |V| increases.

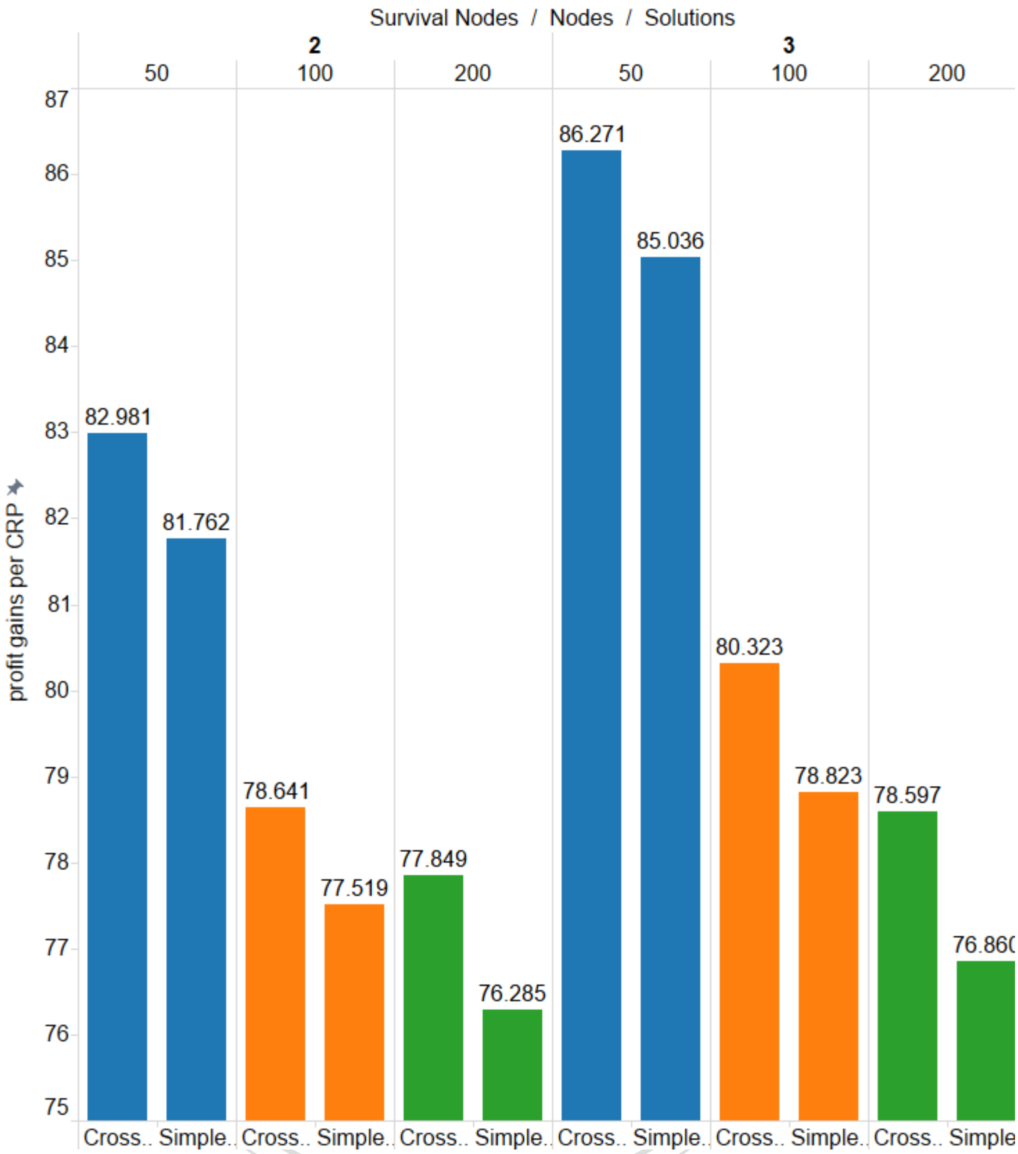


Figure 4.9. Characteristics of Simple and Cross FT (optimal solution)

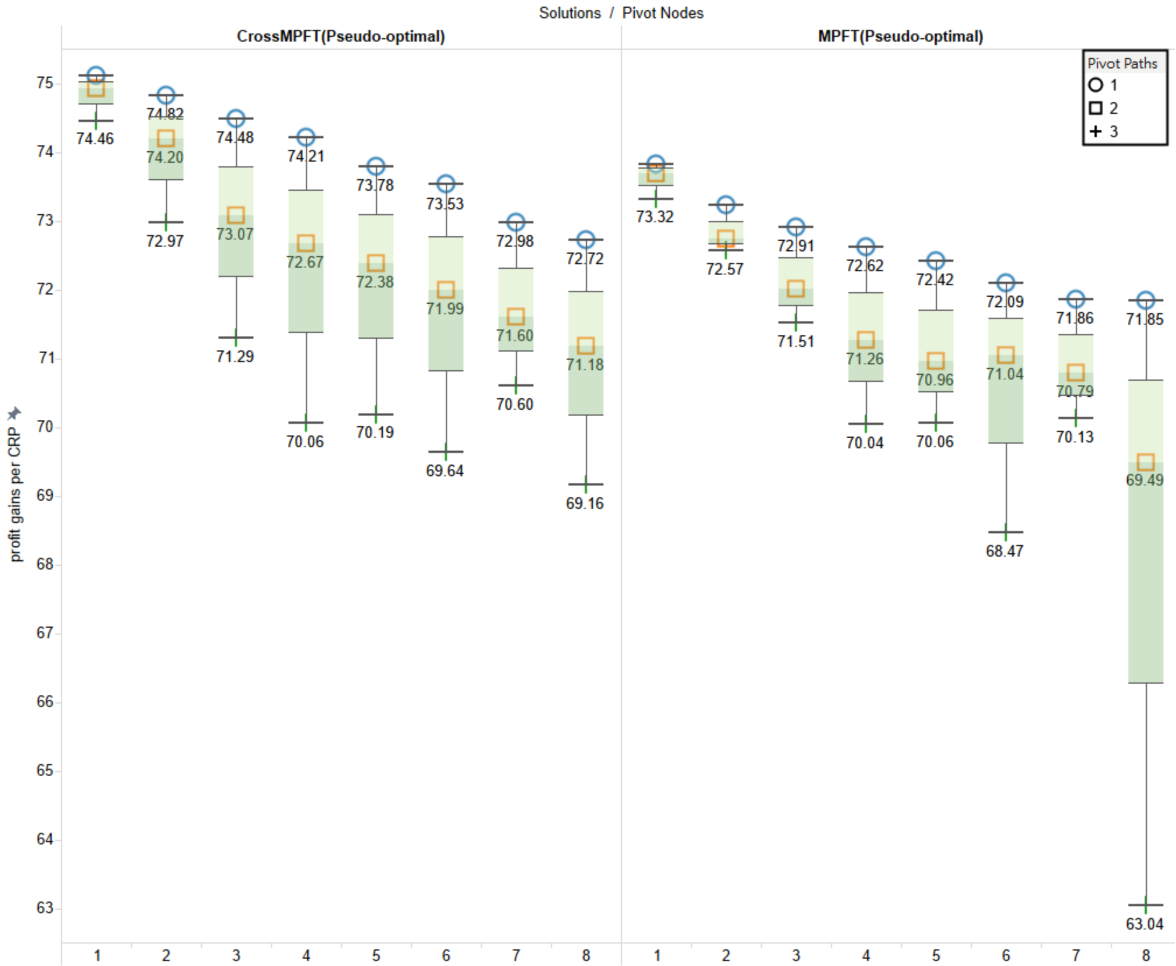


Figure 4.10. Characteristics of MPFN and Cross MPFN (number of pivot nodes/paths)

The characteristics of MPFN and Cross MPFN are showed in Fig. 4.10. The x-axis is solutions/number of pivot nodes and the y-axis is the unit profit gains. Shapes ○, □ and + represent |Q| = 1, 2 and 3, respectively. The maximum unit profit gain is 75.1 when |Φ|=1, |Q|=1 and network topology type is Cross MPFN. The minimum unit profit gain is 63 when |Φ|=8, |Q|=3 and network topology type is Cross MPFN. Increasing the values of |Φ| and |Q| will cause the loss of profit. The length of the box in Fig. 4.10 represents the profit loss when the value of |Q| increase. The average length of box in Cross MPFN is longer than that in MPFN.

(b) Experiment 2: Performance analysis of THDA.

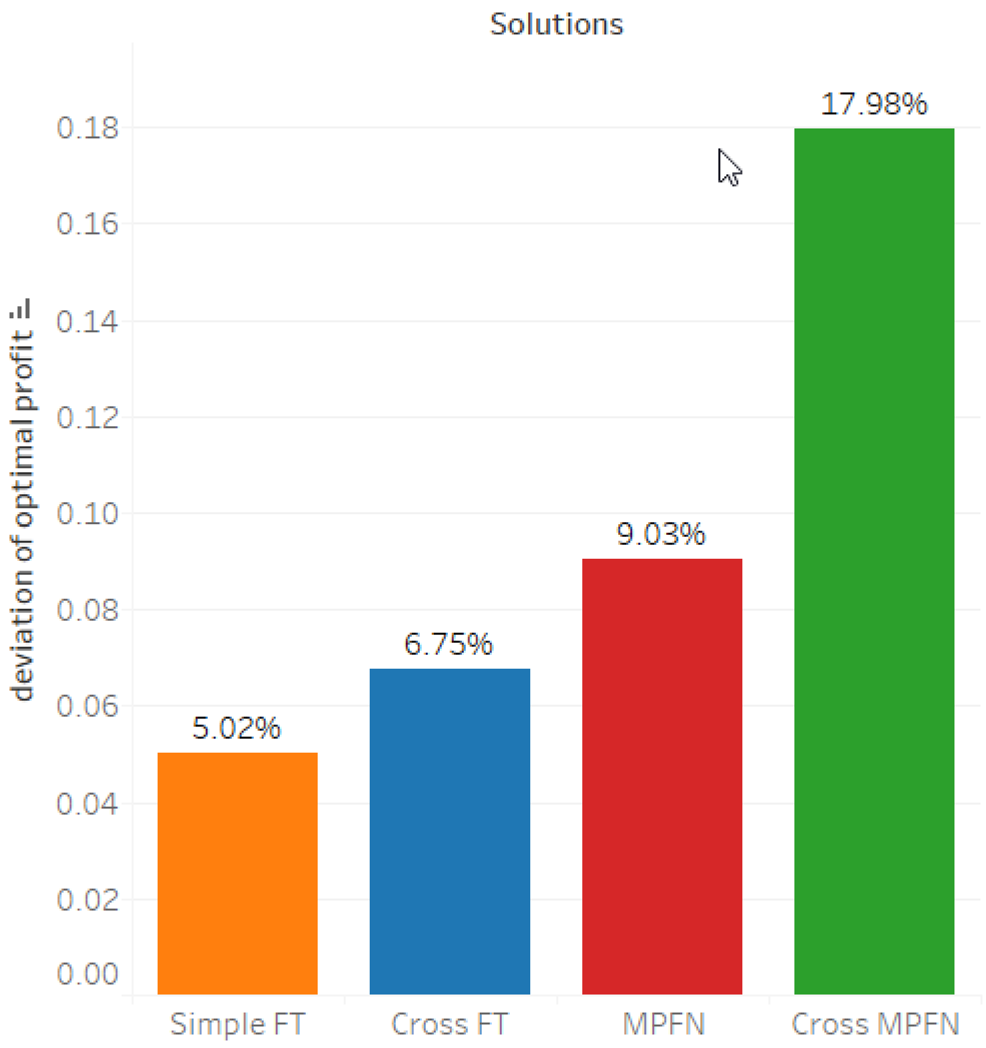


Figure 4.11. Performance of TDHA (deviation of optimal profits)

The performances of TDHA in solving Simple FT, Cross FT, MPFN and Cross MPFN are shown in Fig. 4.11. The deviation of optimal profits of Simple FT, Cross FT, MPFN and Cross MPFN are 5.02%, 6.75%, 9.03% and 17.98%, respectively.

