A Study on Improving Throughput and Delay of Post-Disaster Communication Networks Based on Portable Resource Units

災害時における移動式リソースユニットを用いた
通信ネットワークのスループット及び遅延性能改善に関する研究

A dissertation presented
by

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To my family

Abstract

In recent years, the significant impact of disasters on human life has drawn a great deal of research attention on disaster responses. In this thesis, we focus on Post-Disaster Communication Networks (PDCNs), which are deployed in disaster affected areas where the network infrastructure can be damaged or even destroyed. We particularly focus on the PDCNs based on Portable Resource Units (PRUs) in order to provide an agile system that can be promptly deployed in disaster areas. There are many challenges for designing PDCNs based on PRUs that we need to address. For instance, after a disaster occurs, the demand from users is likely to be very high because everyone wants to use network services to confirm the safety of family members and friends. At the same time, the infrastructure is damaged/destroyed while the facilities carried by the PRUs are limited. Therefore, we need to focus on efficiency inside the system in order to provide as high performance as possible, especially in terms of throughput and delay. Furthermore, due to the variety of post-disaster scenarios, we need to make the PDCNs adapt to different situations and utilize the remaining resources effectively.

In order to address the above-mentioned challenges, we aim at improving the throughput and delay of PDCNs based on PRUs in three different aspects: *efficiency*, *adaptiveness*, and *application*. For each aspect, we provide the possible extensions as follows. Regarding the *efficiency*, we propose a method that considers both spectrum and energy constraints and aims to maximize the utilization of these resources. The proposal consists of two phases, namely, topology formation and transmission division. The topology formation phase constructs a topology composed of Access Points (APs) and links that belong to the top k spectrum-efficient disjoint paths. The resulting topology is used by the transmission division phase to split the transmissions from APs to the PRU. Through analysis, we prove that there

exists a value of k such that the spectrum-energy efficiency of a given topology is maximized. Our experimental results also confirm these analytical findings.

Regarding the *adaptiveness*, we propose two topology control methods for different deployment scales of PDCNs. On one hand, for a small scale PDCN based on a single PRU, we suggest the use of cooperative communications and propose a topology control cooperative method that optimally decides the number of cooperative agents in order to maximize the throughput gain while guaranteeing a reasonable computational time. We provide an analysis of the effect of k on the throughput gain, the cooperative computation time, and the utility, throughput gain speed. The analysis is validated by conducting simulations. On the other hand, for a large-scale PDCN which is based on multiple PRUs, we consider PRUs as Cognitive Radio Base Stations (CRBSs) that are equipped with multiple antennas to utilize all the available spectrum in the area. We propose an adaptive topology control method that aims to maximize the cognitive radio adaptability while guaranteeing the routing computation time on the resulted topology. Also, we prove that there is a value of k for a given network that optimally solves the trade-off relationship between cognitive radio adaptability and the routing computation time. Additionally, extensive simulations are conducted to verify our analysis.

Regarding the *application*, we propose a method for safety confirmation application which includes four phases, i.e., resizing and storing images, broadcasting small-size images, routing, and deciding the image size to deliver to users. The objective of our method is to minimize the image searching time of users. We estimate the expected searching time for each different size of images and choose the most appropriate image size based on a mathematical analysis using an absorbing Markov chain. Extensive computer-based simulations are conducted to verify the findings of our analysis. Furthermore, the simulation results prove the existence of the optimal image size that minimizes the searching time. The results also demonstrated the effectiveness of our proposed method.

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List of Acronyms

AIPR Approximately Ideal-Path Routing

AP Access Point

AWGN Additive White Gaussian Noise

BSAA Binary Search Assisted Ascent

COLT Cell On Light Truck

COW Cell On Wheels

CRAI Cognitive Radio Adaptability Index

CRAI Cognitive Radio Adaptability Index

CRBS Cognitive Radio Base Station

DSER Distributed Spectrum Efficient Routing

DTN Delay/Disruption Tolerant Networking

ECV Emergency Communication Vehicle

FWA Fixed Wireless Access

GABS Gradient Assisted Binary Search

MDRU Movable and Deployable ICT Resource Unit

MST Minimum Spanning Tree

NDR Network Disaster Recovery

PDCN Post-Disaster Communication Network

PRU Portable Resource Unit

QoS Quality of Service

SNR Signal-to-Noise Ratio

UAV Unmanned Aerial Vehicle

VoIP Voice over Internet Protocol

Chapter 1

Introduction

1.1 Background

In the recent years, the earth has been affected by many strong natural disasters. Furthermore, the natural hazards around the globe have continued to increase in a significant manner. Due to the significant impact of disasters on human life, research works on disaster responses have drawn a great deal of attention. On one hand, after a disaster occurs, the network infrastructure in the disaster affected area can be damaged or even completely destroyed. As a result, the remaining infrastructure can only provide limited capacity. On the other hand, after a disaster, the demand of using network communication services increases significantly because people want to know the situation and confirm the safety of their families and friends. Therefore, one of the most important disaster response tasks is to rapidly transport necessary infrastructure to the disaster site and deploy a response network that can temporarily provide reasonable services to people in the area.

In this thesis, we focus on Post-Disaster Communication Networks (PDCNs), which are deployed in disaster affected areas to replace the damaged/destroyed infrastructure or support the remaining network. There are three main challenging issues that PDCNs need to deal with. Firstly, the situations after disasters are always emergency cases. Therefore, a fast deployment of PDCN is required in order to promptly provide the network services in the disaster affected areas. Accordingly, the system providing the PDCN needs to be very portable in order to be transported and deployed easily. Secondly, there will be a high demand from users while the remaining resources have a limited capacity. It requires PDCNs to focus on efficiency inside the system in order to provide a high performance, especially in throughput and delay. Finally, post-disaster scenarios can be different in different cases. The differences are usually in the scale of the affected area or in the level of damages. Consequently, the remaining resources in the disaster area are also not predictable. In order to relax the critical situations as much as possible, PDCNs need to adaptively utilize the remaining resources.

Regarding the requirements of prompt deployment and system portability, the concept of Portable Resource Units (PRUs) has been considered in the literature. For instance, the American Telephone & Telegraph (AT&T) company has considered the concept of Cell On Light Truck (COLT) and Cell On Wheels (COW) for their disaster response networks, which aim to recover the local cellular networks in disaster areas [1]. In Japan, the Ministry of Internal Affairs and Communications (MIC) introduced the concept of the Movable and Deployable ICT Resource Unit (MDRU) for their disaster recovery network [2]. The MDRU-based disaster recovery network aims to recover the network services in a disaster affected area by constructing a wireless mesh network composed of the MDRU, portable Access Points (APs), and user devices. The considered network scenarios and assumptions in this research are similar to those in the MDRU-based disaster recovery network.

We particularly focus on the PDCNs based on PRUs (either a single PRU or multiple PRUs). Additionally, this research is motivated by the second and the third challenges mentioned above, which are the issue of limited capacity versus high demand, and the requirement of adapting with various post-disaster scenarios. In order to address the limited capacity versus high demand issue, we focus on efficiency and optimization. Particularly, we consider both spectrum efficiency and energy efficiency in our proposed method to make the performance as high as possible. Furthermore, the characteristics of typical applications of the system are also considered to improve the delay in using the applications.

1.2 Research Objectives

Figure 1.1 demonstrates the objectives of this research. The final target of this research is to improve the throughput and delay of PDCNs based on PRUs. In order to achieve that, the research in this dissertation attempts to propose methods considering three aspects. The first aspect considered, in this thesis, is the *efficiency* of the PDCNs. In particular, spectrum and energy resources are limited and need to be efficiently used. The issue of limited spectrum resource is important not only in disaster scenarios but also in any wireless network nowadays. However, in order to deal with the critical demand of network services in disaster affected areas, spectrum-efficient methods become more vital. On the other hand, the power supply problem is certainly critical after disasters due to power outages and the damages in infrastructure. Therefore, the portable network facilities equipped with batteries and renewable energy functions should be used together with energy-efficient methods. Spectrum efficiency is a measure of how efficiently the limited frequency spectrum is utilized to transmit packets, i.e., how much throughput can be achieved with a limited frequency bandwidth. However, contemporary methods, such as those in [3–6], that aim to improve spectrum efficiency fail to consider the limited energy resources in practical disaster recovery networks. On the other hand, energy efficiency is a measure of how efficiently the energy is utilized to transmit packets, i.e., how many packets can be transmitted with a limited energy. However, existing energy efficient methods, e.g., the works in [7–10], fail to take into account the limited frequency

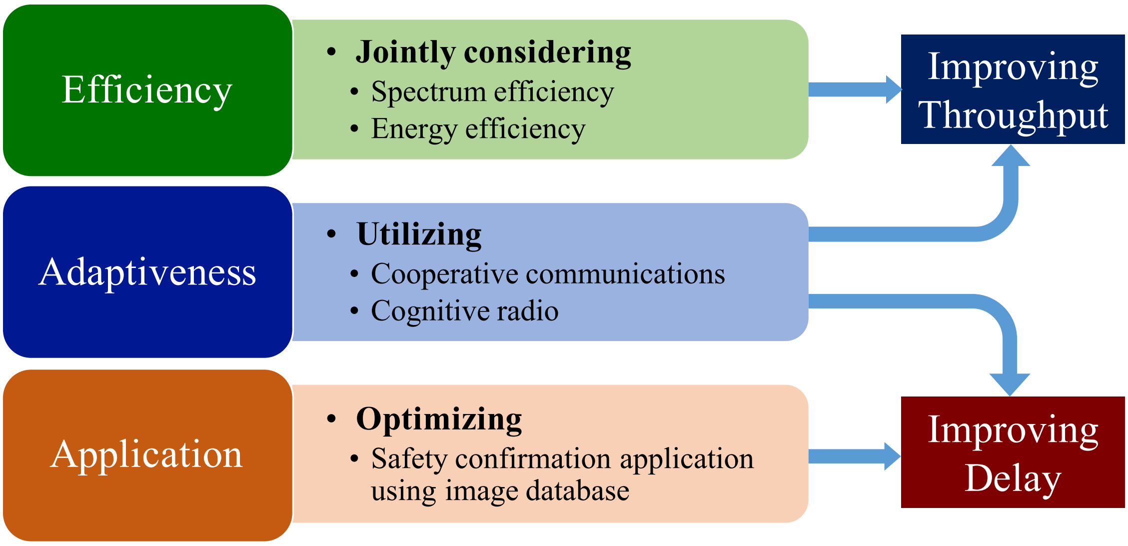

Figure 1.1: The main objectives of this research.

spectrum. Therefore, an effective method that considers both spectrum efficiency and energy efficiency is required. This thesis proposes such a method in order to deal with the limited spectrum and energy resources in disaster affected areas.

The second aspect considered, in this thesis, is the *adaptiveness* with different disaster situations. We consider two different scales of PDCNs based on PRUs. A small-scale PDCN consists of a single PRU connected with several portable APs. An AP provides services to mobile terminals within its transmission range. The APs can also connect to other APs using a mesh network paradigm to extend the service coverage of the PRU. However, the backbone network constructed by the APs can become the bottleneck if the traffic originating from the local network of each AP is excessively high. In this case, we suggest using cooperative communications to support the capacity of the backbone network. Some mobile terminals can act as both users and cooperative agents that relay packets from an AP to another AP to achieve throughput gain of the connection between the two APs. We then propose a topology control cooperative algorithm, that optimally decides the number of cooperative agents in order to maximize the throughput gain while guaranteeing a reasonable additional computation time. On the other hand, a large-scale PDCN consists of multiple PRUs connecting to each other in a multi-hop paradigm. The local network under each PRU can be considered as a small-scale PDCN. In this considered network, each PRU also called a Cognitive Radio Base Station (CRBS) is equipped with multiple antennas and able to use available spectrum in the area. For this large-scale PDCN based on CRBSs, we propose an adaptive topology control method aiming to maximize the cognitive radio adaptability while guaranteeing the routing computation time.

The third considered aspect is the *application* of PDCNs based on multiple PRUs. This thesis introduces the safety confirmation application using image databases on-board the PRUs as a typical application of PDCNs. There are three main challenges for the considered application and the considered network, including how to synchronize distributed databases, how to deal with non-uniform distribution of users, and how to deal with congestions in the network composed of PRUs, which is referred to as the backbone network. In order to address the challenges, we propose a safety confirmation method that has four phases: resizing & storing images, broadcasting small-size images to other PRUs, routing in the backbone network, and deciding the image size for delivering to users. Especially, in the last phase, the method uses an absorbing Markov chain to estimate the image searching time and decide the image size so that the searching time is minimized.

1.3 Research Contributions

In this thesis, we focus on improving the throughput and delay of PDCNs based on PRUs. The main contributions of the dissertation are summarized as follows.

- We propose a method that considers both spectrum and energy efficiencies to find routing paths in a PDCN based on a single PRU. The method comprises the paths based on the top k spectrum-efficient paths and the transmission capabilities of the APs. By analyzing the relationship between the value of k in the topology formation phase and the two objectives, namely, spectrum and energy efficiencies, we show that a higher value of k decreases the average spectrum efficiencies of the paths and increases the total number of transmissions that can be sent. Additionally, we introduce a new metric, namely, spectrum-energy efficiency, to measure how many transmissions that can be carried out with a limited frequency band and limited energy resource. Furthermore, we prove that a value of k exists that leads to the maximum spectrum-energy efficiency of the PDCN. By conducting extensive simulations, we validate the accuracy of our analyses.

- We propose two topology control methods for different scales of PDCNs. For a small-scale PDCN based on a single PRU, by using cooperative communications, we propose a topology control cooperative method, that optimally decides the number of cooperative agents in order to maximize the throughput gain while guaranteeing a reasonable computation time. For a large-scale PDCN based on multiple PRUs, we propose an adaptive topology control method that aims to maximize the cognitive radio adaptability while guaranteeing the routing computation time. The effectiveness of the two methods is validated by both analytical and simulation-based evaluations.

- We propose a method for the safety confirmation application that helps users search for images that look similar to the people they are looking for. Considering a PDCN based on multiple PRUs where the image databases are distributed, the method guarantees the minimum searching time of users by deciding the most appropriate size of images for responding to the users. We analyze the relationship between the expected searching time and image size based on an absorbing Markov chain. By using the findings in the analysis, the algorithm for deciding the image size is introduced. By conducting extensive simulations, we verify the existence of the image size that minimizes the expected searching time.

1.4 Thesis Outline

The remainder of this thesis is organized as follows.

Chapter 2: Overview of Post-Disaster Communication Networks Based on Portable Resource Units. In this chapter, we first provide an overview of PDCNs and the existing PDCNs that consider using PRUs. We then point out the challenges and requirements of PDCNs based on PRUs and highlight throughput and delay as the main requirements that need to be addressed.

Chapter 3: Proposed Spectrum and Energy Efficient Method for Post-Disaster Communication Networks. In this chapter, we first identify the requirements of spectrum and energy efficiencies in PDCNs. After that, the proposed spectrum and energy efficient method for PDCNs is introduced. Finally, analytical and simulation-based performance validations are presented.

Chapter 4: Proposed Adaptive Topology Control for Different Scales of Post-Disaster Communication Networks. In this chapter, we point out the necessity of having adaptive topology control methods for different scales of PDCNs. We then propose two adaptive topology control methods for small-scale and large-scale PDCNs, respectively. For small-scale PDCNs, the utilization of cooperative communications is considered. On the other hand, cognitive radio is considered in the scenario of large-scale PDCNs which are based on multiple PRUs. In the explanation of each method, we provide analytical and simulation-based validation to prove the effectiveness of the method.

Chapter 5: Post-Disaster Communication Network Application Performance Enhancement. In this chapter, we introduce a typical application of PDCNs, which is the safety confirmation application using image databases equipped with PRUs in the multiple PRUs based PDCNs. After that, the proposed Markov-based performance optimization of the application is presented. In this proposal, an absorbing Markov chain is used to find the image size that minimizes the expected image searching time. Finally, the analysis and evaluation of the proposal are demonstrated.

Chapter 6: Conclusion. This chapter demonstrates the summary of the thesis and the related discussion. Finally, possible future directions of this work are presented at the end of the dissertation.

Chapter 2

Overview of Post-Disaster Communication Networks Based on Portable Resource Units

2.1 Introduction

In this chapter, we intend to provide a comprehensive overview of the research works on PDCNs in literature. Particularly, this chapter focus on existing PDCNs that are based on the concept of PRUs. This chapter also points out the challenges of PRUs based PDCNs and the corresponding requirements. Among the requirements of PDCNs based on PRUs, we highlight the importance of network performance in terms of throughput and delay.

2.2 Post-Disaster Communication Networks

In spite of the advancing technologies, people still have to deal with many natural disasters. There are many different types of disasters, such as floods, hurricanes, tornadoes, volcanic eruptions, earthquakes, tsunamis, and so forth. In fact, Japan is the most well-known country in the world for earthquakes and tsunamis. Recently, there were two strong earthquakes that hit Japan. In 2011, the Great East Japan earthquake and its triggered powerful tsunami destroyed a large area in Tohoku region of Japan. Furthermore, in 2016, a series of earthquakes in Kumamoto also damaged/destroyed many buildings. Depending on the type and scale of the disaster, the effects on human life, which are generally undesirable, can be different case by case. Specifically, regarding the impacts of disasters on the communication networks, the most common consequences are usually the damaged/destroyed network infrastructure and the power outages.

Due to the significant influence of disasters on human life, many research aspects related to disasters and communications could be found in the literature. The researchers have paid attention to both pre and post-disaster approaches. While many research works focus on the planning and preparation of communication technology or the necessity of the redundancy in designing communication infrastructure [11–14], the post-disaster response has also become a hot topic [15–18]. On one hand, some of the existing researches on post-disaster response have focused on situation management and supporting disaster responders. For instance, George *et al.* [15] introduced the DistressNet, which is a wireless ad-hoc and sensor network architecture aiming to improve the situational awareness. Pace and Aloi [16] focused on utilizing space technologies and satellite applications to monitor the disasters and mitigate their effects. On the other hand, many different works have paid attention to making the disaster response more effective. For example, 911-network on wheels (911-NOW) proposed by Abusch-Magder *et al.* [17] attempts to use the network on wheels concept to make a portable wireless system for emergency response and disaster recovery. Wang *et al.* [18] concentrates on more service-oriented architectures to support disaster response. Relay-by-Smartphone [19] can be also considered as a method to make the communication in the disaster area more effective. The main idea of Relay-by-Smartphone is to use the only Wi-Fi functionality of smartphones to send and relay messages among the devices. Therefore, when the cellular network is out of service due to the effect of the disaster, this technology can be used to make the communications between people possible.

However, each of the above-mentioned works only considers one part of the whole solution for disaster response. Therefore, a complete solution needs to be taken into account, that includes deploying networks, providing and managing services, and so forth. In order to come up with such a solution, not only academic research but also industrial developments need to contribute their efforts. In Japan, Nippon Telegraph and Telephone Corporation (NTT) has focused on preventing the effects of disasters on their telecommunication network for more than twenty years [20]. Three fundamental principles, namely improving network reliability, preventing isolation, and rapidly restoring services, have been considered in their efforts to make NTT networks more resilient to disasters. However, these efforts only benefit the users using the NTT carrier. A more "carrier-free" solution is required for the general disaster responses. In this thesis, we focus on the PDCNs based on PRUs, which are able to construct a wireless network by using the equipment carried by the PRUs to the disaster area. With this consideration, the constructed network will be independent of the carriers and aim to provide Internet access to every user in the disaster affected area.

2.3 PDCNs Based on PRUs

2.3.1 What is a PDCN Based on PRUs?

Figure 2.1 demonstrates an example of PDCNs based on a single PRU, which can carry multiple portable APs and other necessary equipment for constructing a PDCN. After an occurrence of disasters, the PRU will be transported to the disaster affected area. Once it arrives at the disaster site, the equipment carried by

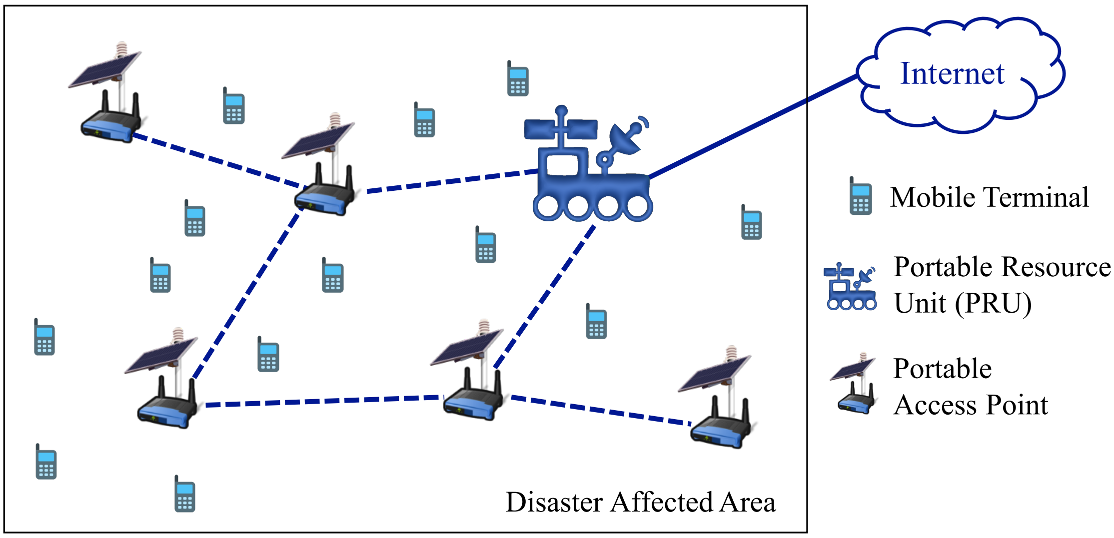

Figure 2.1: An example of PDCNs based on a single PRU.

the PRU will be used to deploy the PDCN providing network services to the mobile terminals in the area. The PRU has the capability to communicate with outside areas by using different methods. For example, if there is a remaining optical cable in the area, the PRU can use that to connect to outside. The PRU can also have a functionality to communicate with satellites. As a result, the PRU can act as a gateway to relay the communication traffic from/to the disaster affected area. Inside the constructed PDCN, each portable AP is equipped with battery replenished by using renewable energy. The portable APs are connected to each other in the multi-hop fashion to extend the coverage of the network. Users can connect to the closest portable APs to use the network services provided by the PDCN.

When the disaster area is large and one PRU cannot provide enough coverage, multiple PRUs can be used, as shown in Figure 2.2. The PRUs can connect to each other in a multi-hop manner. The PRU that are closest to outside area can be the gateway to route all the traffic originated from and targeted to the disaster area.

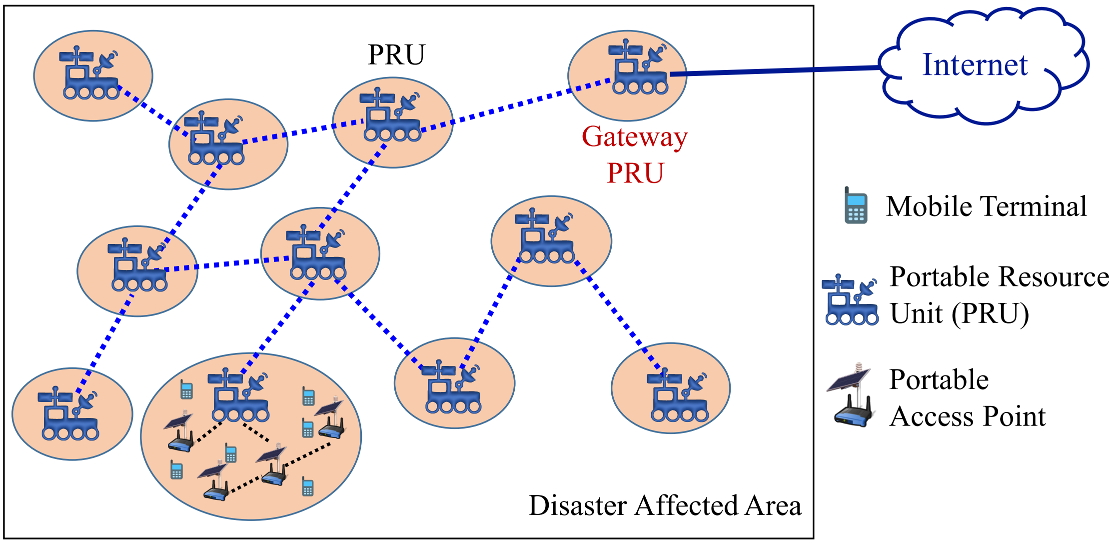

Figure 2.2: An example of PDCNs based on multiple PRUs.

2.3.2 Why is a PDCN Based on PRUs Necessary?

After a disaster occurs, it is expected to have an explosive increase in demand for services. People attempt to use communication services to confirm the safety of their family, relatives, and friends. The government and companies also want to use services for management. On the other hand, the service supply will be very limited. This is because the disaster can cause power outages and the damages in information and communications resources. As a result, there will be a critical gap between service supply and demand. In order to relax this situation, traditional approaches using ad-hoc networks, wireless mesh networks, delay/disruption tolerant networking (DTN), or satellites were considered for use in the disaster areas. As demonstrated in Table 2.1, each of them has its own strong points but is still prone to significant shortcomings. For instance, ad-hoc networks, mesh networks, and DTN share the same advantage, which is the easy configuration even in disaster areas. However, while DTN and ad-hoc networks can be constructed by using only user devices, mesh networks required remaining infrastructure to be set up. Regard-

Approaches	**Advantages**	**Disadvantages**
Ad hoc networks	• Easy configuration	• High energy consumption of devices • Small coverage • Limited number of users
Mesh networks	• Easy configuration	• Existing infrastructure required
DTN	• Easy configuration	• High delay • High energy consumption of devices
Satellite-based networks	• Large coverage	• Very limited number of users
PDCNs based on PRUs	• *Easy configuration* • *Low delay* • *Large coverage* • *High number of users*	• *PRUs required*

Table 2.1: The advantages and disadvantages of the approaches to relax the demand-supply critical situation in disaster areas.

ing the disadvantages of the three types of networks, the high communication delay is the main disadvantage of DTN while that of ad-hoc networks is the limited number of users. Furthermore, both DTN and ad-hoc networks need to consume much energy of user devices, which usually becomes critical in disaster areas. The power supply is also one of the main issues for mesh networks in such an area because there might be power outages. Using satellite-based networks to provide services such as satellite phones is a very different approach. Using satellites is superior to the above three methods in terms of service coverage. However, the cost of the satellite-related equipment is relatively high, which causes the limited number of users able to use satellite services.

In fact, the users in disaster areas need all the above-mentioned advantages. Users need a network that is easily configured and is possible to provide services to a high number of users while still can cover a large area. With the concept of PDCNs based on PRUs, those features can be provided. Therefore, it is necessary to advance the research focusing on PRU-based PDCNs.

2.3.3 Existing PDCNs Using the Concept of PRUs

There have been many research works focusing on PDCNs and use the similar concept of PRUs. The existing works are not only in academia but also in industrial development. Some significant works can be listed as follows.

Bell Labs

Abusch-Magder *et al.* [17] introduced the vision of the 911-Network On Wheels (911-NOW) solution, which aims to enable first responders and emergency management teams to communicate mission-critical information on a secure and rapidly deployable wireless network. The features of 911-NOW include capability to be mounted on a variety of different platforms, self-configuration, multi-hop and mesh networking capabilities, amenability to different air interfaces, applications to support multiple missions in emergency response, and secured communications.

AT&T

The Network Disaster Recovery (NDR) team of the AT&T company has considered using a portable cell site, which is a cell on light truck (COLT) or cell on wheels (COW), for their disaster response networks [1]. With the assumption that there is no conventional communication method available at the disaster site, the NDR team uses an emergency communication vehicle (ECV), which is usually a four-wheel drive van having a connection to the satellites, in order to establish first-in communication capabilities. After that, a portable cell site, i.e., COLT or COW, is used to replace the service provided in the damaged sited. With these efforts, the users of AT&T can use the cellular service again after the damaged cellular site is replaced by the temporary one.

The Ministry of Internal Affairs and Communications of Japan

The MIC of Japan launched a national project involving industry and academia to come up with a solution for the critical situation in disaster affected areas. As one of the outputs of the project, the Movable and Deployable ICT Resource Unit (MDRU) has been researched and developed. An MDRU accommodates communication equipment, servers and storage, power supply equipment, and so forth. As the name implies, MDRU is portable and can be used to promptly deploy a disaster recovery network at the disaster site. The required features of an MDRU-based disaster recovery network include:

- Agile and easy transportation
- Prompt installation
- High performance and capacity
- Large coverage
- Useful disaster-time applications
- Carrier-free and seamless usability

Different versions of the MDRU have been researched and developed to use for different situations. Figure 2.3 shows different versions of the MDRU and the comparison in terms of size, capacity/robustness, and mobility/scalability/flexibility.