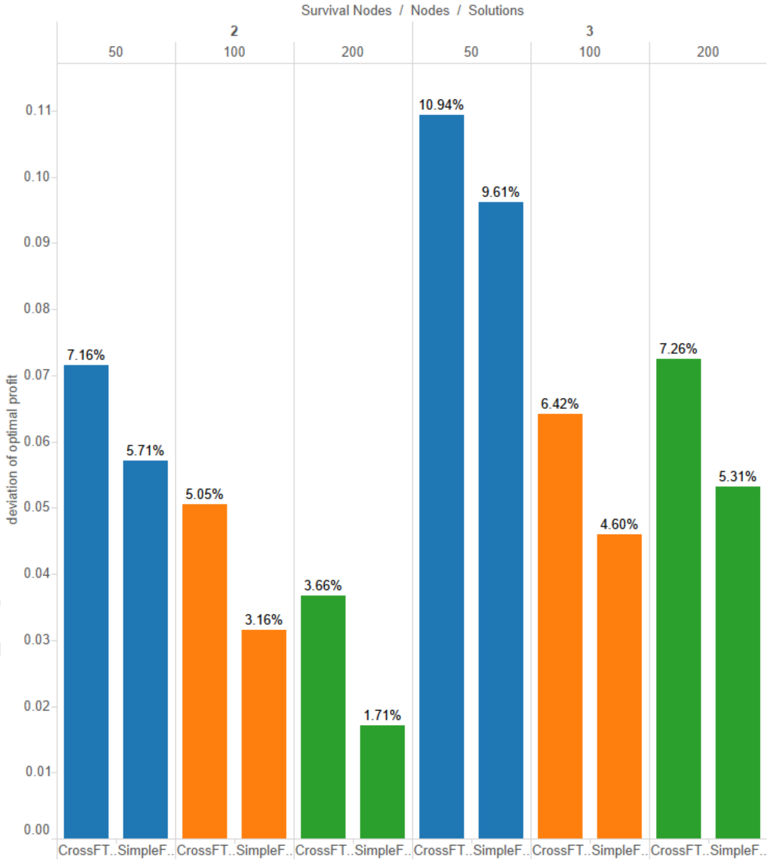


Figure 4.12. Performance analysis of TDHA (Simple and Cross FT)

The performance of TDHA in solving Simple FT and Cross FT is showed in Fig. 4.12. The deviation of optimal profits range between 0 and 1. The smaller the value is, the better the performance is. The minimum deviation of optimal profit is 1.71% when |S|=2, |V|=200 and network topology type is Cross FT. The maximum deviation of optimal profit is 10.94% when |S|=3, |V|=50 and network topology type is Simple FT. The average original deviation of profit of Cross FT is greater than that of Simple FT. The profit deviations of Cross FT and Simple FT are 6.96% and 5.02%, respectively. The profit deviation are 4.46% to 7.369% when |S|=2 and |S|=3, respectively.

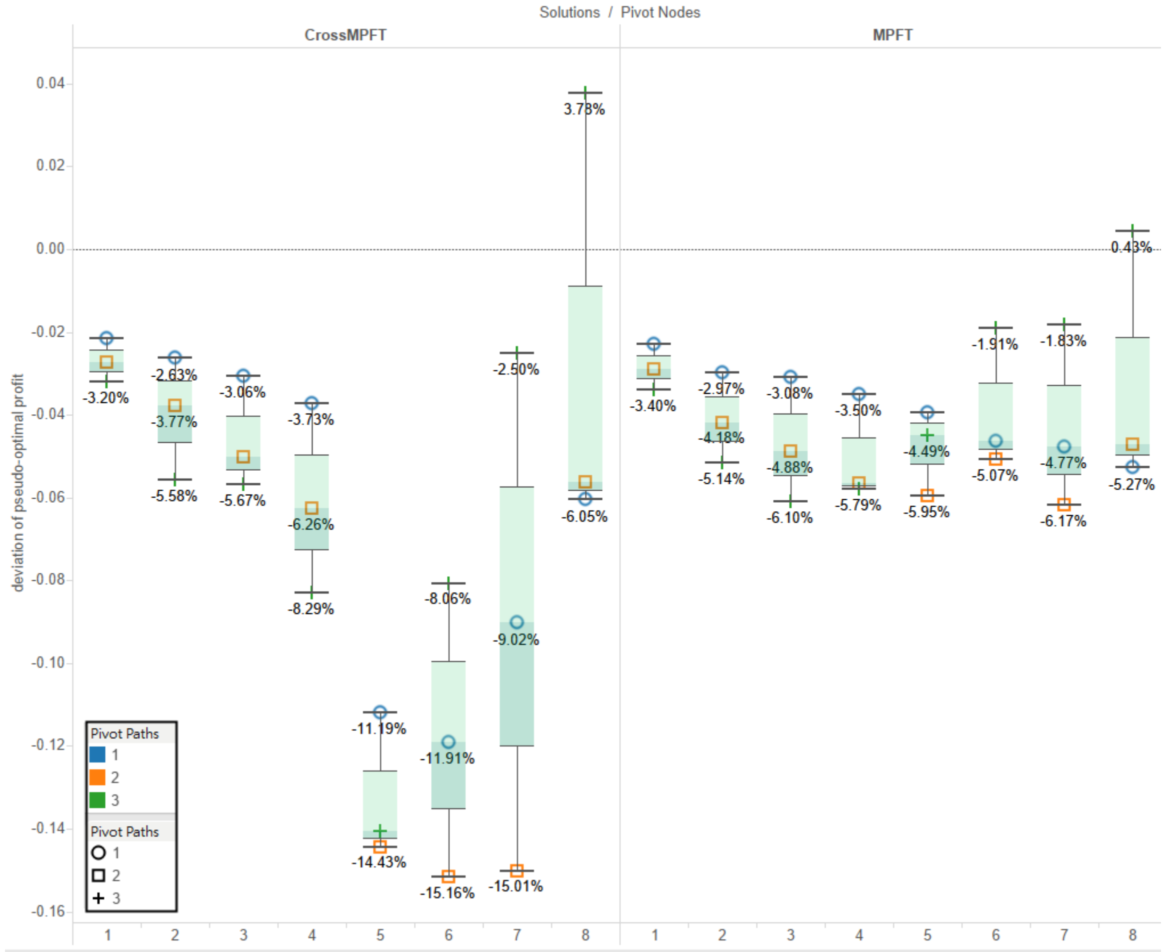


Figure 4.13. Performance analysis of TDHA (MPFN and Cross MPFN)

The performance of TDHA in solving MPFN and Cross MPFN is showed in Fig. 4.13. Because the heuristic solutions are greater than the pseudo-solutions in most test cases, the values of deviations in Fig. 4.13 are negative. The smaller the the deviation is, the better the performance is. The minimum deviation is -15.16% when | Φ |=6, |Q|=2 and network topology type is Cross MPFN. The maximum deviation is 3.78% when |Φ |=8, |Q|=3 and network topology type is Cross MPFN. The average deviations of MPFN and Cross MPFN are -5.42% and -3.76%. Although, the performance of TDHA in solving Cross MPFN is better than MPFN, the performance of TDHA is more stable in solving MPFN. The average deviations are -4.44% and -4.86% when |S| is 2 and 3. The average deviations are -4.98% and -4.43% when |U| is 4 and 6. The number of survival nodes and length bound of pivot paths do not have an obvious influence on the performance of TDHA.

(c) Experiment 3: Reliability analysis of multiple path network topology

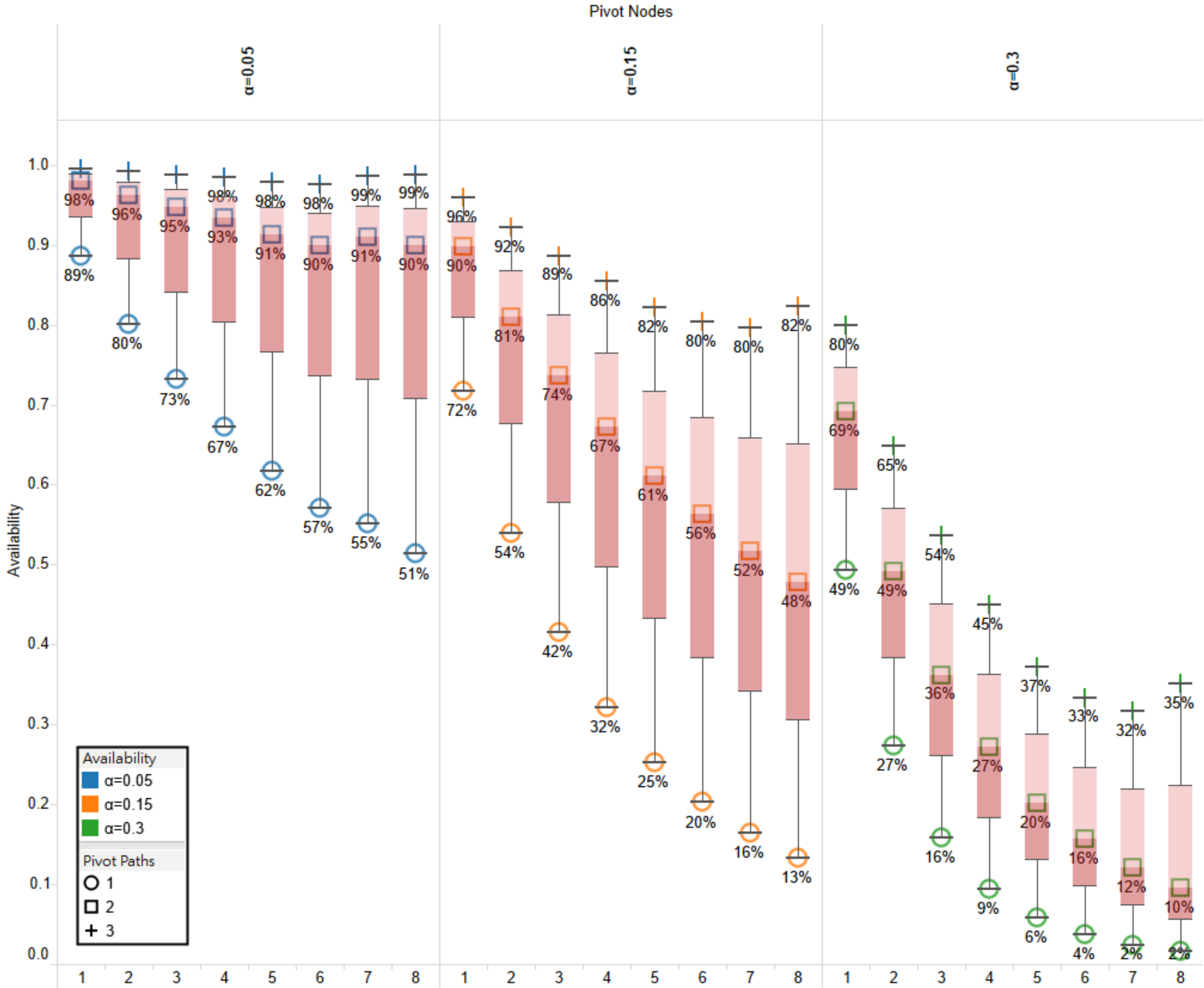


Figure 4.14. Reliability of multi-path network topology (box plot)

The effectiveness of multiple path on the network reliability is showed in Fig. 4.14. The x-axis is the failure rate of edges and the number of pivot nodes. The y-axis is the network reliability. The lengths of boxes represent the effectiveness of multiple path on the network reliability. The network availabilities are significant improved by using multiple path especially when the number of pivot nodes grows.