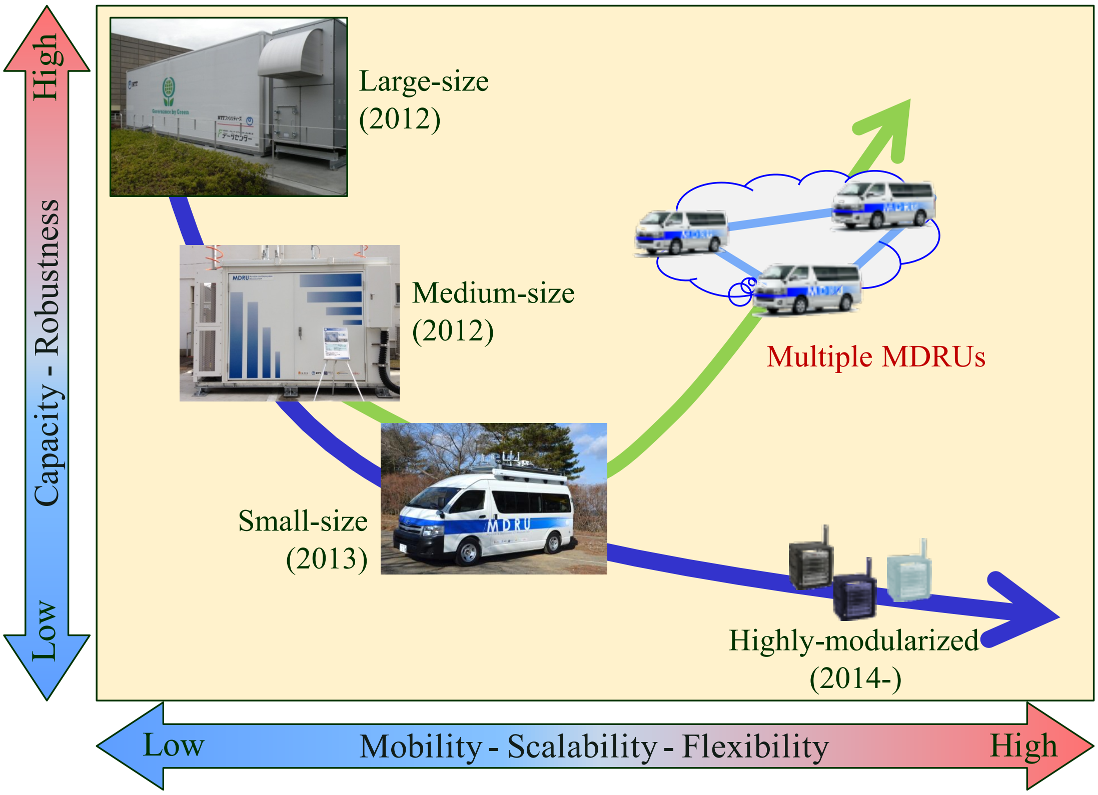

Figure 2.3: Different versions of the MDRU.

Among the developed versions of the MDRU, the small-size MDRU (a.k.a, the van-type MDRU) can be considered as the most typical MDRU [21]. Not only servers, storage, and other static equipment, but also portable modules utilized to construct a standalone wireless mesh network can be carried by the van. Figure 2.4 demonstrates the main modules in a van-type MDRU including a Fixed Wireless Access (FWA) module, a network control module, servers, movable Wi-Fi modules, and the maintenance modules.

In this thesis, our considered network scenarios and assumptions are close to those in the MDRU-based disaster recovery network. Especially, we also consider the PDCNs based on both single PRU and multiple PRUs.

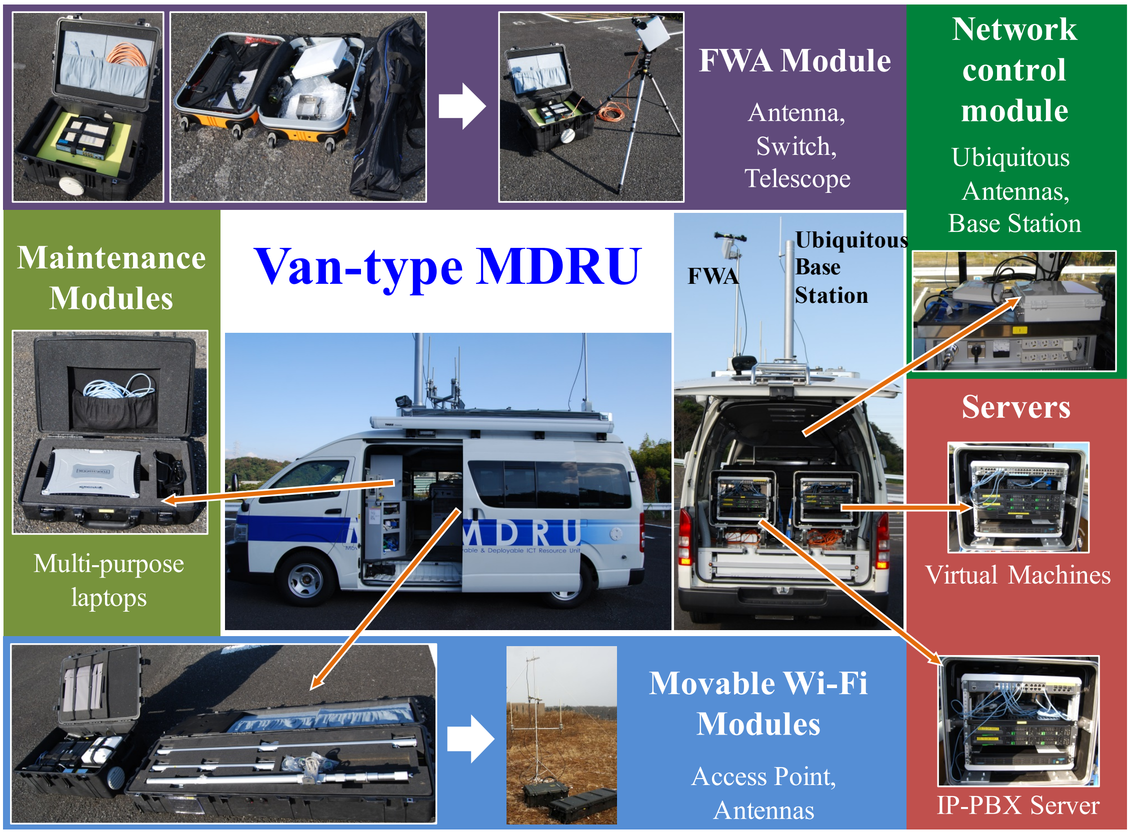

Figure 2.4: The modules in a typical MDRU. ©2016 IEEE.

2.4 Requirements of PDCNs Based on PRUs

2.4.1 Challenges of PDCNs Based on PRUs and the Corresponding Requirements

In order to build a PDCN based on PRUs, there are some challenge issues that we need to take into account. Table 2.2 summarizes the main challenges for PDCNs and the corresponding requirements. The first challenge is that the situations after disasters are always emergency cases. Everyone urges to use network services for safety confirmation and gathering information. Accordingly, the PDCN needs to be a portable system and the deployment of the PDCN needs to be as fast as possible. Secondly, the demand from users, after any disaster, will be exceedingly high. How-

Challenges	Requirements
Emergency situations after disasters	• A portable system • Prompt deployment
High demand from users while the capacity is limited	• High efficiency • High throughput • Low delay
Different scenarios of disasters	• Capability to adapt to different network environments

Table 2.2: The challenges of PDCNs based on PRUs and the corresponding requirements.

ever, the capacity of a PDCN will be limited by the amount of equipment carried to the area and the bandwidth of the connection to the outside area. Therefore, we need to focus on efficiency to improve the performance of the PDCN, especially the throughput and delay. Thirdly, the disaster scenarios are different case by case, and thus, we need a method to adapt to different network environments.

2.4.2 Throughput and Delay Requirements

Among the above-mentioned requirements of PDCNs, the requirements of a portable system and prompt deployment can be fulfilled by using PRUs. Therefore, with the PDCNs based on PRUs, the remaining challenges include limited resources, high demand from users, and the variety of disaster situations. High performance is always the most important requirement for any system. In the case of PDCNs, the importance of having high performance in terms of throughput and delay becomes even more significant. The system needs to have high throughput because the number of users in disaster area will be exceedingly increased after the system is deployed.

The delay requirement comes from the emergency case and the characteristics of the applications that users want to use after disasters.

2.5 Summary

In this chapter, we introduced the overview of the PDCNs and answered two questions: "What is a PDCN based on PRUs?" and "Why is a PDCN based on PRUs necessary?" We also reviewed some significant works using the concept of PRUs for PDCNs. Furthermore, we identified the challenges of PDCNs based on PRUs and the corresponding requirements. Finally, we pointed out the importance of improving throughput and delay in PDCNs, which is the main objective of this thesis.

Chapter 3

Proposed Spectrum and Energy Efficient Method for Post-Disaster Communication Networks

3.1 Introduction

In this chapter, we identify the lack of spectrum and energy resources as one of the most challenging issues for PDCNs and highlight the importance of considering both spectrum efficiency and energy efficiency in PDCNs. However, after investigating the relevant research work in literature, we find out that existing works only consider spectrum efficiency or energy efficiency separately, in spite of the trade-off relationship between them. Therefore, we aim to propose a method to maximize the utilization of both spectrum and energy resources in order to improve the overall system performance. The considered PDCN is composed of portable APs deployed in the disaster area, which can replenish their energy by using solar panels. After modeling the network, the proposed method constructs a topology based on the top k spectrum-efficient paths from each transmitting node and applies max flow algorithm with vertex capacities, which are the number of transmissions each node can send, referred to as transmission capability. We introduce a new metric named spectrum-energy efficiency to measure both spectrum and energy efficiencies of the network. This chapter will present our proposal in detail, including system assumptions, proposed method, analysis, and performance evaluation.

Some parts of the content in this chapter are presented in the following paper, which was written by the author of this dissertation.

- Thuan Ngo, Hiroki Nishiyama, Nei Kato, Toshikazu Sakano, and Atsushi Takahara, "A Spectrum- and Energy-Efficient Scheme for Improving the Utilization of MDRU-based Disaster Resilient Networks," *IEEE Transactions on Vehicular Technology - Special Section on Green Mobile Multimedia Communications*, vol. 63, no. 5, pp. 2027-2037, Jun. 2014.

3.2 Spectrum and Energy Efficiency Requirements of PDCNs

After a disaster occurs, people in the disaster area will try to use network services to confirm the safety of their families and friends. Therefore, the number of network users will increase sharply within a short period of time. Even though the PRU only aims to provide basic services such as VoIP, e-mail, and Internet access, guaranteeing adequate network throughput is a major challenge in the PDCN based on PRUs, where the following issues are very important.

- *Spectrum efficiency:* due to the extremely high demand from users, wide frequency bandwidth is required to achieve good throughput. However, the spectrum resource is limited. Thus, it is necessary to use spectrum-efficient methods for the PDCN based on PRUs to increase the number of users that can be satisfied with the available throughput. Spectrum efficiency is a measure of how efficiently the limited frequency spectrum is utilized to transmit packets, i.e., how much throughput can be achieved with a limited frequency bandwidth. However, contemporary methods such as those in [3, 4] that aim to improve spectrum efficiency fail to consider the limited energy resources in practical PDCNs.

- *Energy efficiency:* in a disaster-struck area, one of the most critical issues is the power supply because the infrastructure for power supply is not available due to damage, safety reasons, and so forth. Hence, the network has to operate in an area where energy is very limited, which renders using energy-efficient methods for PDCN based on PRUs to be of utmost importance. Energy efficiency is a measure of how efficiently the energy is utilized to transmit packets, i.e., how many packets can be transmitted with a limited energy. However, energy-efficient methods such as those introduced in [7, 8] fail to consider the limited frequency spectrum.

The approaches about spectrum efficiency alone or energy efficiency alone, which are widely discussed in the literature, cannot be used in this kind of network because there is a tradeoff relationship between the two. Therefore, the desired solution for the aforementioned challenges is a method that considers both spectrum and energy efficiencies to maintain high throughput for the PDCN based on PRUs, which is limited in energy and spectrum resources. This objective is referred to as spectrum-energy efficiency in this thesis.

3.3 Existing Works Related to Spectrum Efficiency, Energy Efficiency, and Routing

Routing in multi-hop networks has been a well-known topic in literature. Most of the conventional works in this research area, such as those in [22,23], aim to improve the network throughput by introducing new routing metrics and modifying the existing routing protocols to apply the metrics. However, in those works, the limitations of the physical layer have not been considered adequately. Recently, routing with limited spectrum resource, in contrast, has become the new trend. Sikora *et al.* analyzed the performance of some practical routing schemes for wireless networks and figured out the schemes that are most suitable for power-limited networks and the schemes that are most acceptable for bandwidth-limited networks [24]. The authors in [24] also proposed a new information-theoretic scheme, referred to as multi-hop with recursive backward interference cancellation, to remove all interference from the multi-hop system with an arbitrarily small rate loss. However, the assumptions in this research are relatively strict with a linear network while the number of relays and their locations are design parameters. Chen *et al.* considered a more flexible assumption an arbitrary number of randomly located nodes in a linear network and introduced the objective function for the optimal spectrum-efficient routing problem [3]. The authors noted that the problem cannot be solved by using simple shortest path algorithms because the routing metric is neither isotonic nor monotone. Thus, they proposed two suboptimal solutions, namely Approximately Ideal-Path Routing (AIPR) and Distributed Spectrum Efficient Routing (DSER). AIPR is a location-assisted routing algorithm which aims to approximate the ideal routing path by calculating the optimum inter-relay distance D_{hop} and choosing the relay node with the distance to the source closest to D_{hop}. On the other hand, DSER modifies the objective function of the optimal spectrum-efficient routing problem so that the problem can be solved in a distributed way. In DSER, the weight function of a link l is calculated as $1 + \frac{\beta}{\rho_l}$, where β is the routing coefficient, ρ_l is the signal-to-noise ratio (SNR) of the link l, and 1 is the penalty for an additional hop. By using this weight function, DSER can find the routing path by using shortest path routing algorithms. Furthermore, Saad [4] proposed two algorithms to solve the original problem of finding the maximum spectrum-efficient path in polynomial computation time. These algorithms rely on the iterative use of a shortest path algorithm on a graph modified by removing unnecessary links. However, the above-mentioned algorithms are based on the assumption that all nodes in the network are connected with abundant power supplies, which sometimes cannot be guaranteed. In many cases, such as post-disaster scenarios, the power supplies are limited and energy is one of the critical issues, which leads to the requirements of considering energy efficiency.

In fact, energy efficiency has become an important topic in literature and has attracted much attention [25–29]. For example, Srinivas and Modiano studied the minimum energy disjoint path routing problem in wireless ad hoc networks [7], and proposed two optimal solutions for minimum energy 2 link-disjoint paths and minimum energy k node-disjoint paths, respectively. Also, two heuristic algorithms were provided to reduce the complexity of the optimal algorithms. On the other hand, Miao *et al.* focused on the energy-efficient link adaptation in [8]. They proved that a unique globally optimal link adaptation solution exists and proposed two iterative algorithms, namely, Gradient Assisted Binary Search (GABS) and Binary Search Assisted Ascent (BSAA), to obtain the optimum solution. However, the above-mentioned algorithms for energy efficiency do not consider the limited spectrum resource as a co-objective in their method.

In this chapter, we consider a network with the limitations of both frequency bandwidth and energy resources. To come up with the solution for the joint problem of finding both spectrum-efficient and energy-efficient routing paths, we propose a method consisting of two phases, which will be introduced in the next section.

In this section, we describe the assumptions for our considered PRU-based PDCN, define the network model, and introduce the metrics including transmission capability and spectrum-energy efficiency.

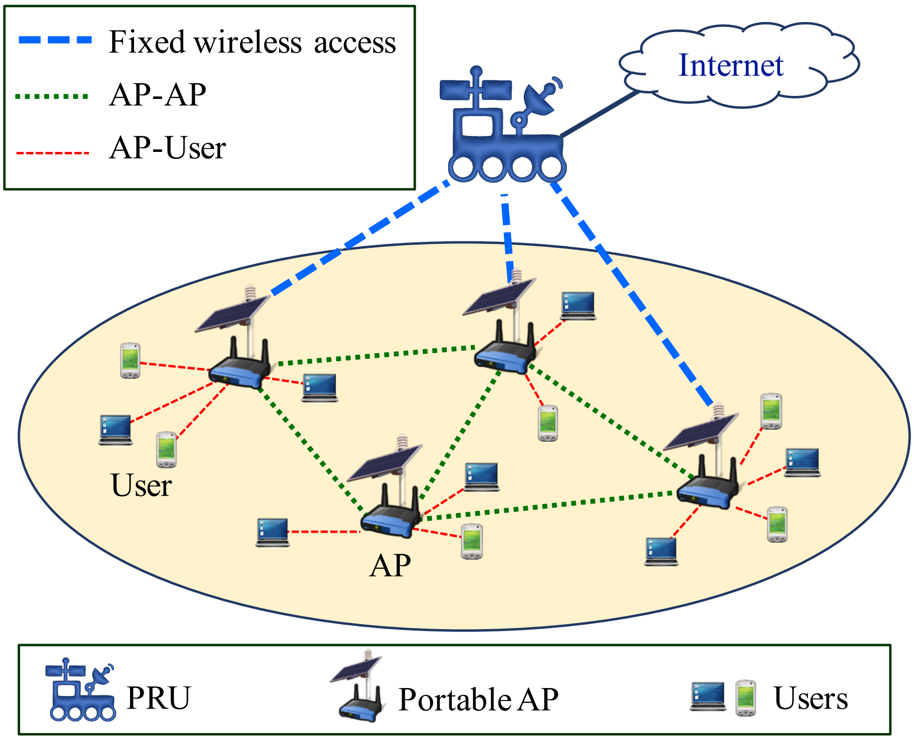

Figure 3.1: Considered PRU-based PDCN. ©2014 IEEE.

3.4 System Assumptions and Definitions

3.4.1 System Assumptions

Figure 3.1 shows the our considered PRU-based PDCN. Portable APs are deployed within the PRU's service area radius, to construct a backbone network that provides Internet connectivity to the users in the disaster area. In order to alleviate the power outage in the disaster area, the APs are equipped with batteries, which are rechargeable with solar panels. Some APs can directly connect to the PRU by using the Fixed Wireless Access (FWA), which is similar to the assumption in [2]. The APs can forward the packets from their surrounding users to the PRU. Each AP can also relay the data from other APs to either the PRU or the next AP in multi-hop path to the PRU. The connections between APs equally share the frequency bandwidth, which is a widely accepted assumption [3, 4, 24]. Since the available energy can be different depending on time and each individual AP, the PRU needs to decide which AP should send packets directly to the PRU and which AP has to send packets by using the multi-hop network composed of APs. The PRU uses a special frequency band for controlling APs, which is different from the frequency band for data transmission, to reduce the influence of the controlling transmissions on network performance.

3.4.2 Network Model

In order to model the multi-hop network composed of APs, we use a directed graph $G(V, E)$, where V is the set of APs and E is the set of directed links between APs. For a given link $l \in E$, $t(l)$ and $r(l)$ represent the transmitting node and receiving node, respectively. A path L from node s to node d in the network can be defined in two ways as follows:

1. It can be defined as an ordered sequence of nodes $u_1, u_2, u_3, ..., u_n \in V$, where $u_1 = s$ and $u_n = d$.

2. It can be defined as an ordered sequence of links $l_1, l_2, l_3, ..., l_n \in E$, where $t(l_1) = s$, $r(l_n) = d$, and for each $1 \leq i \leq n-1$, $r(l_i) = t(l_{i+1})$.

We also use $t(L)$ and $r(L)$ to represent the starting node and the ending node of a path L, respectively.

As shown in Figure 3.2, the nodes in the graph are categorized into three sets:

- Senders (S): the set of APs that send data from their local users and transmit the data over the multi-hop network.

- Forwarders (F): the set of APs that receive data from other APs and directly send the data to the PRU.

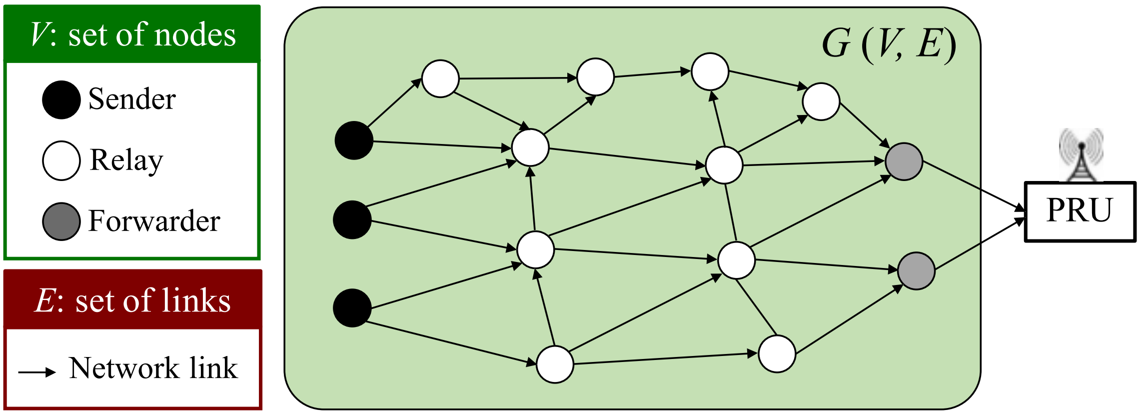

Figure 3.2: The categories of nodes in the network $G(V, E)$. In the real network, the forwarders are the APs that have direct connections with the PRU in the routing paths. ©2014 IEEE.

- Relays (R): the set of APs that do not exists in S or F and are able to relay data from other APs in S or R.

The three sets satisfy the following equation:

$$S \cup F \cup R = V. \tag{3.1}$$

We use $\mathcal{L}$ to represent the set of all paths from any sender to any forwarder:

$$\mathcal{L} = \{L | t(L) \in S, r(L) \in F\} \tag{3.2}$$

3.4.3 Metrics

There are three important metrics that are used in this chapter, namely spectrum efficiency, transmission capability, and spectrum-energy efficiency. While spectrum efficiency was already defined in literature, this research introduces the other two metrics.

Spectrum Efficiency

Spectrum efficiency of a path L, $\Re_L$, has been defined as the bandwidth-normalized end-to-end rate [24], which can be calculated as follows:

$$\Re_L = \frac{C_L}{B}, \quad (3.3)$$

where C_L is the end-to-end achievable rate of path L, and B is the given bandwidth constraint of path L. The unit of $\Re$ is bit per second per hertz (b/s/Hz). With the assumption of equal bandwidth sharing [3], $\Re_L$ can be calculated based on the SNR of links as follows:

$$\Re_L = \min_{l \in L} \frac{1}{|L|} \log(1 + SNR_l). \quad (3.4)$$

In this research, we define the spectrum efficiency of a network $G(V, E)$, $\Re_G$, as the average spectrum efficiency of the paths from the senders to the forwarders.

$$\Re_G = \frac{\sum_{L \in \mathcal{L}} \Re_L}{|\mathcal{L}|}. \quad (3.5)$$

Transmission Capability

We introduce a metric named transmission capability in order to measure the number of transmissions which can be carried out with a given specific amount of energy. The transmission capability of a node u, Γ_u, is the number of transmissions that node u can transmit to its next hop v with its remaining energy:

$$\Gamma_u = \frac{E_u}{e_{(u,v)}}, \quad (3.6)$$

where E_u is the remaining energy of node u and $e_{(u,v)}$ is the energy needed to carry out a transmission from node u to node v. Considering a network with constant transmission power, which is similar to the assumption in [3,4,24], Γ_u can be derived as follows:

$$\Gamma_u = \frac{E_u}{e}, \tag{3.7}$$

where e is the energy for a single transmission. The transmission capability of a path L, Γ_L, is the minimum transmission capability of nodes in the path:

$$\Gamma_L = \min_{u \in L} \Gamma_u. \tag{3.8}$$

To be used in this chapter, we define the transmission capability of a network $G(V, E)$, Γ_G, as the total of the transmission capability of paths from senders to forwarders:

$$\Gamma_G = \sum_{L \in \mathcal{L}} \Gamma_L. \tag{3.9}$$

Based on the transmission capability, the energy efficiency of the network $G(V, E)$, $\mathcal{E}_G$, can be calculated as follows:

$$\mathcal{E}_G = \frac{\Gamma_G}{\sum_{L \in \mathcal{L}} \sum_{u \in L} E_u}, \tag{3.10}$$

where E_u is the remaining energy of node u. $\mathcal{E}$ is measured in 1 over joule (1/J).

Spectrum-Energy Efficiency

To come up with a metric measuring both spectrum efficiency and energy efficiency of a network, we introduce *spectrum-energy efficiency*. The meaning of this metric is to measure the energy-normalized spectrum efficiency of a network. We calculate the spectrum-energy efficiency of a network $G(V, E)$, Ω_G, as the product of spectrum efficiency and energy efficiency of the network:

$$\Omega_G = \Re_G \times \mathcal{E}_G. \tag{3.11}$$

Since $\Re$ is measured in b/s/Hz and $\mathcal{E}$ is measured in 1/J, the unit of Ω is b/s/Hz/J.

3.5 Proposed Spectrum and Energy Efficient Method

Based on the metrics mentioned in the previous section, the problem statement can be defined as follows:

Problem statement: "Given a AP network $G(V, E)$, the set of senders S, the set of forwarders F, and the set of relays R, find the routing paths from the senders to the forwarders such that the spectrum-energy efficiency of the network, Ω_G, is maximum."

In order to solve the problem, we proposed a spectrum and energy-efficient method. From each sender, we find k disjoint paths with the highest spectrum efficiency, $\Re$, by iteratively applying the optimal spectrum-efficient routing algorithm [4]. The nodes and links of the resulting paths are used to construct a topology. After that, the max flow algorithm with vertex capacities is applied to the constructed topology, where the capacity of a node u is its transmission capability, Γ_u. Finally, the transmissions from nodes are split according to the result of the max flow algorithm.

The proposed method is composed of two phases: topology formation and transmission division. The topology formation phase carries out two steps:

1. From each sender, find the top k spectrum-efficient disjoint paths to any of the forwarders.

2. Construct a new topology using nodes and links of the paths found in step 1.

After that, the transmission division phase carries out three steps:

1. Calculate the transmission capabilities of nodes in the topology created from topology formation phase.

2. Carry out the max flow algorithm with vertex capacities, where the capacities are the transmission capabilities of nodes.

3. Split the transmissions from nodes following the result of max flow algorithm.

The following sub-sections present in detail the above-mentioned phases. The proposed method is described in Procedures 1 and 2.

3.5.1 Topology Formation

In our proposal, the first step is to find top k disjoint paths, in terms of spectrum efficiency, from each sender to any of the forwarders. After that, a new topology, $\hat{G}(\hat{V}, \hat{E})$, is constructed by using all nodes and links of the resulting paths. Finding the best spectrum-efficient routing path from a sender s to a forwarder d can be formulated as finding the solution for following optimization problem [3].

$$\max_{L \in \mathcal{L}} \Re_L. \tag{3.12}$$

Here, we need to, however, find paths from each sender to any of the forwarders, which is not one-source one-destination problem. In order to transfer the problem into a one-source one-destination problem, we create an extended graph $G'(V', E')$ from $G(V, E)$ by adding a virtual destination d' to V and adding a link from each forwarder to d'. The SNR of the links from the forwarders to d' are set to infinity.

$$V' = V \cup \{d'\} \tag{3.13}$$

$$E' = E \cup \{l | t(l) \in F, r(l) = d', SNR_l = \infty\} \tag{3.14}$$

Now the problem becomes finding top k disjoint paths, in terms of spectrum efficiency, from each sender s to the virtual destination d'. The process is carried out as shown in Procedure 1. In each routine, we find the most spectrum-efficient path from sender s to the d' in the graph G' by using the optimal algorithm proposed in [4]. All the nodes and links of the resulting path are added to the topology $\hat{G}$. After that, all nodes (except s and d') and links of the resulting path are removed

Procedure 1 Topology formation

Input: The original AP network $G(V, E)$, set of senders S, set of forwarders F, and the value of k.

Output: The topology $\hat{G}(\hat{V}, \hat{E})$.

```
Create a graph Ĝ(V̂, Ê) with V̂ = V and Ê = {}.
Create a graph G′(V′, E′) with V′ = V and E′ = E.
Add a virtual destination d′ to V′.
for all f ∈ F do
    Add link l_(f,d′) to E′ with SNR_l = ∞.
end for
for all s ∈ S do
    for i = 1 to k do
        In G′, find the best spectrum-efficient path L from s to d′ by using the optimal algorithm proposed in [4].
        Add all links of L to Ê except the links from forwarders to d′.
        Remove from E′ all links and nodes that belong to L except nodes s and d′.
    end for
end for
return Ĝ(V̂, Ê).
```

from G'. The routine is repeated until we find k paths or no more path from s to d' can be found. The resulting $\hat{G}$ is the topology we need to find.