Although multiple path can improve the network reliability, it may cause profit degradation. Therefore, it is important to balance the network reliability and total profit. The relationship between the network reliability and unit profit gain of heuristic solutions are showed in Fig. 4.15. As we can see from Fig. 4.15, the solutions obtained by the TDHA have very high network reliability but with nominal profit degradation.

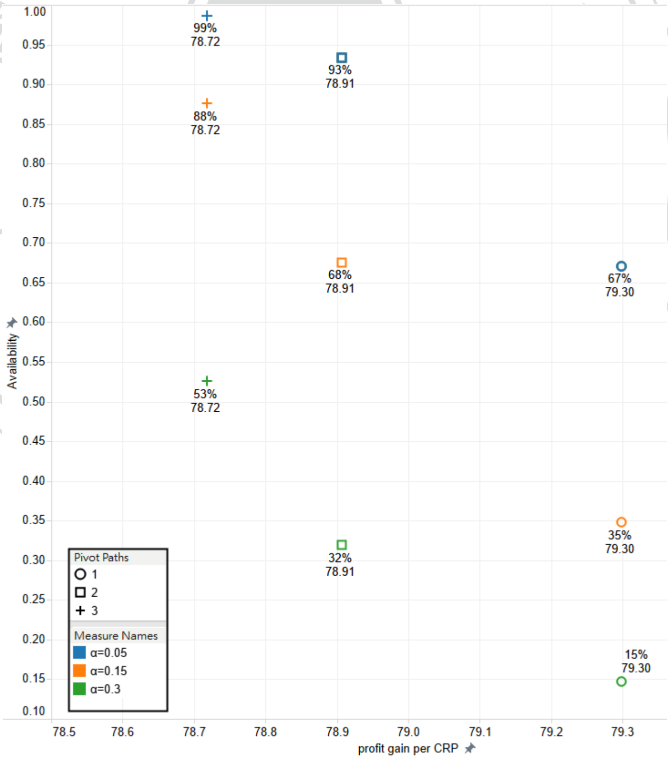


Figure 4.15. Network reliability and unit profit gain

(d) Experiment 4: Reliability analysis of multiple path network topology

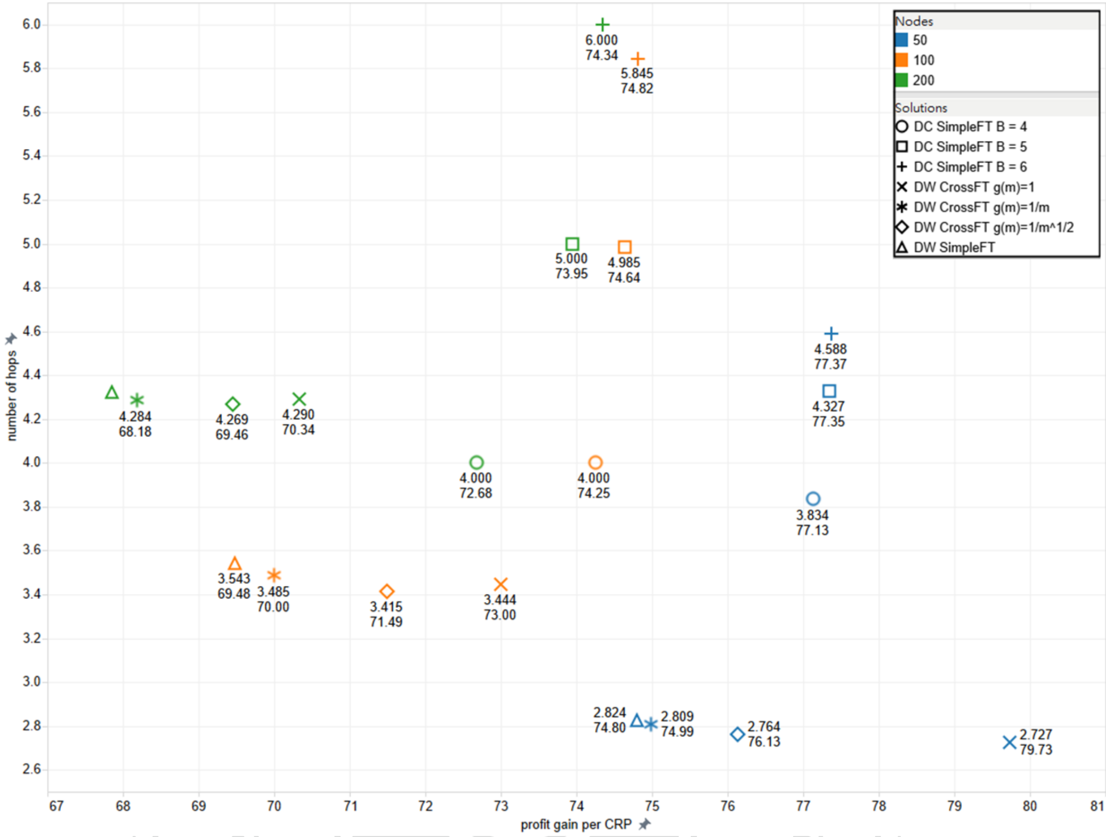


Figure 4.16. Depth weight based vs. depth bound based

Comparisons of the unit profit gain of depth weight based and depth bound based is showed in Fig. 4.16. The x-axis is the unit profit gain and the y-axis is the average hop count of network topologies. The profit gains of depth weight based are better than depth bound based in most cases. The hop count of depth weight based is also greater than depth bound based in most cases. It means that depth weight based is more aggressive and probe deeper than depth bound based.

Chapter 5. Deployment Scheduling

5.1. Considerations of Deployment Scheduling

CCN can support existing cellular users with limited capability. Such a system will be able to support many voluntary disaster responders and victims in the early hours of catastrophic natural disasters, and thus saving many lives. Topology design not only determines the CCN topology, it also determines the base stations that are to be recovered. In the next stage, CRPs are to be deployed into the disaster areas to recover the selected base stations.

Because the number of wireless link devices which is called Inter-Cell Communication Module (ICC Modules) [24] is limit, only some of base stations would be selected and equipped to form an Ad Hoc network. We propose Network Topology Planning Algorithm to select base stations and find the 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 the core network hop by hop through the root. 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 of the forwarding tree is missing.

Since the transportation capacity may be very limited, it may need many rounds to transport all CRPs to all selected areas. How to transport all CRPs quickly according to the disaster response demand to minimize life loss is really an important issue. The transport sequence must not only take into account the emergency level of afflicted area, but also satisfy the scheduling constraint that ancestor nodes have to be recovered before their child. That is because a child node cannot connect to the core network without the forwarding service provided by its ancestors.

5.2. Related Works

CCN deployment scheduling problem is similar to fleet routing and scheduling problems [21] 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. The objective of the formulas is minimizing the unsatisfied demand or maximizing the demand satisfied. Several formulas and solutions are proposed in [12,21,41]. The 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 strive to transport resource to disaster points with shortest time and minimum cost. Beside transport time and cost, CCN deployment scheduling problem has more issues to address. First, the emergency levels of disaster areas are different, the profit of recovering a base station is also variant. The higher emergency level is, the higher priority is. Second, the profit of recovering a base station is not constant but decreasing with time. Third, the deployment sequence has to meet the scheduling constraints.

The CCN Deployment Scheduling (CCN-DS) Problem [27] is similar to the conventional Single and Multiple machine Scheduling (SMS) problems. The non-preemptive CCN-DS 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-DS problem. We proposed a mathematical model to formulate CCN-DS problem and use CCN-DS algorithm to find a deployment schedule to maximize the efficiency of disaster response operation [27]. However, CCN-DS didn't take the traveling time of each selected path into account. This research is trying to improve the CCN-DS model by taking traveling time into account.

5.3. Resource Delivery Path Dependent Deployment Scheduling

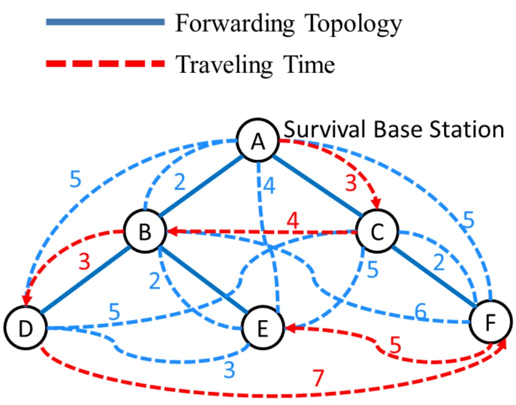
The emergency level of the area covered by a base station is represented by a time-variant profit parameter, which has to be defined by the disaster response authority because they have not only the necessary knowledge for disaster response, but also the official authority as well as situation statistics.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

The Resource Delivery Path Dependent CCN Deployment Scheduling Problem is formulated into two optimization models: the first one, CCNDS-AC, is with Antecessor Precedence Constraint, and the second one, CCNDS-UC, is without the constraint. We assume one or more forwarding tree is calculated in advance.

The non-preemptive CCNDS-AC is as follows. A set of nodes organized in a tree structure has to be fixed by work teams; a preceding node must be rescued before its descendants; the profit of fixing a node is a function of time; the traveling time from each node to every other node is also given; the CCNDS-AC problem is to find a deployment sequence such that the total profit is maximized. An example is shown in Fig. 5.1.

The graph on the left of Fig. 5.1 is the forwarding tree. The blue edges are the wireless links and the red paths are traveling paths labeled with traveling time. The table on the right shows the deployment sequence labeled with traveling time. The value in each table cell is a time-variant profit.

Mathematical model of CCNDS-AC is as follows.