3.5.2 Transmission Division

In order to have the best possible transmission strategy from senders to the forwarders, we apply a *max flow algorithm with vertex capacities* [30] for the topology $\hat{G}$ where the *capacities* are the nodes' transmission capabilities. In order to apply the max flow algorithm, the topology $\hat{G}(\hat{V}, \hat{E})$ needs to be transformed to a one-source one-destination topology with links' capacities. We consider the extended

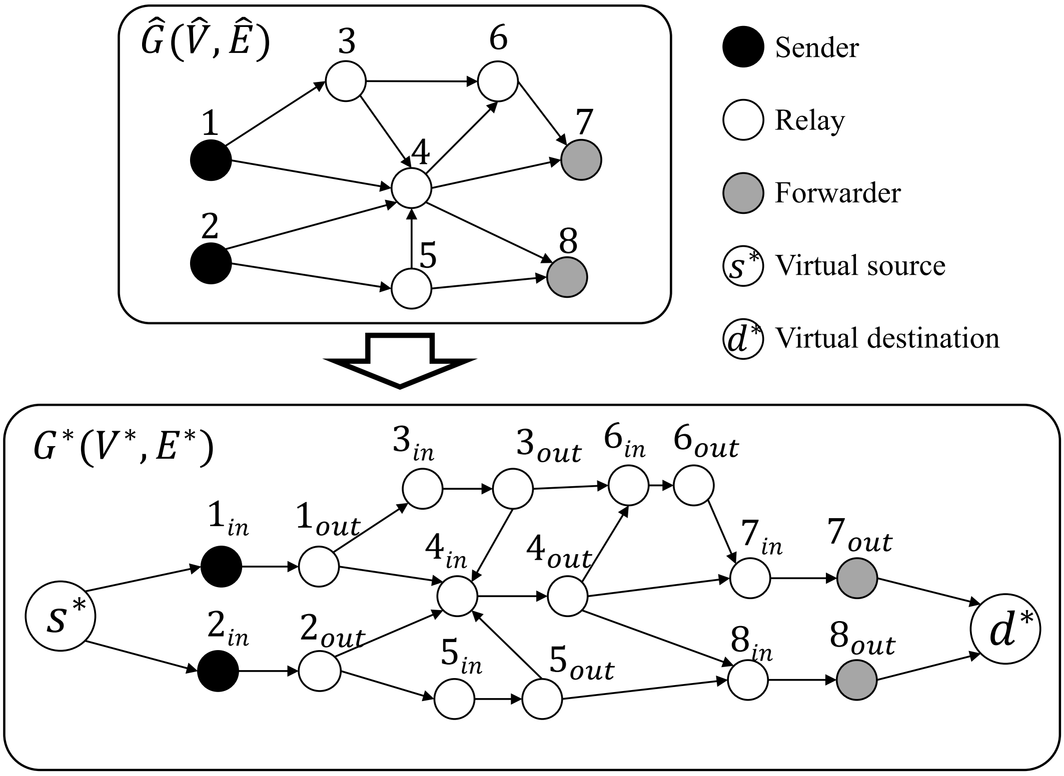

Figure 3.3: Transforming the topology $\hat{G}(\hat{V},\hat{E})$ to an extended graph $G^*(V^*,E^*)$. Every node v in $\hat{G}$ is transformed to two nodes, v_{in} and v_{out}, in G^*. A virtual source s^* and a virtual destination d^* are added to G^*. ©2014 IEEE.

graph extended graph of $\hat{G}$, $G^*(V^*,E^*)$, as shown in Figure 3.3. G^* is the extended version of $\hat{G}$ with the addition of virtual source s^* and virtual destination d^*. Furthermore, every node v in $\hat{G}$ is transformed to two nodes, v_{in} and v_{out}, in G^*. The set of nodes of G^* can be calculated as follows:

$$V^* = \{s^*, d^*\} \cup \{v_{in}, v_{out} | \forall v \in \hat{V}\}. \tag{3.15}$$

The set of links in the extended graph, E^* includes the links in $\hat{E}$ with the capacities set to infinity. E^* also has links from s^* to all senders S and links from all forwarders F to d^* with the capacities of links are set to infinity. In addition, for any corresponding node v of $\hat{G}$, there is a link from v_{in} to v_{out} in G^*, with the capacity

Procedure 2 Transmission division

Input: The topology $\hat{G}(\hat{V}, \hat{E})$, set of senders S, and set of forwarders F.

Output: The transmission division strategy from the senders to the forwarders.

Create a graph $G^*(V^*, E^*)$ with $V^* = \{\}$ and $E^* = \{\}$.
Add a virtual source s^* and a virtual destination d^* to V^*.
for all $v \in \hat{V}$ **do**
    Calculate the transmission capability of node v, Γ_v, by using Eq. 3.7.
    Add two nodes v_{in} and v_{out} to V^*.
    Add link $l_{(v_{in},v_{out})}$ to E^* with the capacity of the link $cap(l_{(v_{in},v_{out})}) = \Gamma_v$.
end for
for all $l_{(u,v)} \in \hat{E}$ **do**
    Add link $l_{(u_{out},v_{in})}$ to E^* with the capacity of the link $cap(l_{(u_{out},v_{in})}) = \infty$.
end for
for all $u \in S$ **do**
    Add link $l_{(s^*,u_{in})}$ to E^* with the capacity of the link $cap(l_{(s^*,u_{in})}) = \infty$.
end for
for all $v \in F$ **do**
    Add link $l_{(v_{out},d^*)}$ to E^* with the capacity of the link $cap(l_{(v_{out},d^*)}) = \infty$.
end for
Carry out a max flow algorithm for the graph $G^*(V^*, E^*)$ with sender is s^* and destination is d^*.
return The flow passing through the links of $G^*(V^*, E^*)$.

is v's transmission capability. The set of links E^* can be calculated as follows:

$$
\begin{aligned}
E^* = \{ & l_{(u_{out},v_{in})} | l_{(u,v)} \in \hat{E}, cap(l_{(u_{out},v_{in})}) = \infty\} \\
& \cup \{l_{(s^*,u_{in})} | u \in S, cap(l_{(s^*,u_{in})}) = \infty\} \\
& \cup \{l_{(v_{out},d^*)} | v \in F, cap(l_{(v_{out},d^*)}) = \infty\} \\
& \cup \{l_{(v_{in},v_{out})} | v \in \hat{V}, cap(l_{(v_{in},v_{out})}) = \Gamma_v\},
\end{aligned} \tag{3.16}
$$

where $cap(l_{(u,v)})$ is the capacity of link $l_{(u,v)}$.

By applying a max flow algorithm for the extended graph G^*, we can calculate the maximum total number of transmissions that the virtual source s^* can send to the virtual destination d^*. This value is the same as the maximum total number of transmissions that senders S can send to the forwarders F. After knowing the result of the max flow algorithm, the nodes can split their transmissions following the algorithm's result. Note that this phase only considers the transmission capabilities of nodes and do not need to use real-time status of network traffic.

3.6 Analysis

In this section, we analyze the relationship between the value of k and the three metrics, spectrum efficiency, transmission capability, and spectrum-energy efficiency. The complexity of the proposed method is also discussed in this section.

3.6.1 Relationship Between k and Spectrum Efficiency

Theorem 1. *Given a network $G(V, E)$, the average spectrum efficiency of k paths from a sender to any of the forwarders monotonically decreases when the value of k increases.*

Proof. Assume that $\{L_1, L_2, ..., L_i, ..., L_k\}$ are the top k spectrum-efficient paths from a sender s to the virtual destination d' via any of the forwarders. The paths are found by using Procedure 1. As shown in Procedure 1, in every loop i, $1 \leq i \leq k$, we find the ith best routing path from s to d' in the current graph and after that remove all nodes and links of path L_i. Therefore, the spectrum efficiency of the paths will satisfy $\Re_{L_1} \geq \Re_{L_2} \geq ... \geq \Re_{L_k}$. Considering the total spectrum efficiency of the top k spectrum-efficient paths, we have:

$$\sum_{i=1}^{k} \Re_{L_i} \geq k\Re_{L_{k+1}} \tag{3.17}$$

$$k\sum_{i=1}^{k} \Re_{L_i} + \sum_{i=1}^{k} \Re_{L_i} \geq k\sum_{i=1}^{k} \Re_{L_i} + k\Re_{L_{k+1}} \tag{3.18}$$

$$(k+1)\sum_{i=1}^{k} \Re_{L_i} \geq k\sum_{i=1}^{k+1} \Re_{L_i} \tag{3.19}$$

$$\frac{1}{k}\sum_{i=1}^{k} \Re_{L_i} \geq \frac{1}{k+1}\sum_{i=1}^{k+1} \Re_{L_i}. \tag{3.20}$$

Which means the average spectrum efficiency of the paths will monotonically decrease when k increases.

■

3.6.2 Relationship Between k and Transmission Capability

Theorem 2. *Given a network and energy level of nodes, the total number of transmissions that the senders can transmit to the forwarders monotonically increases when the value of k in the topology formation phase increases.*

Proof. Assume that $\hat{G}_k(\hat{V}_k, \hat{E}_k)$ is the topology formed by using the Procedure 1 with a given value of k. Since in every loop, we attempt to find one more path from s to d' and add the nodes and links from the path to the topology, $\hat{V}_k \subseteq \hat{V}_{k+1}$ and $\hat{E}_k \subseteq \hat{E}_{k+1}$. Accordingly, in the transmission division phase, G^*_{k+1} will have more nodes and links than G^*_k: $V^*_k \subseteq V^*_{k+1}$ and $E^*_k \subseteq E^*_{k+1}$. The total number of transmissions that senders can transmit to the forwarders is the flow that the virtual source s^* can send to the destination d^* in Procedure 2. Therefore, the flow calculated from G^*_{k+1} will be greater or at least equal to the value calculated from G^*_k. In other words, the total number of transmissions that the senders can transmit to the forwarders monotonically increases when the value of k increases. ■

3.6.3 Choosing k to Maximize Spectrum-Energy Efficiency

Given a network $G(V, E)$, set of senders S, set of forwarders F, and the information about the energy level of nodes, we need to find the value of k, bounded by $|F|$, that maximizes the spectrum-energy efficiency of the network.

Let $\Re(k)$ be the average spectrum efficiency of the paths from the senders to the forwarders, $\Gamma(k)$ is the total number of transmissions that the senders can send to the forwarders, and $\mathcal{E}(k)$ is the network energy efficiency, the spectrum-energy efficiency of the network is calculated as follows:

$$\begin{aligned} \Omega(k) &= \Re(k) \times \mathcal{E}(k) \\ &= \Re(k) \times \frac{\Gamma(k)}{\sum\limits_{L \in \mathcal{L}} \sum\limits_{u \in L} E_u}, \end{aligned} \tag{3.21}$$

where E_u is the remaining energy of node u and $\mathcal{L}$ is the set of all paths from senders to forwarders. When k increases, the total number of paths from senders to forwarders increases. Thus, $\sum_{L \in \mathcal{L}} \sum_{u \in L} E_u$ monotonically increases with the increase of k. According to Theorems 1 and 2, $\Re(k)$ monotonically decreases and $\Gamma(k)$ monotonically increases with the increase of k. Also, k is bounded by $|F|$, which is generally a small number. Therefore, we can choose the value k, from 1 to $|F|$, that maximizes the value of $\Omega(k)$.

3.6.4 Complexity of the Proposed Method

As shown in Procedure 1 at line 9, we use the optimal routing algorithm proposed in [4]. That algorithm has the complexity of $O(|V|^2|E|)$, where V and E are the set of nodes and the set of links in the network, respectively. Therefore, the complexity of the topology formation phase is $O(k|S||V|^2|E|)$, where S is the set of senders and k is the number of spectrum-efficient paths which need to be found from each sender to the forwarders. As shown in Procedure 2, we use a max flow algorithm for the extended graph. The complexity of the max flow algorithm is $O(|V|^2|E|)$ when using *Dinitz blocking flow algorithm* [31], or $O(|V|^3)$ in case of *push-relabel maximum flow algorithm* [32]. Hence, the complexity of our proposed spectrum and energy-efficient method is $O(k|S||V|^2|E|)$.

3.7 Performance Evaluation

In this section, we evaluate the performance of our proposed spectrum and energy-efficient method in a PRU-based PDCN by using extensive computer simulations. In order to validate the analysis results, we confirm the relationship between the value of k and the three metrics of the network, namely, spectrum efficiency, transmission capability, and spectrum-energy efficiency. Furthermore, the proposed method is compared with the optimal spectrum efficiency and the optimal transmission capability methods.

3.7.1 Simulation Settings

Table 4.2 describes the settings of our simulation. In the coverage area of the PRU, which has a radius of 500 meters, 100 APs are uniformly distributed. This is a large number of APs because, with 100 APs, approximately 4000 users can be serviced (given that each AP can provide service for up to 40 users). Each AP has a battery with the average remaining energy varying from 1000 to 2000 mJ. The energy consumed per transmission is set to 20 mJ. Similar to the works in [3, 4, 24], the additive white Gaussian noise (AWGN) channel model is used in our simulation to calculate the spectrum efficiency of paths and the network. As mentioned in Section 3.4.1, the PRU can determine the role of each AP, which can be either a sender, a relay, or a forwarder, in the AP network. The problem of categorizing the

Parameter	**Value**
PRU's coverage radius	500 m
Number of APs	100
AP distribution	Uniform
Number of senders	5
Number of forwarders	5
Number of disjoint paths (k)	1 - 5
Network SNR	30 - 40 dB
Pathloss exponent	2
Energy consumed per transmission	20 mJ
Average APs' remaining energy	1000 - 2000 mJ
Number of different network scenarios	1000

Table 3.1: Simulation settings for evaluating the proposed spectrum and energy efficient method. ©2014 IEEE.

nodes into senders, forwarders, and relays is outside the scope of this thesis. For the simulation, we choose five APs with the smallest amount of remaining energy to be senders and five APs with the highest amount of remaining energy to be forwarders. The packets from senders go through the AP network to the forwarders before arriving the PRU. Since we find k disjoint paths from each sender to the PRU to build a topology, the value of k is bounded by the number of forwarders, which is 5 in the simulation settings. The remaining energy of APs is randomly generated in the simulations. The experiment simulations are executed 1000 times, each with a different topology.

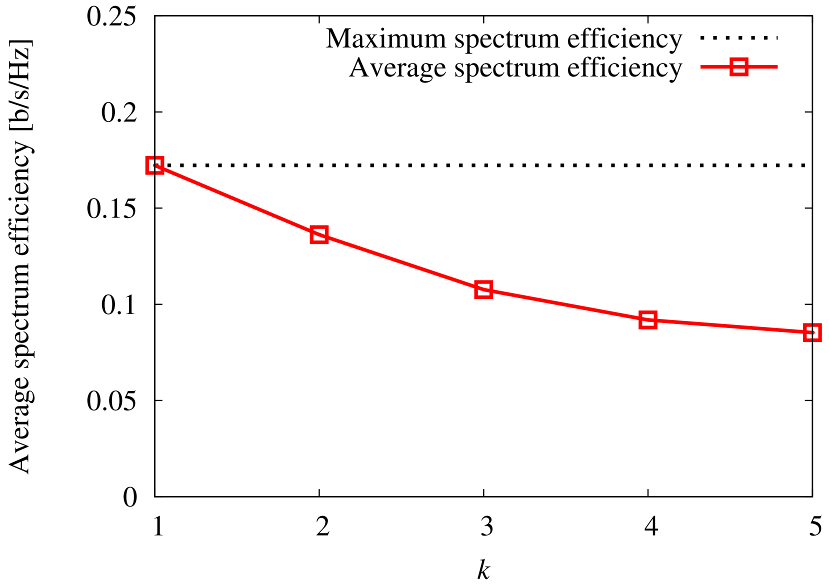

Figure 3.4: Average spectrum efficiency of the network ($\Re_G$) with different values of k. ©2014 IEEE.

3.7.2 The Relationship Among k, Spectrum Efficiency, Transmission Capability, and Spectrum-Energy Efficiency

Figure 3.4 shows the relationship between the value of k and the average spectrum efficiency of the network. Note that $k = 1$ means that we try to find only the most spectrum-efficient path from each sender to the PRU. Therefore, when $k = 1$, our result in terms of spectrum efficiency is the same as the maximum possible value. The figure demonstrates that when k increases, the average spectrum efficiency decreases. This is reasonable because when k increases, more paths with a lower value of spectrum efficiency will be added to the topology and will be used in the transmission division phase of the proposed method. This result validates the conclusion of Theorem 1.

Figure 3.5 illustrates how the transmission capability of the PRU-based PDCN changes with different values of k. As shown in the figure, the optimal spectrum-efficient method, which can be considered as the case $k = 1$, achieves only about

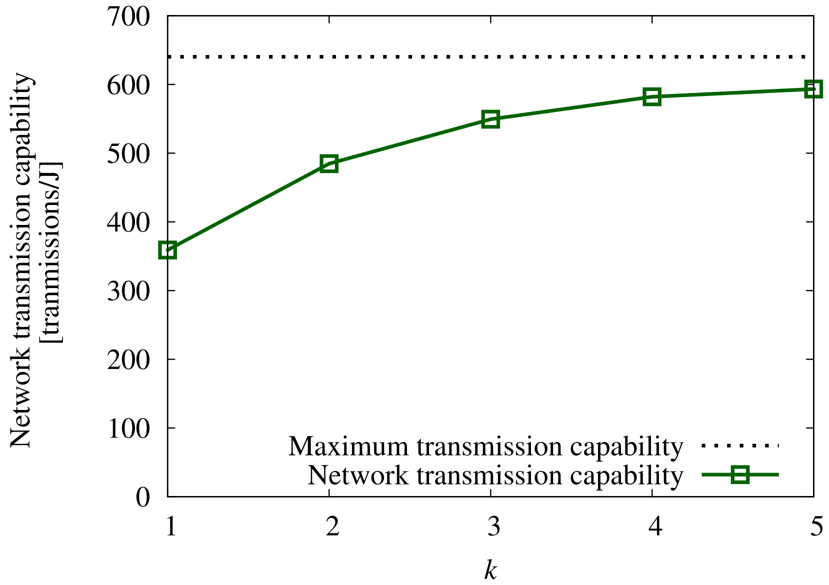

Figure 3.5: Transmission capability of the network (Γ_G) with different values of k. ©2014 IEEE.

50 percent of the maximum transmission capability. When k increases to 5, the network transmission capability becomes close to the maximum value. The result proves that the transmission capability can be improved when k increases. The reason is that when k increases, the number of paths participating in transferring data from the senders to the forwarders increases, which results in a higher total number of transmissions that can be conducted. This result validates the conclusion of Theorem 2.

Figure 3.4 and 3.5 prove that when k changes, the average spectrum efficiency and the transmission capability of the network change with opposite trends. Since k is a tuning factor, we can find the value of k that optimizes the trade-off relationship between spectrum efficiency and transmission capability.

Figure 3.6 demonstrates the change of the network spectrum-energy efficiency when the value of k changes in simulated topologies. The figure shows that the optimal value of k, which maximizes the spectrum-energy efficiency in the simulated

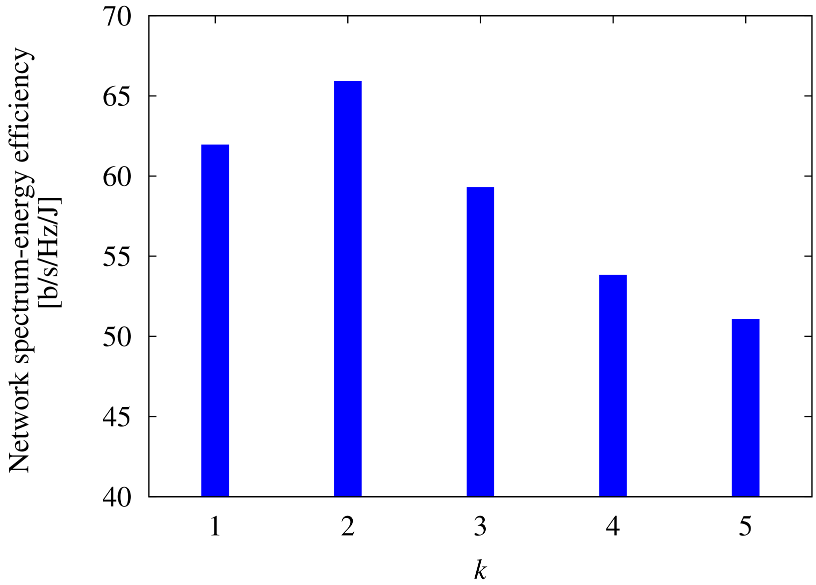

Figure 3.6: The optimal value of k to maximize spectrum-energy efficiency (Ω_G) in simulated topologies. ©2014 IEEE.

topologies, is 2. Note that the optimal value of k in this figure is the average value after simulating many topologies by using considered parameters. Different variations of the network can lead to different optimal values of k.

3.7.3 Evaluating the Improvement in Spectrum-Energy Efficiency

In order to conduct comparisons with traditional methods, i.e., the methods that optimize spectrum efficiency and transmission capability, respectively, we dynamically choose the value of k for our proposed method to optimize the spectrum-energy efficiency of each specific topology. Figure 3.7 demonstrates the change of network spectrum efficiency when the network SNR changes for our proposed method compared to the traditional methods. According to the results, the spectrum efficiency of our proposal is less than that of the optimal spectrum-efficient method but more than that of the optimal transmission capability method. This is because our pro-

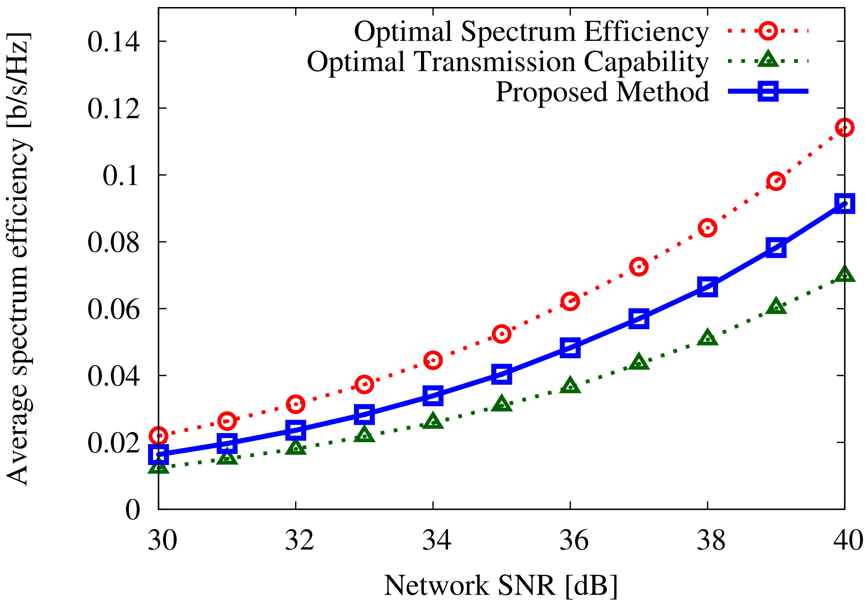

Figure 3.7: Average spectrum efficiency of the network ($\Re_G$) with different values of network SNR. ©2014 IEEE.

posed method employs the top k spectrum-efficient paths that have a lower average spectrum efficiency compared with the one optimal spectrum efficient path.

Figure 3.8 shows the network transmission capability of the network for different values of average remaining energy per node. The figure demonstrates that the transmission capability of proposed method is between the two traditional methods. The reason is that the optimal transmission capability method only considers transmission capability of nodes while our proposal considers both transmission capability and spectrum efficiency.

Regarding the most important metric in this research, spectrum-energy efficiency, Figure 3.9 indicates the performance of the proposed method compared to traditional methods. According to the result, our proposal achieves highest spectrum-energy efficiency compared to the optimal spectrum efficiency and optimal transmission capability methods.

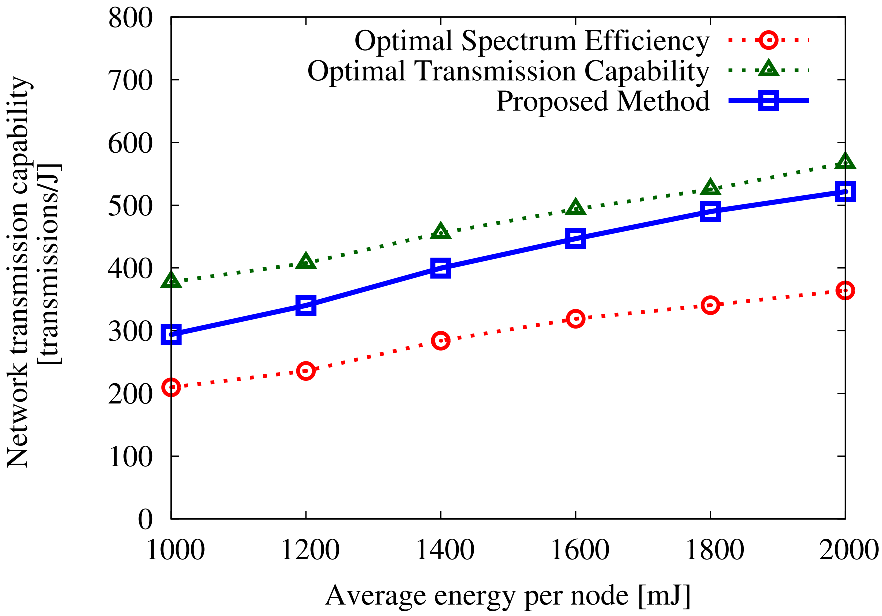

Figure 3.8: Transmission capability of the network (Γ_G) with different values of the average energy per node. ©2014 IEEE.

In conclusion, the results of the computer simulations show that our method can improve the spectrum-energy efficiency of the PRU-based PDCN by choosing top k spectrum-efficient paths.

3.8 Summary

The lack of spectrum and energy resources is a critical problem in PRU-base PDCNs, where the throughput requirement becomes very important. However, existing works in literature only consider the problems of spectrum efficiency and energy efficiency separately, in spite of the fact that they are conflicting objectives. Hence, we proposed a method to improve the utilization of both spectrum and energy resources in order to increase the performance of PRU-based PDCNs. The proposed method consists of two phases, namely, topology formation and transmission division. The topology formation phase constructs a topology composed of APs and

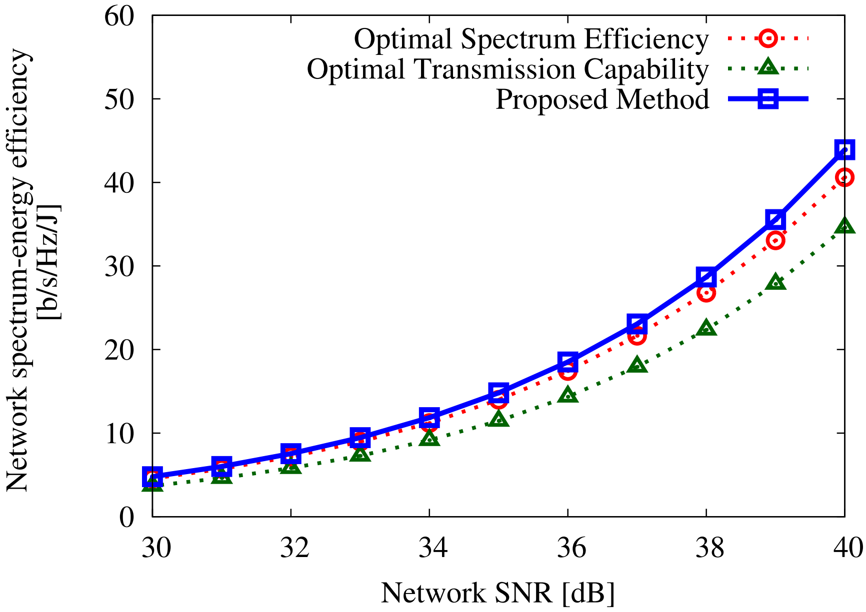

Figure 3.9: Network spectrum-energy efficiency (Ω_G) with different values of network SNR. ©2014 IEEE.

links that belong to the top k spectrum-efficient disjoint paths. The resulting topology is used by the transmission division phase to split the transmissions from the sender APs to the PRU through the forwarder APs. The splitting is conducted via the max flow algorithm with vertex capacities, in which the capacities are the transmission capabilities of the APs in the resulting topology. We defined a new metric, spectrum-energy efficiency, that reflects both spectrum and energy efficiencies of the network. Through analyses, we proved that we can dynamically choose the value of k to maximizes the spectrum-energy efficiency of a given topology. Our experimental results confirmed our analytical findings. Furthermore, simulations showed that by appropriately selecting the value of k, the proposal can improve the spectrum-energy efficiency compared to traditional approaches.

Chapter 4

Proposed Adaptive Topology Control for Different Scales of Post-Disaster Communication Networks

4.1 Introduction

In this chapter, we first discuss the requirement of using available resources in disaster affected areas for different scales of PDCNs based on PRUs. Here, a small scale PDCN consists of a single PRU and multiple portable APs, a large-scale PDCN consists of multiple PRUs. Therefore, a large scale PDCN can be considered as the integration of multiple small scale PDCNs. By considering the characteristics of PDCNs in different scales, we suggest the use of cooperative communications and cognitive radio for small scale and large scale PDCNs, respectively. For each of extensions of PDCNs, i.e., using cooperative communications or cognitive radio, we propose an adaptive topology control method to improve the system performance. This chapter will provide the details of the proposed topology control methods, which aim to adapt to different available resources in the disaster area.