Schedule 1：
A→ C→ B→ D→ F→ E
Total Time：
3+4+3+7+5=22
Total Profit：
12+5+7+1+4+1=30

Time	A	B	C	D	E	F
0	12	11	7	6	9	13
1	12	10	6	5	8	11
2	12	10	5	4	8	10
3	11	10	5	4	7	10
4	11	9	5	3	7	9
5	11	9	4	2	6	9
6	10	8	3	2	6	9
7	10	7	3	2	6	8
8	10	7	3	2	5	8
9	10	7	3	1	5	7
10	9	6	2	1	5	7
11	9	6	2	1	5	6
12	8	5	1	1	4	6
13	8	4	1	1	4	6
14	7	4	1	1	3	5
15	6	3	1	1	2	4
16	5	2	1	1	2	4
17	4	2	1	1	2	4
18	4	2	1	1	2	3
19	3	1	1	1	1	1
20	3	1	1	1	1	1
21	2	1	1	1	1	1
22	1	1	1	1	1	1

Profit

Figure 5.1. Example of deployment schedule

The input parameter are $G'(V,E), R, \pi, D, P$ that are defined as follows. The input graph, G', is the network topology CCN.

- $V = \{v_i \mid i=0,1,2,\ldots,n\}$, is the set of base stations and v_0 is the root which has an external link.

- $E = \{e_{i,j} \mid e_{i,j}, v_i,v_j \in V\}$is the set of link.

- $R = \{r_i \mid i=1,2,\ldots,n$ and $r_i > 0\}$ is the set of construction time of the isolated station v_i.

- $\pi=\{\pi_a \mid \pi_a = (\pi_a(1),\ldots,\pi_a(n))$ is the set of CCN deployment schedules, where a is a positive integer. $\pi = \{\pi^i \mid (\pi(1), \ldots, \pi(i)), i = 1, \ldots, n\}$. $\pi_a(i)$ is the position of v_i in schedule π_a.

- $D=\{d_{i,j} \mid v_i,v_j \in V\}$ is the set of traveling time.

- $P = \{P_i(t) \mid v_i \in V\}$ is the set of profit, $P_i(t)$ is the profit of v_i when it is constructed at time t and with respect to a schedule π_a , the construction time of v_i is $\sum r_{\pi a(k)}$ where k is a node precedes node v_i in schedule π_a.

The CCN deployment scheduling problem is to find a deployment schedule π_a from π, to

Maximize

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

Subject to

$\pi_a(i)$ precedes $\pi_a(j)$, where v_j is the descendant of v_i for all $v_i,v_j \in V$.

For the sake of discussion, an *isolated node* is defined as a node whose parent node hasn't been rescued (visited). The antecessor precedence constraint in CCNDS-AC forces the transportation vehicle to ignore any isolated node even if the vehicle passes such a node.

However, it might be beneficial to visit such an isolated node before its preceding nodes. Even though a rescued isolated node is not able to provide any service immediately after it is rescued, it can be activated without an extra rescue trip immediately after its parent node is rescued. Taking the example shown in Fig. 5.2, the red path (*A*,*B*,*E*) in the left graph is a solution of CCNDS-AC and the path (*E*,*B*,*A*) in the right graph is a solution ignoring antecessor precedence constraint. Both paths started from the headquarter that is located near node *E*. As we can see that the traveling time of the path on the right graph is smaller than its counterpart on the left graph. Take this consideration, we propose another model, Unconstrained CCN Deployment Scheduling Problem (CCNDS-UC) which is the same as CCNDS-AC but ignoring antecessor precedence constraint.

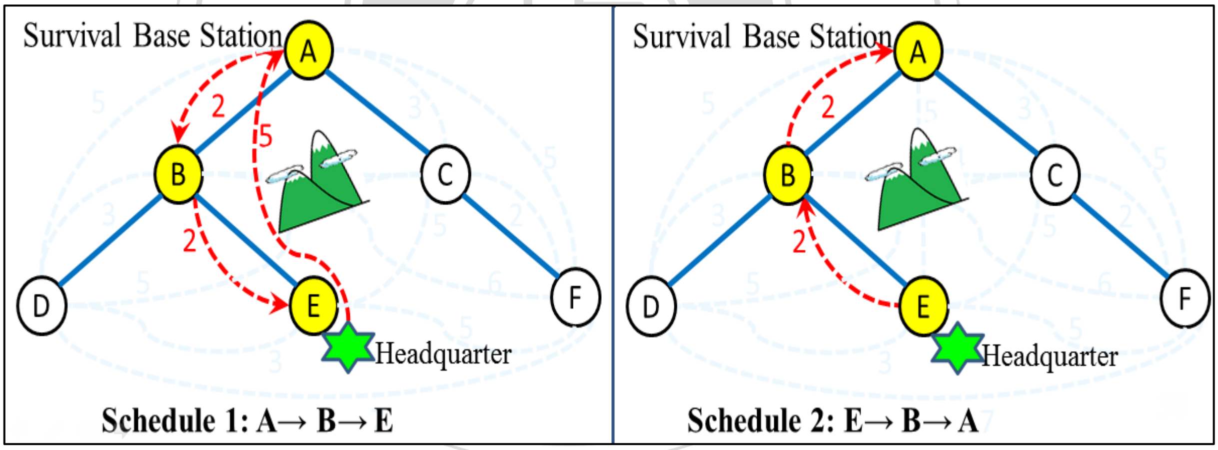


Figure 5.2. A path ignoring antecessor precedence constraint.

5.4. Complexity Analysis

Similar to the conventional machine scheduling problem, CCNDS-AC can be easily proven NP-hard.

CCNDS-AC is in NP：

We first show that CCNDS-AC ϵ 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 visited before its child nodes in T. The verification algorithm can affirm that the schedule is a valid CCNDS-AC schedule within $O(n^2)$ time.

CCNDS-AC is NP-Hard：

We now prove that CCNDS-AC problem can be reduced to the single machine scheduling problem (SMS) straightforwardly.

SMS is defined as follows: Given a set J of n independent jobs that has to be scheduled on a single machine. Each job $j_i \in J$ contains uninterrupted processing time $u_i \in U$ and weight $w_i \in W$, where u_i and w_i are positive integers. The single machine can handle only one job at a time.

SMS is to find a schedule π such that $\sum_{i=1}^{n}(w_i * C_i(\pi))$ is minimized, where π is a permutation of all jobs ($k = 1, 2, 3, \dots, n!$), $C_i(\pi)$ is the time at which job j_i completes in the given schedule π.

Given an instance A:[J,W,U] in SMS, we can find an instance B:[V,E,R,D,P] with a single-level forwarding tree in CCNDS-AC such that an optimal solution π_b for B is also an optimal solution for A. Let V=J, D={0|all paths}, R=U, P={ $-w_i t$, | $w_i \in W$ }, E={$e_{root,i}$|v_{root},v_i ϵ V}. The verification can be performed in polynomial time. Let total weighted completion time of π for SMS is TWC(π) = $\sum_{i=1}^{n}(w_i * C_i(\pi))$, total weighted profit of π for CCNDS-AC is TWP(π) = $-$TWC(π). We prove the following 3 Lemmas first：

Lemma 1: Any valid schedule π_b for *B* is a valid solution for *A*.

Proof: Any permutation of *J* is a valid schedule for *A*, and π_b is a permutation of *V*, which is equal to *J*. Therefore π_b is a valid solution for *A*. Q.E.D.

Lemma 2: Any valid schedule π_a for *A* is also a valid schedule for *B*.

Proof: Any given schedule π_a for *A* is a permutation of *J* which is equal to *V*. Therefore, π_a is a permutation of *V.* Since each node in *B* can directly connect to the root of *B* such that the ancestor precedence constraint is always non-existing. Therefore, π_a, a permutation of *V,* is 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 π_b for *B* must be an optimal solution for A. By Lemma 1, we know π_b is also a valid schedule for *A*, whose total weighted completion time is $TWC(\pi_b)$. Assume π_b is not an optimal schedule for *A*, there must be another schedule π_a, whose total weighted completion time $TWC(\pi_a)$ is smaller than $TWC(\pi_b)$. By Lemma 2, π_a is also a valid schedule for *B*, whose total weighted profit is $TWP(\pi_a)$. By Lemma 3, we can obtain $TWP(\pi_a)$ is greater than $TWP(\pi_b)$. This contradicts to the fact that π_b is an optimal solution for *B*. Therefore, π_b must be an optimal solution for *A*. Q.E.D.

Similarly, CCNDS-UC can also be proven to NP-hard in a similar way.

5.5. Heuristic DS-ACG Algorithm

Sine CCNDS-AC is a NP-hard problem, we designed a heuristic approximated algorithm, DS-ACG, to solve it. The algorithm is basically a greedy algorithm. The antecessor precedence constraint effectively reduces the number of choices in each iteration in the algorithm. Therefore, a greedy algorithm might perfectly fit the problem itself and obtain a very good performance.

In the algorithm, a forwarding tree $T(V,E)$, a set of nodes π_a and all input parameters are given initially. The candidate list, CL, is initialized to the children of the root. In each iteration, the DS-ACG algorithm chooses a node from CL which has the maximum profit to attach to the tail of π_a. The children of the newly selected node are included into CL. The procedure is repeated iteratively until CL is empty. The time complexity of DS-ACG is $O(n^2)$. Although the algorithm is rather simple, it outperforms easily our previous algorithm CCN-DS [27] because DS-ACG takes into account the traveling time. The pseudo code is shown in Appendix III.

5.6. Heuristic DS-UCB Algorithm

Because of the extremely stringent time constraint in disaster response, most heuristic solutions we developed so far are polynomial time greedy algorithms, which select the best choice that has the largest estimated profit iteratively, based on the current state without backtracking. Heuristic algorithms often offer near optimal solutions because the number of choices is usual very limited due to the ancestor precedent constraint. Unfortunately, because the ancestor precedent constraint is relaxed in CCNDS-UC, not only the number of choices in each iteration is much more than that of CCNDS-AC, but also the estimated profits for isolated nodes are unknown unless a looking-ahead and backtracking computation steps is included in the algorithm. A greedy algorithm will perform poorly under such a condition. Therefore, we propose DS-UCB algorithm that is basically a modification of DS-ACG with a limited looking-ahead and backpacking mechanism. DS-UCB is still an approximated algorithm without any guarantee of optimality. Similar to DS-AC, each iteration of DS-UCB algorithm consists of two major steps: the first step is to find a temporary path, which is actually a temporary sub-schedule, from the current selected node upward to a node whose profit is computable; then the second step is to compute the best path from the head to the tail of the path among all possible paths within three hops of the temporal path. The selected best path is the new sub-schedule to be added to the tail of the current schedule. Set the node nearest to the current node to be the new current node. Initial current node is the node nearest to the command center. The iteration is repeated until all nodes are included in the schedule. The time complexity is $O(n^3)$. However, it is still a polynomial complexity and will be acceptable if the number of nodes is not too high, say, under 1000. Note that the topology in the real world will not be fully connected so that the complexity will rarely reach 1000^3). The pseudo code is shown in Appendix IV.

5.7. Performance Evaluation

The two proposed CCN deployment scheduling algorithms, DS-ACG and DS-UCB were evaluated against our previous scheduling algorithm CCN-DS [27] and optimal solutions by simulation. CCN-DS algorithm aims a deployment schedule to maximize the efficiency of disaster response operation. However, CCN-DS didn't take the traveling time of each selected path into account. DS-ACG and DS-UCB improve the CCN-DS model by taking traveling time into account.

The profit function of a base station is assumed a two-segment piecewise linear time-variant function. 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. Their values were generated randomly as shown in TABLE 5.1.

TABLE 5.1 Parameters of test instances in experiment I

Parameters	Range of values
Initial Profit	*x* ~ *Uniform(30, 100)*
Traveling Time	*d* ~ *Uniform(0.5, 10) hr*
Profit	*P ~ Uniform (0, 168) hr*
Slope 1	*s1 ~ Uniform (-1, 0)*
Slope 2	*s2* **(|*s2*|>=|*s1*|)** ~ *Uniform (-1, 0)*
Construction Time	r_i ~ *Uniform (50, 80) hr*
Forwarding Tree Size	*8-12*

$$\textbf{\textit{Original Deviation}} = 1 - \frac{Algorithm\ solution}{Optimal\ solution} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.1)$$

$$\textbf{\textit{Normalize Deviation}} = \frac{Optimal\ solution - Algorithm\ solution}{Optimal\ solution - Worst\ solution} \quad \ldots\ldots\ldots(5.2)$$

Test instances were generated by uniform random functions. The ranges of values used in Experiment I are shown in TABLE 5.1. In Experiment II, the same set of parameters was used to generate test cases except that the size of graph is 50. In this size, there is no way to obtain optimal solutions for such a NP-hard problem in reasonable time. Therefore, we took the best solution out of 10 million solutions as the pseudo optimal solution to evaluate the performance of our algorithms. The evaluation metrics are total profit, total traveling time, original profit deviation and normalized profit deviation as shown in (5.1) and (5.22).

The results of Experiment I and II are shown in Fig. 5.3 (only the case of 12 nodes is shown) and Fig. 5.4. As we can see from these figures that both DS-ACG and DS-UCB outperform CCN-DS [27] by a very large margin in both small and large cases. These results show that the traveling time is a significant factor in deployment scheduling and cannot be ignored. Furthermore, DS-UCB performs the best among all three heuristic algorithms. This shows that relaxing the antecessor precedence constraint is beneficial. Finally, the normalized deviations from optimal solutions in terms of total profile and total time are all nominal, under 5%, which is not shown here for space saving. These results show that our heuristic algorithm is effective although they are simple.

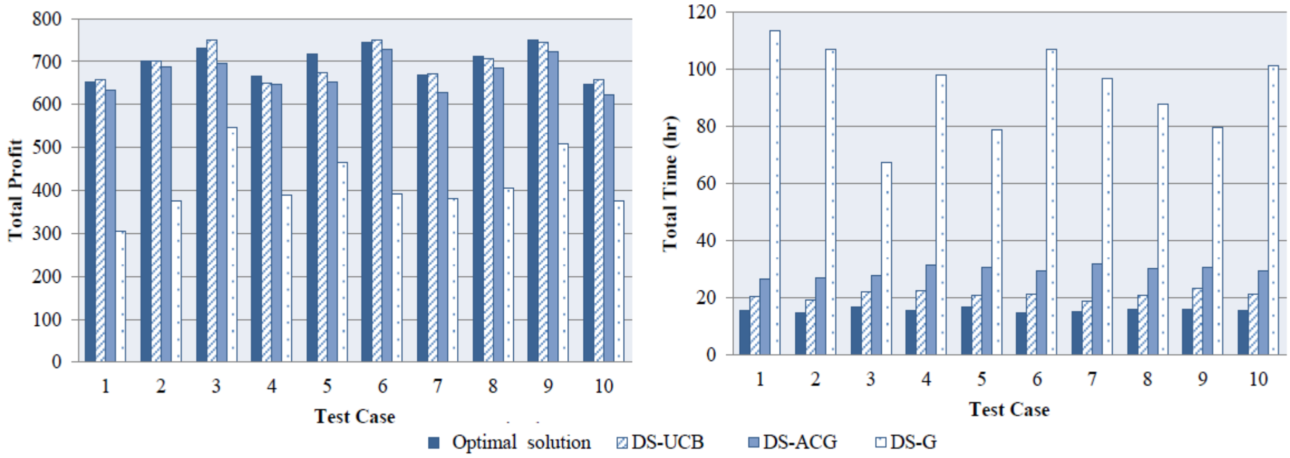


Figure 5.3. Total profit and total deployment time in experiment I

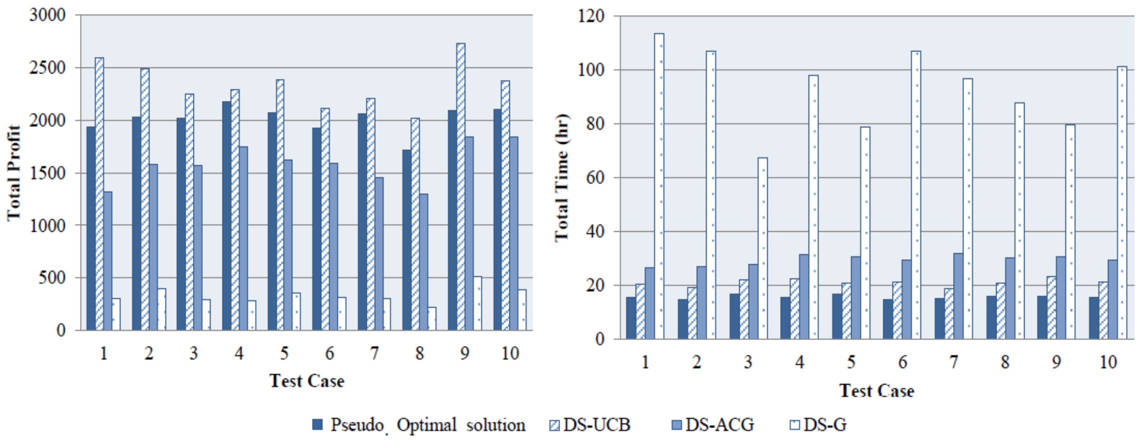


Figure 5.4. Total profit and total deployment time in experiment II

Chapter 6. Bandwidth Allocation

6.1. Considerations of Bandwidth Allocation

Because the information needs to be forwarded 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 [45] 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, such a traffic demand is far beyond the capacity of CCN. If the bandwidth is not allocated appropriate, it may result in the degradation of disaster response inefficiency. The worse-case scenario is that the bandwidth may be occupied by the less disastrous area and the more disastrous areas may not receive any bandwidth at all. Therefore, it is necessary to allocate bandwidth properly to the base stations in order to maximize disaster response inefficiency.

6.2. Bandwidth Allocation Mathematical Model

Assuming a CCN forwarding tree is given, each node has m channel classes to choose. When a channel of a particular class is assigned to a node, the disaster response profit corresponding to that class is earned. The channels assigned to the node cannot exceed the capacity of upward links of the wireless links. 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.

The input parameter are *G'(V,E), B, P, A, F* that are defined as follows. The input graph, *G'*, is the network topology of CCN.

- $V = [v_i]_{n\times 1}$, *where* $i = 1,2,\ldots,n-1$ *and* v_i *is the disaster operation efficiency of node i.* v_1 *is the node that has an external link and* v_0 *is a virtual node that represents the core network.*
- $E = [e_{i,j}]_{n\times n}$. e_{ij} *is the edge between* v_i *and* v_j, *where* 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, where* b_k *is the required bandwidth of channel class k.*
- $P=[p_{i,j}]_{n\times n}$. $p_{i,j}$ *is the path from* v_i *to* v_j.
- $A=[a_{i,j,k}]_{n\times n\times m}$, where $a_{i,j,k}$ *represents the amount of channel class k assigned to path* $p_{i,j}$.
- $F=[f_{i,j,k}]_{n\times n\times m}$. $f_{i,j,k}(a_{i,j,k})$ *is the profit of channel class k assigned to path* $p_{i,j}$.

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

Maximize

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

Subject to

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

6.3. Complexity Analysis

In this section, we will prove that the time complexity of CCN-BA problem is NP Hard. Some variables are added in order to prove the time complexity of CCN-BA problem. The definitions of these variables are as follows.

- *C* is a positive number that represents the capacity of the knapsack.
- $W=\{w_i|i=1,2,\ldots,m\}$ represents the weights of items, where w_i is the weight of the item that belongs to type *i*. There are *m* types of items.
- $S=\{s_i|i=1,2,\ldots,m\}$ represents the values of items, where s_i is the value of the item that belongs to type *i*.
- $Z=\{z_i|i=1,2,\ldots, m\}$ represents the amounts of items filled the knapsack.
- *X(C,W,S)* is a problem instance of 0-1 Knapsack problem. Given a set of items, with weights, *W*, and values, *S*, 0-1 Knapsack problem is to select the valuable items to fill the knapsack while maximizing the total value and being constrained by the size of the knapsack, *C*. 0-1 Knapsack problem is NP Hard.
- *Y(G'(V,E),B,P,F)* is a problem instance of CCN-BA problem. Definitions of the input parameters, *G'(V,E),B,P and F*, can be referred to Section 6.2.

(A) Lemma 1: For any 0-1 Knapsack problem instance, *X(C,W,S)*, there exist a

CCN-BA problem instance, *Y(G'(V,E),B,P,F)*, that can be transformed into the problem *X* in polynomial time.

Proof: Given any 0-1 Knapsack problem instance, *X(C,W,S)*, we can find a dedicated CCN-BA problem instance, *Y(G'(V,E),B,P,F)* that can be transformed into the problem *X* in polynomial time. Given a set of channels, with bandwidth consumptions *B*, and profits, *F*, CCN-BA problem instance, *Y(G'(V,E),B,P,F)*, is to assign channels to paths, *P*, while maximizing the total profit and being constrained by bandwidth capacities of paths, *P*. Since, the bandwidth capacities of *P* are decided by the edges, *E*, CCN-BA problem is similar to a nested 0-1 Knapsack problem. The process of transforming problem *Y* into problem *X* is showed as follow.

Let the size of *G'(V,E)* be equal to 1, |*E*|=1. $V=\{v_0,v_1\}$; $E=\{e_{0,1}\}$; $P=\{p_{0,1}\}$ and $F=\{f_{0,1,k}\}$. The path, $p_{0,1}$, is composed by $e_{0,1}$. The bandwidth capacity of $p_{0,1}$ is equal to $e_{0,1}$. Given a set of channels, with bandwidth consumptions *B*, and profits, *F*, CCN-BA problem instance, *Y(G'(V,E),B,P,F)*, is to assign channels to the path, $p_{0,1}$, while maximizing the total profit and being constrained by bandwidth capacities of paths, $p_{0,1}$. Therefore, the CCN-BA problem is reduced to a 0-1 Knapsack problem by setting the size of *G'(V,E)* to 1.

Let the bandwidth consumptions of channels, *B*, be equivalent to the weights of items, *W*. Let the profit gains, *F*, be equivalent to the values of item, *S*. Let the bandwidth capacity of the path, $p_{0,1}$, be equivalent to the size of knapsack, *C*. Then, the CCN-BA problem instance, *Y(G'(V,E),B,P,F)*, is equivalent to the 0-1 Knapsack problem instance, *X(C,W,S)*. Obviously, the time complexity of the transformation is polynomial. Q.E.D.