Some parts of the content in this chapter are presented in the following papers, which were written by the author of this dissertation.

- Thuan Ngo, Hiroki Nishiyama, Nei Kato, Satoshi Kotabe, and Hiroshi Tohjo, "GHAR: Graph-based Hybrid Adaptive Routing for Cognitive Radio Based Disaster Response Networks," *2016 IEEE International Conference on Communications (ICC 2016)*, Kuala Lumpur, Malaysia, May 2016.
- Thuan Ngo, Hiroki Nishiyama, Nei Kato, Satoshi Kotabe, and Hiroshi Tohjo, "A Novel Graph-based Topology Control Cooperative Algorithm for Maximizing Throughput of Disaster Recovery Networks," *2016 IEEE 83rd Vehicular Technology Conference (VTC2016-Spring)*, Nanjing, China, May 2016.

4.2 The Requirement of Adaptive Topology Control for Different Scales of PDCNs

As discussed in Chapter 2, improving throughput and delay of PDCNs based on PRUs is one of the most important objectives of this research. The most challenging issue is that in order to make the PRUs more portable, the PRUs need to be compact with limited network facilities carrying to the disaster area. Therefore, the PRUs and the transported network equipment cannot provide significantly high performance. On the other hand, in the disaster area, there might be some resources that are still available. If we can utilize the available resources in the disaster site, we can further improve throughput and delay of the network. Figure 4.1 demonstrate this idea of extension.

PDCNs based on PRUs can have different scales. A small scale PDCN, which aims to provide a relatively small coverage area, consists of a single PRU and multiple portable APs. On the other hand, when the disaster affected area is too large, a large-scale PDCN consisting of multiple PRUs is required. In the large scale PDCN,

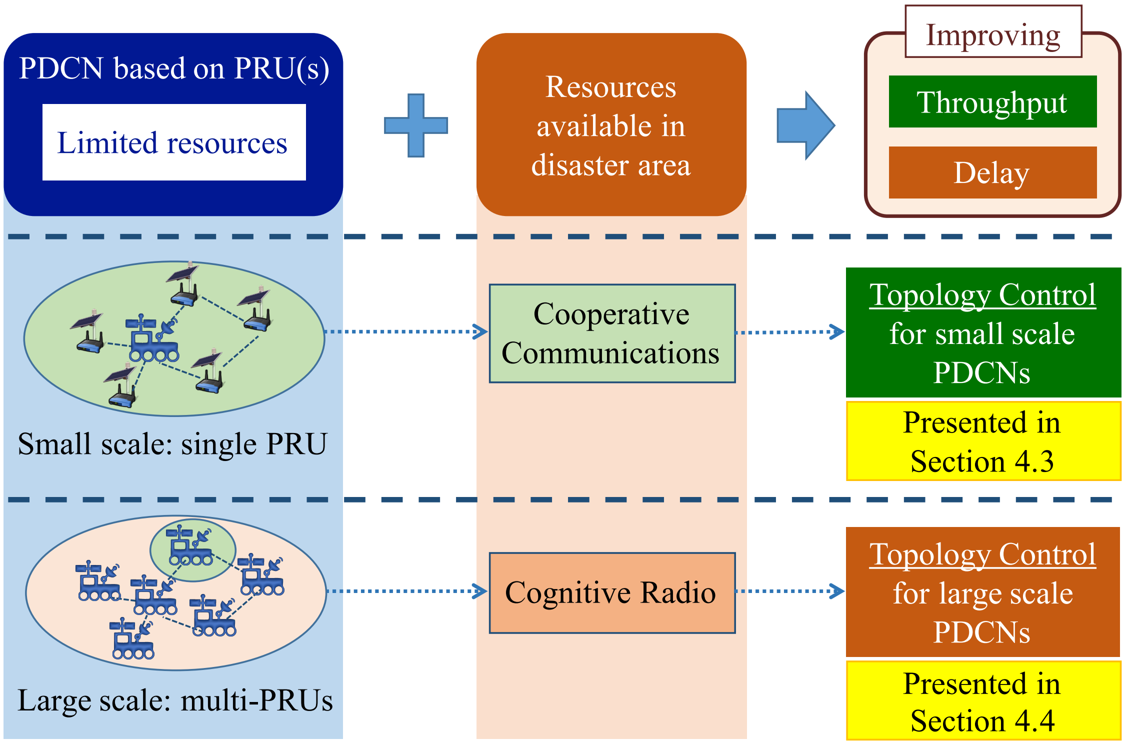

Figure 4.1: The possible adaptive extensions that can be made with the PDCNs based on PRUs. Cooperative Communications and Cognitive Radio can be used with different scales of the PDCNs. Sections 4.3 and 4.4 provide the extensions, which are the adaptive topology control methods for different scale of PDCNs.

there are multiple portable APs under each PRU. We can consider that one large scale PDCN consists of many small scale PDCNs.

In the next sections, we introduce two adaptive topology control methods for different scales of PDCNs to adapt with the varying available resources in the disaster area. With a small scale PDCN, we aim to utilize cooperative communications to improve the capacity in the backbone network composed of the portable APs. With a large scale PDCN, we aim to utilize cognitive radio to exploit available spectrum resources in the area. The two adaptive topology control methods for different scales of PDCNs are provided in Sections 4.3 and 4.4.

4.3 Proposed Adaptive Topology Control Method for Small Scale PDCNs Based on Cooperative Communications

In this section, we focus on utilizing cooperative communications to improve the capacity of the backbone network, which is constructed by the APs, in a small scale PDCN based on a single PRU. We also formulate the trade-off relationship between the gained throughput and the additional computation time. In order to exploit that trade-off relationship and provide a solution to maximize the gained throughput while guaranteeing a reasonable computation time, we propose a topology control method for the PDCN based on cooperative communications. In the next sub-sections, we will introduce the motivation of the research, the considered scenario, the network model, the proposed method, some analytical findings, and the performance evaluation of the proposed method.

4.3.1 Motivation and Challenges of Utilizing Cooperative Communications for Small Scale PDCNs

In order to construct a PDCN, many approaches have been introduced in the literature which include the use of advanced technologies such as satellite networks [33–36], unmanned aerial vehicles (UAVs) [37–40], and device to device networks [41–44]. Among the existing approaches, deploying portable APs in the disaster affected areas is considered as the most practical technique to construct PDCNs, which aim to provide wireless network access to the users [2, 10, 46]. The advantage of these portable APs includes their ability to operate on battery power, which can be replenished by energy harvesting technology using solar panels and/or other power generation methods. In addition, a portable AP can be connected to other APs using a mesh network paradigm to extend the service coverage. However, there are, indeed, shortcomings of deploying portable APs in such a fashion. For example, since the number of portable APs is likely to be limited and it is difficult to deploy many APs in the disaster area, the APs are anticipated to be generally located far from each other. As the result, the capacity of the backbone network constructed by the APs becomes significantly low. In other words, the inter-AP links do not have adequate capacity to deal with the high traffic originating from the users in each AP's local network. In order to improve the capacity of the backbone network constructed by the portable APs, we consider cooperative communications to be a promising technique. Cooperative communications have a noticeable feature in improving the network performance by exploiting each network node as both user and relay [47–50]. Therefore, in this work, we aim to utilize cooperative communications to improve the performance of the PDCN.

The idea of utilizing cooperative communications for the PDCN, which has the backbone network constructed by portable APs, is that some mobile terminals can act as both users and cooperative agents. Cooperative agents can relay packets from an AP to another AP to improve the throughput of the connection between the two APs. However, the problem is to answer the question: "How many cooperative agents should be used in the network?" If an excessive number of cooperative agents is used, it will lead to a significantly high additional computation time. On the other hand, when only a few cooperative agents are used, the gained throughput may not be sufficient. Therefore, finding the optimal number of cooperative agents for each inter-AP link constitutes the main challenge of our work.

4.3.2 Considered Scenario

The considered network, as illustrated in Figure 4.2, consists of portable APs and mobile terminals. Some mobile terminals can act as both users and cooperative agents that relay packets from an AP to another AP to achieve throughput gain of

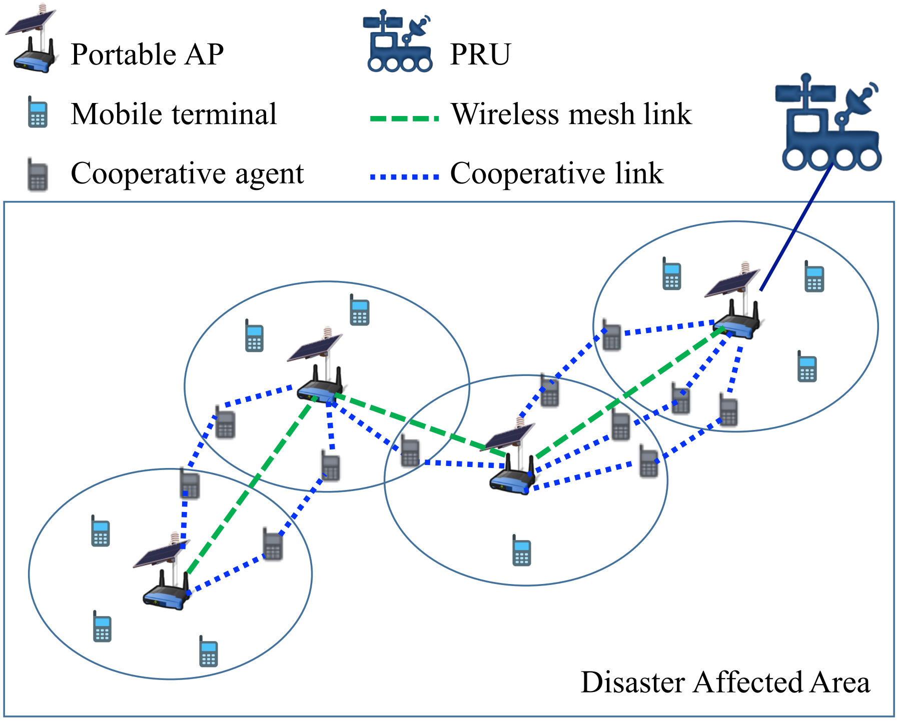

Figure 4.2: Considered PDCN constructed by portable APs and mobile terminals. Cooperative links connecting APs via mobile terminals, which also act as cooperative agents, are used to improve the throughput of inter-AP links. ©2016 IEEE.

the connection between the two APs. However, the problem is to determine how many cooperative agents should be used in the network. If an excessive number of cooperative agents is used, the computation time needed to utilize the cooperative links will be high. On the other hand, when only a few cooperative agents are used, the gained throughput may not be sufficient. Therefore, in order to effectively utilize cooperative communications for the PDCN, the problem in this trade-off relationship between the gained throughput and the additional computation time needs to be solved.

In order to address that problem, we propose a topology control method based on graph theory. The network is modeled as a graph with the nodes are all APs and mobile terminals. There is a logical link connecting two nodes if they are in the transmission range of each other. In order to form a topology, we first try to find k non-overlapping paths from each AP to the other AP in the backbone network. Then we use nodes and links of the resulting paths to construct the topology. The necessary cooperative agents for each inter-AP link can be found in the topology. Given a requirement of throughput gain, we can find the value of k to satisfy the requirement while minimizing the computation time for using cooperative communications.

4.3.3 Network Model

To model the considered network, we define a graph $G(V, E)$, where V is the set of nodes, i.e., either AP or mobile terminal, and E is the set of links connecting the nodes. In this section, we use index number i to represent the node i and a pair (i, j) to represent the link connecting nodes i and j.

Cooperative Agent Availability

In order to relay traffic among two APs, a mobile terminal needs to be in between the APs. However, due to its random mobility, there is a likelihood that the mobile terminal will move out of range of an AP, and hence cannot be the cooperative agent. We define ρ_i as the probability that the node i is available to be a cooperative agent during a given time period. The probability ρ_i is considered to be related to the moving speed. The higher the moving speed, the higher probability that the node moves out of the required area to be a cooperative agent. Because APs are also modeled as nodes in the graph, they have cooperative agent availability as well. Here, any AP j has $\rho_j = 1$.

Path

A path p_{sd} from node s to node d is defined as a list of nodes $n_1, n_2, ..., n_k$ where $n_1 = s$, $n_k = d$, and $(n_i, n_{i+1}) \in E$ with any i that satisfies $1 \leq i < k$. Let $\mathcal{A}$ denote the set of all portable APs. The set of all paths between any two APs, $\mathcal{P}$, is calculated as follows:

$$\mathcal{P} = \{p_{sd} : s \in \mathcal{A}, d \in \mathcal{A}\}. \tag{4.1}$$

4.3.4 Metrics

In order to evaluate the performance of the considered PDCN, we introduce the following metrics.

Cooperative Throughput Gain

The cooperative throughput gain of the connection between two APs s and d, $\mathcal{T}_{sd}$, is the throughput which can be gained by using cooperative agents between them.

$$\mathcal{T}_{sd} = \sum_{p_{sd} \in \mathcal{P}} \left(\left(\min_{i \in p_{sd}} t_i \right) \times \prod_{i \in p_{sd}} \rho_i \right), \tag{4.2}$$

where t_i is the gained throughput that node i can provide when it becomes a cooperative agent.

The total cooperative throughput gain of the network, Γ, is calculated as follows:

$$\Gamma = \sum_{(s,d) \in E} \mathcal{T}_{sd}. \tag{4.3}$$

Cooperative Computation Time

Cooperative computation time is the time needed to carry out the cooperative communications between two APs. The cooperative computation time for the connection between two APs s and d, Δ_{sd}, is calculated as follows:

$$\Delta_{sd} = \delta_0 + \sum_{p_{sd} \in \mathcal{P}} \left(\delta_0^t + \delta_0^r + \sum_{i \in p_{sd}} \delta_i \right), \tag{4.4}$$

where δ_0 is the basic computation time of using cooperative communications; δ_0^t and δ_0^r are the additional time needed for an AP to transmit and receive data, respectively, if a path is added between the two APs; and δ_i is the time needed to relay data via the cooperative agent i.

The total cooperative computation time of the network, Θ, is calculated as follows:

$$\Theta = \sum_{(s,d) \in E} \Delta_{sd}. \tag{4.5}$$

This metric is used to evaluate the additional computation time needed to utilize cooperative communications.

Cooperative Throughput Gain Speed

Let Γ and Θ denote the total cooperative throughput gain and the total cooperative computation time of the network, respectively. The cooperative throughput gain speed, $\mathcal{S}$, is calculated as follows:

$$\mathcal{S} = \frac{\Gamma}{\Theta}. \tag{4.6}$$

We considered $\mathcal{S}$ as the utility in this work.