(B) Lemma 2: If *Sa* is a valid solution of *X(C,W,S)*, then *Sa* is also a valid solution of *Y(G'(V,E),B,P,F)*.

Proof: From Lemma 1, for any 0-1 Knapsack problem instance, *X(C,W,S)*, we can find a CCN-BA problem instance, *Y(G'(V,E),B,P,F)*, where |*E*|=*1*,*B*=*W*, *F*=*S* and *E*=C. *Y(G'(V,E),B,P,F)* is equivalent to *X(C,W,S)*.

Sa is a valid solution of *X(C,W,S)*. Now, we prove that *Sa* is also a valid solution of *Y(G'(V,E),B,P,F)*. Let *Sa*={sa_i|i=1,2,…,*m*}. There are *m* types of items and sa_i denotes the amount of type *i* items fill the knapsack. Since *Sa* is a solution of *X(C,W,S)*, the formula $\sum_{i=1}^{m} sa_i \times w_i \le C$ denotes that the total weight of the items is constrained by the capacity of the knapsack. Let sa_i represents the amount of channel class *i* assigned to path $p_{0,1}$. Because *B*=*W*, *E*=*C* and $\sum_{i=1}^{m} sa_i \times w_i \le C$, it can conduce $\sum_{i=1}^{m} sa_i \times b_i \le E$ which represents the total bandwidth consumed by the assigned channel is equal to or less then the bandwidth capacity of *E*. Therefore, *Sa* is also a valid solution of *Y(G'(V,E),B,P,F)*. Q.E.D.

(C) Lemma 3: If S_b is a valid solution of *Y(G'(V,E),B,P,F)*, then S_b is also a valid solution of *X(C,W,S)*.

Proof: Since S_b is a valid solution of *Y(G'(V,E),B,P,F)*, $\sum_{i=1}^{m} sb_i \times b_i \le E$. Let |*E*|=*1*,*B*=*W*, *F*=*S* and *E*=C, *Y(G'(V,E),B,P,F)* is equivalent to *X(C,W,S)*. The Lemma3 can be proved similar to Lemma2. Q.E.D.

(D) Lemma 4: If *Sa* is an optimal solution of *X(C,W,S)*, then *Sa* is also an optimal solution of *Y(G'(V,E),B,P,F)*.

Since S_a is a solution of $X(C,W,S)$, S_a is also a solution of $Y(G'(V,E),B,P,F)$ where $|E|=1, B=W$, $F=S$ and E=C by Lemma 2. Let $T_X(S_a)=\sum_{i=1}^{m} sa_i \times s_i$ denotes the total value of s_a in problem $X(C,W,S)$ and $T_Y(S_a)= \sum_{i=1}^{m} sa_i \times f_{0,1,i}$ denotes the total profit of S_a in problem $Y(G'(V,E),B,P,F)$. Because F=S, $f_{0,1,i} = s_i$. It can conduce that $T_Y(S_a)=T_X(S_a)$.

Now, we prove by contradiction. Assume that S_a is an optimal solution of X, but not an optimal solution in Y. Since S_a is not an optimal solution in Y, then there exist a solution S_b where $T_Y(S_a)<T_Y(S_b)$. Because $T_Y(S_b)=T_X(S_b)$, $T_Y(S_a)=T_X(S_a)$ and $T_Y(S_a)<T_Y(S_b)$, it implies that $T_X(S_a)<T_X(S_b)$. This contradicts to the assumption that S_a is an optimal solution of X. Therefore, S_a must be an optimal solution of Y. Q.E.D.

Let $TC_X(S_a)$ be the time complexity of obtaining optimal solution S_a in X. From Lemma 1, For any 0-1 Knapsack problem instance, $X(C,W,S)$, there exist a CCN-BA problem instance, $Y(G'(V,E),B,P,F)$, that can be transformed into the problem X in polynomial time. Assume that the transformation time is $T_{Y,X}$ and $TC_Y(S_a)$ be the time complexity of obtaining the optimal solution S_a in Y. $TC_X(S_a) = TC_Y(S_a) - T_{Y,X}$. Because $T_{Y,X}$ is polynomial and $TC_X(S_a)$ is NP Hard, $TC_Y(S_a)$ is NP Hard.

Since S_a is an optimal solution of Y which is proved in Lemma 4, $TC_Y(S_a)$ is the time complexity of CCN-BA problem and had proved as NP Hard. Q.E.D.

6.4. CCN Bandwidth Allocation Heuristic Algorithm

Since CCN-BA is a NP hard problem, the optimal solution of CCN-BA is difficult to find in reasonable 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. 6.1. A forwarding tree *T(V,E)* and matrix *B*, *F* and *P* are given, firstly. Then, the base stations are selected as candidate nodes 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 obtained when all base stations are selected as candidates and assigned channels.

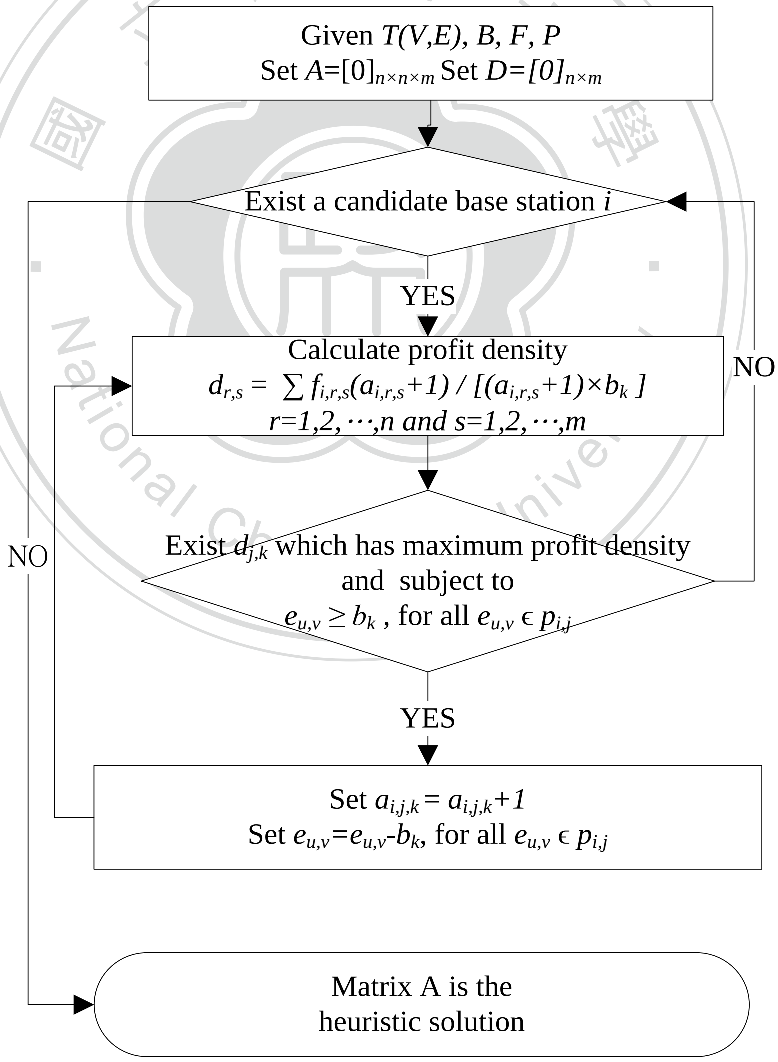


Figure 6.1. Flow chart of BAG algorithm

6.5. 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 select v_0 as the candidate node in the follow experiments.

TABLE 6.1 Three sets of experiments

Experiment \ Parameters	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 6.1. 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 be compared directly. We use original and normalize deviation to evaluate them. The formula of the normalize deviation is listed as follow.

$$\textbf{\textit{Original Deviation}} = \frac{optimal\ solution - algorithm\ solution}{optimal\ solution} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.1)$$

$$\textbf{\textit{Normalize Deviation}} = \frac{pseudo\ optimal\ solution - algorithm\ solution}{pseudo\ optimal\ solution - pseudo\ worst\ solution} \quad \ldots\ldots\ldots\ldots\ldots (6.1)$$

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

The profits of channels assigned to paths, bandwidth capacities of edges and channel classes of test instances are shown in TABLE 6.2. Values of these given parameters are generated from uniform random functions.

TABLE 6.2 Parameters for test instances

Parameters	**Range of values**
$F=[f_{i,j,k}]_{n\times n\times m}$	$f_{i,j,k} \sim Uniform(30, 100)$
$E[e_{i,j}]_{n\times n}$	$e_{i,j} \sim Uniform(32, 100)$
$B[b_k]_{3\times 1}$	$b_k \sim Uniform(16, 32)$

Normalize deviations of experiment I and II are shown in Fig. 6.2. The best normalize deviation in experiment I and II are 2.5% and 3.14%, respectively.

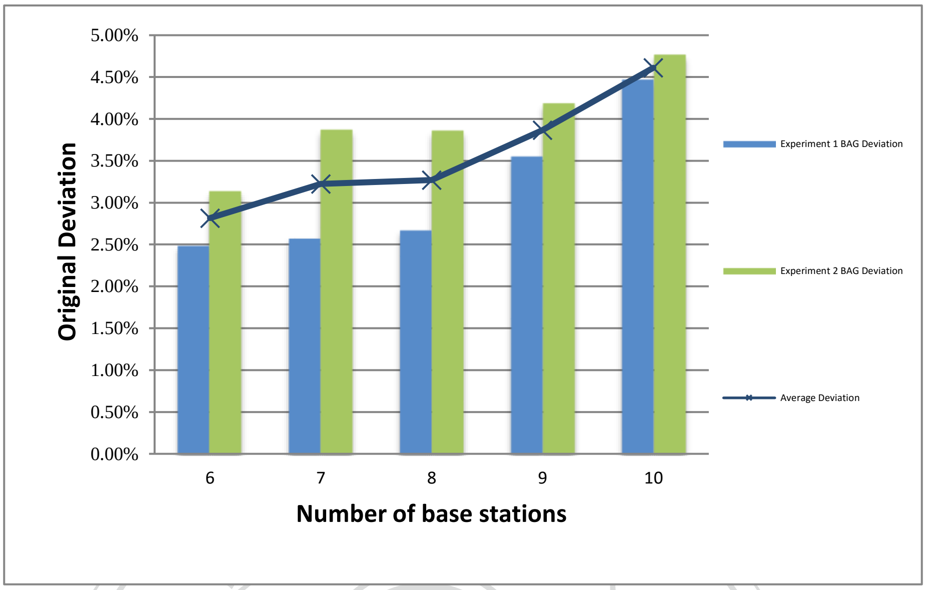


Figure 6.2. Normalize Deviations of experiment I, II.

The original deviations of experiment I are smaller than that of experiment II in all test cases. The BAG while can obtained better solutions while $g(k) = \frac{1}{\sqrt{k}}$ than $g(k) = \frac{1}{k}$.

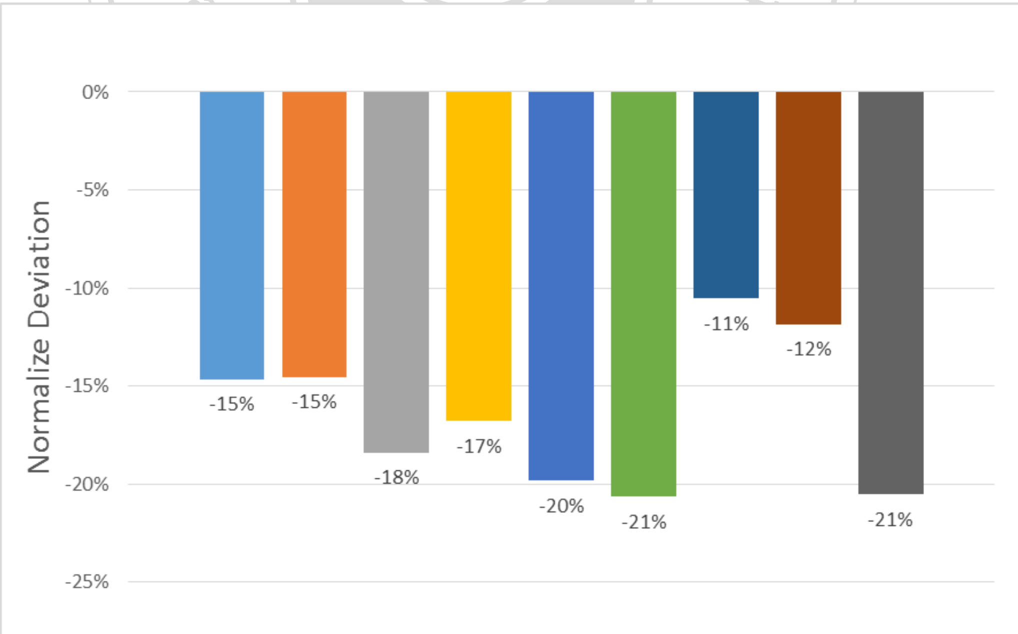


Figure 6.3. Pseudo deviations of experiment III.

As shown in Fig. 6.3, the best and average normalize deviation are -21% and -16.4%, respectively. The BAG solution is better than the pseudo optimal solution, so the normalize deviations are negative numbers. The experiment results show that the BAG algorithm performance good in our experiment environments.

Chapter 7. Conclusion

When stricken by a catastrophic natural disaster, many communication systems were crashed, including cellular networks. The loss of communication system may have a catastrophic consequence such that there is a need to design and develop a low-cost large scale emergency communication network to support the disaster response operation in the forthcoming unavoidable large scale natural disasters.

We first summarized a set of practical requirements including both user end and operator end for emergency communication networks and briefly reviewed the currently available solutions based on the proposed requirements as well as pointing out their advantages and limitations. To take advantage of the fact that most base stations remain physically intact but lost their power or the connections to the core network, we proposed to use long range wireless links to connect such base stations to form a multi-hop cellular network to provide emergency communication services.

Some important planning and deployment issues such as topology design, deployment scheduling and bandwidth allocation were discussed. Topology design, deployment scheduling and bandwidth allocation problems are formulated into mathematic models and proved as NP-Hard problems. Since the network topology, bandwidth management, deployment scheduling are needed in urgent, we propose heuristic algorithms to solve these problems quickly. Effectiveness and efficiency of these heuristic algorithms are verified by simulated results.

Four different types of topology design problems, Simple FT, Cross FT, MPFN and Cross

MPFN, are formulated by using a comprehensive mathematic model and solved by TDHA. In order to verify the TDHA's solutions against the optimal solutions, we also propose the binary linear programming transformation methodology to transform the CNTD into BILP problem and use the BILP algorithm to obtain the optimal solutions. The experiment results show that the TDHA has good effectiveness and efficiency.

MPFN and Cross MPFN increase the network reliability by constructing multiple outgoing disjoint paths. The experiment results show that constructing multiple outgoing paths of pivot nodes is a well approach to network reliability. It greatly increases the reliability and only loses few profits.

In topology design, we proposed two types of depth control mechanisms in our models, Depth Bound and Depth Weight. The total profit of Depth Bound is less than Depth Weight's in most cases, although the depth of Depth Weight solutions is likely deeper than Depth Bound solutions. If a CCN network is delay sensitive, the CCN operator can use Depth Bound with a tolerable depth bound to find the forwarding tree. Otherwise, the operator can use Depth Weight to find the forwarding tree that may have higher total profit and deeper depth.

Since the transportation capacity may be very limited in a disaster area, scheduling of CCN deployment order according to the demand of disaster response operation becomes an important issue. We proposed two optimization models aiming to maximize the disaster response efficiency. Both models take traveling time into account, but one does have antecessor precedence constraint and the other doesn't.

Both problems are proven NP complete problems so that we proposed two heuristic algorithms, DS-ACG and DS-UCB, to solve the problems in limited time. Both algorithms were evaluated using simulation. From our experiments, we can see that both algorithms outperform our previous algorithm that was designed without taking traveling time into consideration by a very large margin. This proves that traveling time has a significant impact to the effectiveness of CCN deployment scheduling problem.

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 Nested 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.

The profit definition, the combinatorial optimization models and even the solution algorithms we have designed are all very primitive and far away from realistic. More researchers from different areas such as social science are needed and encouraged to make the models more adequate and more realistic. Finally, the implementation of a CCN production system requires the participation of cell phone vendors and operators.

We hope that this dissertation may provide a helpful guideline to those who are willing to devote themselves to the research of emergency communication network, and thus, may save more lives.

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Appendix I : Pseudo Code of Total profit maximization Process

Input parameters of function *maximize_total_profit* are *G,C,D,R,S,N’, lowerBound, maxExeTime*. Outputs are *G’* and its total profit. Function *maximize_total_profit* uses sub-function *findNetworkTopologyByHuristic* to find a heuristic solution, iteratively. In while loops, if profit is less than *lowerBound* then *X* nodes, which are added into *G’* latest, are moved from *G’* to *DrawbackList*. *X* is a positive integer and generated randomly. The while loops will not stop until a heuristic solution *G’* is found or the computing time exceeding maxExeTime.

The heuristic topology *G’* is solved by using an iterative process. The node with maximum profit and satisfies the follow criterions will be added into *G’* iteratively. The criterions are listed as follows: (1) the node is a neighbor of *N* and not in *DrawbackList;* (2) *Degree*(v_i) is less than or equal to *D* for all v_i belong to *G’* after adding the node. If no node satisfies these criterions then the latest node added into *G’* is move from *G’* to *DrawbackList*. If there exist a node satisfies these criterions then the node is added into *G’* and *DrawbackList* is reset as empty. The iterations will not stop until the number of nodes of *G’* arrives *C*.


```
[Profit, G’] maximize_total_profit (G,C,D,R,S,N’, lowerBound, maxExeTime) {
Set DrawBackList={};

G.Add(S,v0) //Add a dummy node v0 and links connect S and v0 into G
N’.Add((S,v0) //Add v0 and links connect S and v0 into N’
```

```

While ( executeTime < maxExeTime){
[Profit, G’] = findNetworkTopologyByHuristic (G,C,D,R,N’,DrawBackList);
If (Profit < lowerBound) {
Move the latest X nodes from G’ to DrawBackList
// drawback G’ steps and try to find another solution
// G’ is a positive integer and generated randomly
} else {
break; // heuristic solution is found
}
}
Return Profit,G’
}

[Profit, G’] findNetworkTopologyByHuristic (G,C,D,R,N’,DrawBackList) {
Set G’=N’; // N’ is the initial solution

While (|G’|<=C) {
  Set Neighbor={};
Neighbor = findNeighbor(G’);
Set hasProbed={};

      While ( |Neighbor| >= |hasProbed|) {
```

```
MaxNeighbor = FindMaxNodes (Neighbor);
// find a neighbor node of G' that satisfies the follow conditions: // 1. has maximum profit 2. not in hasProbed 3. not in DrawbackList
If (has MaxNeghbor ) {
    Add MaxNeghbor to G'
    If ( Degree(G') <= D) {
Set DrawbackList={}
Break;
    } else {
Add MaxNeghbor to hasProbed;
}
} else {
Set i=|G'|
Move N(i) from G' to DrawbackList // draw back one step
Break;
}
}
}

Profit = calculateProfit (G');
return Profit,G';
}
```

Appendix II : Pseudo Code of Binary Integer Linear Programming Algorithm

In this section, we will present the pseudo code of translating the input graphs into binary equal and use the binary linear programming algorithm to solve the solution. Pseudo codes of main function and some important sub-functions are presented and described as follows.

Function *ComprehensiveBILP* is the main function and the given parameters are *P*, *G*, *Pivots*, *survivalNode, K, num_pivotnode, num_pivotpath, num_survivalNode and LBound*. *P, G, Pivots and survivalNode* denote the set of profit *R*, input graph *G*, set of pivot nodes *Φ* and set of survival nodes, respectively. *K, num_pivotnode, num_pivotpath, num_survivalNode and LBound* represent the number of CRPs, pivot nodes, pivot paths, survival nodes and hop count limit, respectively. Output parameters, *exitflag*, *fval* and *x* denotes the result, total profit and solution. *exitflag=1* denotes a feasible solution is found; otherwise, no feasible is found.

The pseudo codes of function *ComprehensiveBILP* is listed and illustrated as follows. In order to apply binary linear programming to solve the network topology design problem, the input parameters are needed to translate in the form of formula 4.34.

$$min_x \ f^T \ such \ that \begin{cases} A \cdot x \leq b \\ Aeq \cdot x = beq \\ x \ binary \end{cases} \qquad \text{----- (4.34)}$$

Function *ComprehensiveBILP* applies Sub-function retIdxof_x to generate the mapping table of the given graph G and x.

CCN topology design is a maximize problem. Sub-function genObjectiveFunc generates the object function and the object function is multiplied by -1 in order to translate the maximize problem to minimize problem.

Sub-function genEqConstraint generates the equal constraints *Aeq* and *beq*. Constraints of resource limits, 4.27 and 4.33, are generated in this sub-function.

```
function [exitflag,fval,x] =
ComprehensiveBILP(P,G,Pivots,survivalNode,K,num_pivotnode,num_pivot
path,num_survivalNode,LBound)

% execute binary optimal linear programming
%input parameters
% P : profit
% G : graph
% Pivots : set of pivot nodes
% survivalNode : set of survival nodes
% K : number of CPRs
% num_pivotnode : number of pivot nodes
% num_pivotpath : number of disjoint outgoing paths
%  num_survivalNode : number of pivot nodes
% LBound : hop count limit


tStart = tic;
% generates mapping tables of the input graph
% and the binary vector x
[nodesIdx, edgesIdx,mat_edgesIdx, pathIdx, SetofPath,mat_pathIdx] =
retIdxof_x (G,LBound,P,Pivots,num_pivotnode);

% generates  objective function
```

```
[F] = genObjectiveFunc (P,nodesIdx, edgesIdx, pathIdx);
F = -1*F;

% generates matrix Aeq for equal constraints
[Aeq,beq]= genEqConstraint (K,nodesIdx, edgesIdx,
pathIdx,Pivots,survivalNode,num_pivotnode,num_survivalNode);
% generates matrix A for less than constraints
[A,b]= genLTConstraint (nodesIdx, edgesIdx,mat_edgesIdx,
pathIdx,SetofPath,mat_pathIdx,Pivots,survivalNode,num_pivotnode,num
_pivotpath,num_survivalNode,LBound);

constraintTime = toc(tStart);
constraintNum = size(A,1)+size(Aeq,1);

% executes binary integer programming algorithm
% to find the solution
disp('======= call bintprog  size of A is =====');
options=optimset('MaxTime',3600);
[x,fval,exitflag,output] = bintprog(F,A,b,Aeq,beq,[],options);
disp('======= bintprog  fval and output =====');
disp(-1*fval);
disp(output);
BIPtime=output.time;

nodes = size(nodesIdx,1);
edges = size(edgesIdx,1);
paths = size(pathIdx,2);
solution=zeros(nodes);

% draws out the network topology when a feasible solution is found
if (exitflag == 1)

    solution=zeros(nodes);
  for f_edges=1:edges

```

```
      if (x(nodes+f_edges)==1)

solution(edgesIdx(f_edges,1),edgesIdx(f_edges,2))=P(edgesIdx(f_edge
s,2));
      end

  end

  strArray = java_array('java.lang.String', nodes);
 for i=1:nodes
     nodeId = sprintf('%d',i);
     for f_isP=1:num_pivotnode
         if(Pivots(f_isP)==i)
             nodeId = sprintf('Pivot%d',i);
         end
     end
     for f_isSur=1:num_survivalNode
         if(survivalNode(f_isSur)==i)
             nodeId = sprintf('Survival%d',i);
         end
     end

     strArray(i) = java.lang.String(nodeId);
 end

 IdsCellAr = cell(strArray);

bioTree = biograph(solution,IdsCellAr,'ShowWeights','on');
view(bioTree);

end % if (exitflag == 1)


end
```

Sub-function genLTConstraint generates less than constraints *A* and *b*. The pseudo code of Sub-function genLTConstraint are showed in the below. Constraints of the relationship between nodes and edges, 4.21, 4.22 and 4.23, are generated at line 15 to 56. Constraints of the relationship between the outgoing paths and edges, 4.24 and 4.25, are generated at line 57 to 93. Constraint of hop count limit 4.26 is generated at line 94 to 109. Constraints of fixed k-disjoint paths, 4.30 and 4.31, are generated at line 124 to 167.

```
001 sub-function [A,b]= genLTConstraint (nodesIdx, edgesIdx,mat_edgesIdx,
002 pathIdx,SetofPath,mat_pathIdx,Pivots,survivalNode,num_pivotnode,num
003 _pivotpath,num_survivalNode,LBound)
004
005 nodes = size(nodesIdx,1);
006 edges = size(edgesIdx,1);
007 paths = size(pathIdx,2);
008
009 mat_size=ceil(size(mat_pathIdx,1)*size(mat_pathIdx,2)*1.5);
010 tmp_A=zeros(mat_size,nodes+edges+paths);
011 disp('memsize'); disp(mat_size);
012
013 numofCons=0;
014 % ========nodes & edges ======
015 % bei,j - bvi ≤ 0
016 for row=1:edges
017     oneCons = zeros(1,nodes+edges+paths);
018     oneCons(1,edgesIdx(row,1))=-1; % - v(i)
019     oneCons(1,nodes+row)=1; % e(i,j)
020
021     numofCons=numofCons+1;
022     tmp_A(numofCons,:)=oneCons(1,:);
023     b(numofCons)=0;
024 end
025
```

```
% be_{j,i} – bv_i ≤ 0
for row=1:edges
    oneCons = zeros(1,nodes+edges+paths);
    oneCons(1,edgesIdx(row,2))=-1; % - v(j)
    oneCons(1,nodes+row)=1; % e(i,j)

    numofCons=numofCons+1;
    tmp_A(numofCons,:)=oneCons(1,:);
    b(numofCons)=0;
end

% vi –Sum(A^conv(i)) ≤ 0
for row1=2:nodes
    oneCons = zeros(1,nodes+edges+paths);
    oneCons(1,row1)=1; % v(i)

    hasConvEdge=0;
    for row2=1:edges
        if (edgesIdx(row2,2) == row1)
            oneCons(1,nodes+row2)=-1; % -sum(E*,i)
            hasConvEdge=1;
        end
    end

    if (hasConvEdge)
        numofCons=numofCons+1;
        tmp_A(numofCons,:)=oneCons(1,:);
        b(numofCons)=0;
    end
end
disp(numofCons);
% ==============edges & paths========================
for row1=1:paths
% bp^z_{root,y} – be_{i,j}
[pathLen,edgesList] = edgesIdxofPath (row1,nodesIdx, edgesIdx,
```

```
mat_edgesIdx,SetofPath);
   pathLen=0;
   hopCount=size(mat_pathIdx,2);
   for f_onepath=1:hopCount
       if (mat_pathIdx(row1,f_onepath)>0)
           pathLen=pathLen+1;
           oneCons = zeros(1,nodes+edges+paths);
           oneCons(1,nodes+edges+row1)=1; % pzx,y
           oneCons(1,nodes+mat_pathIdx(row1,f_onepath))=-1;%- ei,j
           % add one constraint
           numofCons=numofCons+1;
           tmp_A(numofCons,:)=oneCons(1,:);
           b(numofCons)=0;
       else
           break;
       end
   end

% Sum(p^z_root,y)- bp^z_root,y ≤ | p^z_root,y |-1
    oneCons = zeros(1,nodes+edges+paths);
    oneCons(1,nodes+edges+row1)=-1; % -pzx,y
    for f_pathLen=1:pathLen
        %oneCons(1,edgesList(f_pathLen))=1; % sum(pzx,y)
        oneCons(1,nodes+mat_pathIdx(row1,f_onepath))=1; % sum(pzx,y)
        % add one constraint
    end
    % add one constraint
    numofCons=numofCons+1;
    tmp_A(numofCons,:)=oneCons(1,:);
    b(numofCons)=pathLen-1;

end
disp(numofCons);
% ===============Hop count Limit========================
    %v_i  - sum(P_root,y(h)) ≤ 0
```

```
    for f_nodes=2:nodes
        oneCons = zeros(1,nodes+edges+paths);
        oneCons(1,f_nodes)=1; % vi
        for f_paths=1:paths
             if (findNode (SetofPath(f_paths,:),f_nodes) )
                oneCons(1,nodes+edges+f_paths)=-1; % - sum(Proot,y(h))
            end
        end
        % add one constraint
        numofCons=numofCons+1;
        tmp_A(numofCons,:)=oneCons(1,:);
        b(numofCons)=0;
    end
disp(numofCons);
% ==============Resource Constraints=======================
    % bei,j + bej,i ≤ 1
    for f_edges1=1:edges
        oneCons = zeros(1,nodes+edges+paths);
        oneCons(1,nodes+f_edges1)=1; % ei,j

oneCons(1,nodes+mat_edgesIdx(edgesIdx(f_edges1,2),edgesIdx(f_edges1
,1)))=1; % ej,i
        % add one constraint
        numofCons=numofCons+1;
        tmp_A(numofCons,:)=oneCons(1,:);
        b(numofCons)=1;
    end
    disp(numofCons);
 % ==========fixed k-disjoint paths=================
        % Q - Sum(Proot,y) ≤ 0
     k_pathFlag=1;
    if(k_pathFlag)
        for f_pivot=1:num_pivotnode
            oneCons1 = zeros(1,nodes+edges+paths);
            for f_paths=1:paths
```

```
                if (pathIdx(f_paths) == Pivots(f_pivot))
                    oneCons1(nodes+edges+f_paths)=-1;
                end
            end
            % add one constraint
            numofCons=numofCons+1;
            tmp_A(numofCons,:)=oneCons1(1,:);
            b(numofCons)=-num_pivotpath;
        end
        % Sum(P_root,y(e_i,j)) ≤ 1
        for f_pivot=1:num_pivotnode
            nonDisjointList = nonDisjointPath(edges,mat_pathIdx,pathIdx,edgesIdx,Pivots(f_pivot));
            for f_nonDisjList=1:size(nonDisjointList,1)
                oneCons = zeros(1,nodes+edges+paths);
                for f_nonDisjPath=1:size(nonDisjointList,2)
                    if (nonDisjointList(f_nonDisjList,f_nonDisjPath) >0)
                        oneCons(1,nodes+edges+nonDisjointList(f_nonDisjList,f_nonDisjPath))=1;
                    end
                end
                % add one constraint
                numofCons=numofCons+1;
                tmp_A(numofCons,:)=oneCons(1,:);
                b(numofCons)=1;
            end
        end
    end
 disp(numofCons);
A=zeros(numofCons,nodes+edges+paths);
for i=1:numofCons
    A(i,:)=tmp_A(i,:);
end
```

```
end
```

Appendix III : Pseudo Code of Heuristic DS-ACG Algorithm

```
Input CCN Topology, Traveling Time, Profit
SL=null          /*the Scheduling List*/
CL={}            /*the Set of Candidate nodes*/
CL.add(Survival BS);
while (size of CL !=0) do
for each node in CL do
calculate the node's profit and time
if (profit/time) >(maxProfit/maxTime)
maxProfit = profit
maxTime = time
maxPtofitNode =node
end if
end for
SL=SL+ maxPtofitNode                    /*update Scheduling List*/
totalProfit=totalProfit+maxProfit       /*update total Profit*/
totalTime=totalTime+maxTime             /*update total Time*/
CL.remove(maxPtofitNode)
for each node in maxPtofitNode's childList do
CL.add(node)
```

```
end for
end while
```

Appendix IV : Pseudo Code of Heuristic DS-UCB Algorithm

```
Input CCN Topology, Traveling Time, Profit
SL=null        /*the Scheduling List*/
CL={}          /*the Set of Candidate nodes*/
startNode=the closest node of Headquarter
while(SL.length!=node Number of CCN topology) do
    SL.add(startNode)
    if(startNode don't have profit) do
        /*initial path from start node to SBS*/
        while(startNode don't have profit) do
            temp_Sch.add(parentNode)
            startNode=parentNode
        end while
        backtrack_Sch=Backtrack(temp_Sch);
        max_Sch=temp_Sch
        if profit(temp_Sch) <profit(backtrack_Sch) do
            max_Sch=backtrack_Sch
        end if
        totalProfit=totalProfit+ profit(max_Sch)    /*update total Profit*/
        totalTime=totalTime+ time(max_Sch)          /*update total Time*/
```

```
        SL.add(max_Sch)
        startNode =last node of SL
    else
        totalProfit=totalProfit+ profit(startNode)    /*update total Profit*/
        totalTime=totalTime+ time(startNode)        /*update total Time*/
    end if
    startNode=the closest node of startNode
end while
Backtrack(temp_Sch) do
    Check temp_Sch neighbor and generate finite schedules
    Compare schedules' total profit
    Choose the schedule with largest total profit as the backtrack_Sch
    return backtrack_Sch
end Backtrack
```