4.3.5 Proposed Adaptive Topology Control Method for Small Scale PDCNs

In this section, we propose a topology control method exploiting cooperative communications. Our proposed method includes three phases. In the preliminary phase, the graph-based network model is constructed. In the second phase, the backbone network is formed by portable APs and the direct links connecting them. In the final phase, topology formation for cooperative communications is carried out for each pair of APs (connected by a direct link) by finding suitable cooperative agents to connect the APs via cooperative links.

Preliminary Phase

In this phase, we model the considered PDCN by using a graph $G(V, E)$, where V is the set of APs and mobile terminals. The set of links E consists of all logical links between nodes. There is a logical link between two nodes if they are inside the transmission range of each other. In this phase, the probability that a mobile terminal can be a cooperative agent to connect two APs is calculated based on the method introduced in [51], which uses node moving speed to calculate the probability that a node moves out of the transmission range of another node. The detail of this phase is presented in Procedure 3.

Backbone Network Formation

This phase is to find the topology of the backbone network constructed by only APs. In most of the cases, the number of APs is not too large and the locations of the APs are fixed, and thus, the topology can be manually constructed. The topology can be also dynamically set up, which is out the scope of our current work. In this work, we use $\mathcal{B}$ to denote the set of links in the backbone network topology.

Topology Formation for Cooperative Communications

This phase is based on the graph resulted in the preliminary phase and the topology derived in the backbone network formation phase. On one hand, set of the nodes of the modeled graph can be achieved in the preliminary phase. On the other hand,

Procedure 3 Preliminary Phase

Input: Locations of APs and mobile terminals, mobile terminals' moving speed.

Output: $G(V, E)$.

```
V ← ∅
E ← ∅
for any node i in the network do
    V ← V ∪ i
    range(i) ← transmission range of node i
    if node i is mobile terminal then
        ρ_i is calculated by using the method in [51]
    end if
end for
for any pair of nodes i and j do
    if d_ij < range(i) and d_ij < range(j) then
        E ← E ∪ (i, j)
    end if
end for
return G(V, E)
```

the pairs of APs that are connected by direct links can be pointed out by using the topology constructed in the backbone network formation phase. Due to the long distances between the APs, the direct links connecting APs generally do not have enough capacity to support the traffic from local networks where numerous mobile terminals connect to each AP. Therefore, in order to support the inter-AP links, mobile terminals can be the cooperative agents to relay more packets between two APs. Based on the information of inter-AP links achieved from the backbone network, the cooperative agents are decided based on Procedure 4. The idea of this procedure is that for each pair of APs m and n that has a direct link connecting the two APs, k best non-overlapping paths, in terms of throughput gain, from m to n via mobile terminals are calculated. The nodes inside those paths are the

Procedure 4 Topology Formation for Cooperative Communications

Input: $G(V, E)$, $\mathcal{B}(\hat{V}, \hat{E})$, and k.

Output: Cooperative communications network, $G^*(V^*, E^*)$.

$V^* \leftarrow \hat{V}$
$E^* \leftarrow \emptyset$
for each $(m, n) \in \mathcal{B}$ **do**
  $G'(V', E') \leftarrow G(V, E)$
  for $i \leftarrow 1$ to k **do**
    Find the ith best path p^i_{mn} in $G'(V', E')$
    $V' \leftarrow V' \setminus \{j : j \in V', j \in p^i_{mn}\}$
    $V^* \leftarrow V^* \cup \{j : j \in V', j \in p^i_{mn}\}$
    $E' \leftarrow E' \setminus \{(h, g) : (h, g) \in p^i_{mn}\}$
    $E^* \leftarrow E^* \cup \{(h, g) : (h, g) \in p^i_{mn}\}$
  end for
end for
return $G^*(V^*, E^*)$

selected as cooperative agents. The links connecting the cooperative agents are referred to as the cooperative links. Thus, the subgraph constructed by the APs, cooperative agents, and cooperative links is the desired topology of the cooperative communications network.

4.3.6 Analysis

In this section, we analyze the relationship between k and the metrics introduced in this work, cooperative throughput gain, cooperative computation time, and cooperative throughput gain speed. Using k as a tuning factor, we discuss how to select the value of k to maximize the performance of the proposed method.

Cooperative Throughput Gain and the Value of k

Theorem 3. *Given a network $G(V, E)$ and the value of k, $G^*(V^*, E^*)$ is the topology resulted after applying Procedure 4 on $G(V, E)$. The total cooperative throughput gain calculated on $G^*(E^*, V^*)$ monotonically increases when the value of k increases.*

Proof. Based on (4.2), the total cooperative throughput gain of the network, Γ, is calculated as follows:

$$\Gamma = \sum_{(s,d)\in\mathcal{B}} \mathcal{T}_{sd} \tag{4.7}$$

$$= \sum_{(s,d)\in\mathcal{B}} \sum_{i=1}^{k} \left(\left(\min_{j\in p^i_{sd}} t_j \right) \times \prod_{j\in p^i_{sd}} \rho_j \right), \tag{4.8}$$

where p^i_{sd} is the ith path connecting AP s with AP d. Since $0 \leq \rho_j \leq 1$ and $t_j > 0$, from (4.8) we can see that when k increases, Γ monotonically increases. ■

Cooperative Computation Time and the Value of k

Theorem 4. *Given a network $G(V, E)$ and the value of k, $G^*(V^*, E^*)$ is the topology resulted after applying Procedure 4 on $G(V, E)$. The total cooperative computation time calculated on $G^*(E^*, V^*)$ monotonically increases when the value of k increases.*

Proof. The total cooperative computation time, Θ, is calculated based on (4.4) as follows:

$$\Theta = \sum_{(s,d)\in\mathcal{B}} \Delta_{sd} \tag{4.9}$$

$$= \sum_{(s,d)\in\mathcal{B}} \left(\delta_0 + \sum_{i=1}^{k} \left(\delta^t_0 + \delta^r_0 + \sum_{j\in p^i_{sd}} \delta_j \right) \right). \tag{4.10}$$

This equation proves that when k increases, Θ monotonically increases because δ_0, δ^t_0, δ^r_0, and δ_j are greater than 0.

■

Choosing the Value of k

Let k_{max} be the value such that even if we make k greater than that, no more link is added to E^* in Procedure 4. Therefore, the value of k in Procedure 4 needs to satisfy $(1 \leq k \leq k_{max})$. As proved above, when k increases, both Γ and Θ monotonically increases. Therefore, based on (4.6), for each network scenario,we choose the value of k between 1 and k_{max} that maximizes the cooperative throughput gain speed, $\mathcal{S}$, which is considered as the utility.

4.3.7 Performance Evaluation

In order to validate the analytical findings and evaluate the performance of our proposed algorithm, extensive computer-based simulations have been conducted. Here, we present the simulation settings and the performance evaluation results.

Simulation Settings

The simulation settings are summarized in Table 4.2. In the area of 500 m $\times$ 500 m, 25 portable APs are deployed. The number of mobile terminals randomly deployed in the area is set to either 200, 500, or 1000. To simplify the relationship between the moving speed of mobile terminals and their availability to be cooperative agents, we randomly assign each mobile terminal i a value of ρ_i from 0 to 1. The transmission range of cooperative agents is set to 65 m. The throughput each mobile terminal can share for cooperative communications is varied from 1000 to 1500 kbps. The maximum number of agents per inter-AP link can be 1, 2, or 3. Each simulation is conducted with 1000 different scenarios generated randomly in order to calculate average values.

Parameter	Value
Simulation area	500 m × 500 m
Number of APs	25
Number of mobile terminals	200, 500, 1000
ρ_i of mobile terminal i	0.00 - 1.00
Throughput shared by cooperative agent i (t_i)	1000 - 1500 kb/s
Transmission range of cooperative agents	65 m
Number of different scenarios	1000
δ_0	1.0 s
δ_0^t and δ_0^r	0.2 s
δ_i for any cooperative agent i	0.1 s

Table 4.1: Simulation settings for evaluating the proposed topology control method for PDCNs based on cooperative communications. ©2016 IEEE.

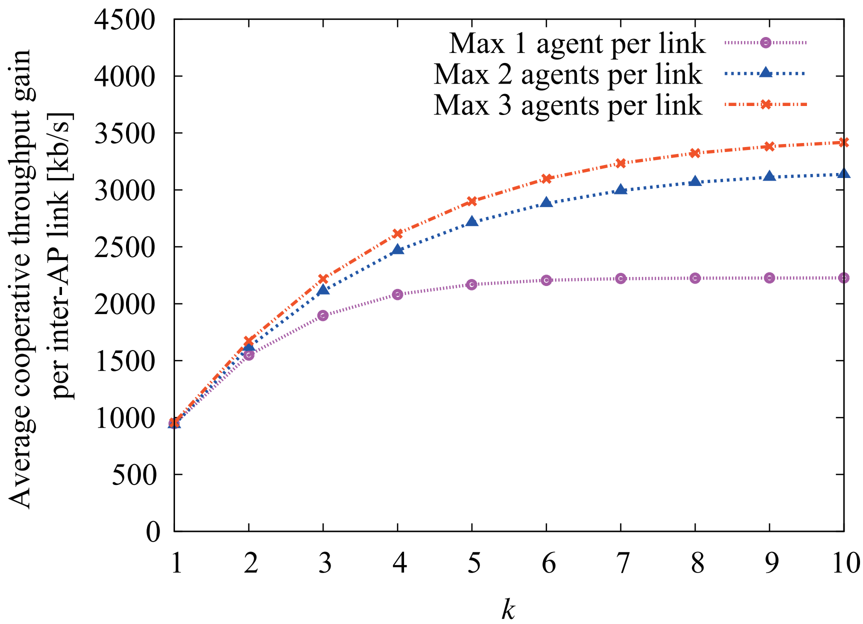

Figure 4.3: The average throughput gain per inter-AP link versus k. ©2016 IEEE.

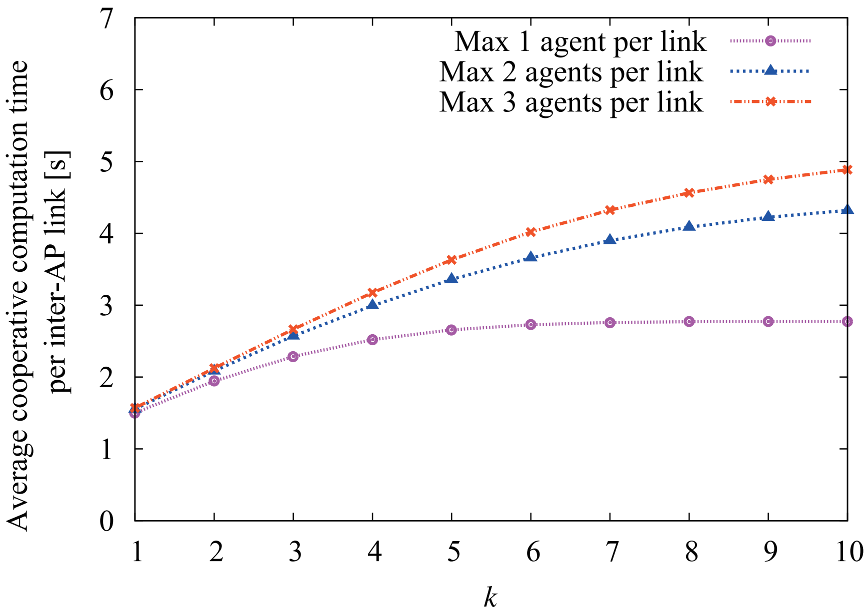

Figure 4.4: k versus the average computation time per inter-AP link. ©2016 IEEE.

The Relationship Between k and Throughput Gain

Figure 4.3 demonstrates the changes of the average expected throughput gain per inter-AP link when k changes. This metric takes into account both the probability that a mobile terminal is available to be a cooperative agent and the throughput it can share. The simulation results show that when k increases, the throughput gain for each inter-AP link also increases. Furthermore, the simulation is run with different maximum numbers of agents per inter-AP link, and the results illustrate that when we use multi-hop paradigm for cooperative agents, the throughput gain increases even faster.

The Relationship Between k and Cooperative Computation Time

Figure 4.4 shows the computation time needed to carry out the cooperative communications. The results validate that when k increases, the cooperative computation time increases. Also, when we accept a larger number of cooperative agents per

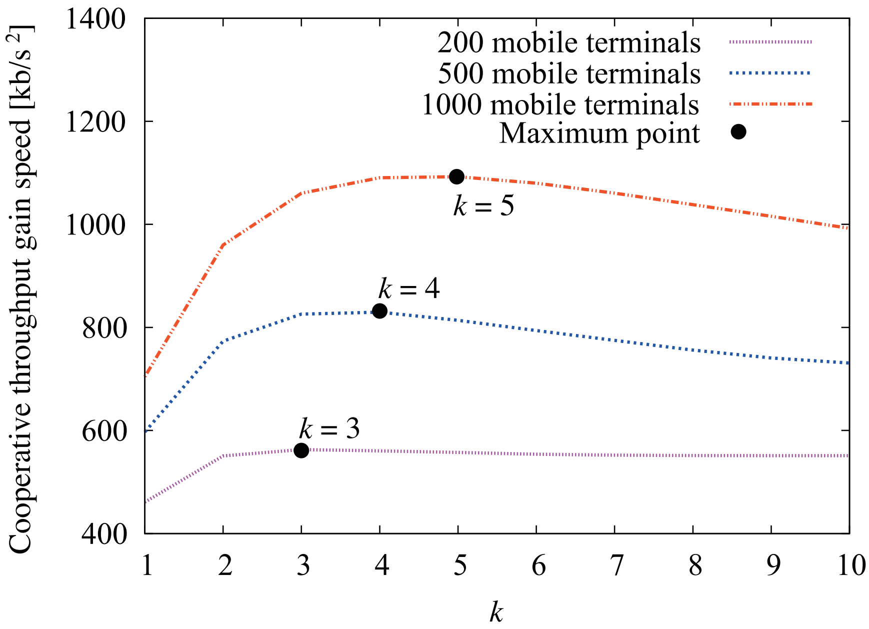

Figure 4.5: k versus the cooperative throughput gain speed. ©2016 IEEE.

multi-hop path connecting two APs, the increase of the cooperative computation time becomes more significant.

The Relationship Between k and Cooperative Throughput Gain Speed

Figure 4.5 illustrates the relationship between k and cooperative throughput gain speed, which is considered as the utility in this work. The figure shows that even though different network scenarios might lead to different results, there is a value of k that maximizes the utility.

These results prove that the trade-off relationship between cooperative throughput gain and cooperative computation time can be optimized by finding the value of k that maximizes the cooperative throughput gain speed. From the optimal value of k, we can decide the cooperative agents for use to improve the capacity of the backbone network constructed by APs.

4.4 Proposed Adaptive Topology Control for Large Scale PDCNs Based on Cognitive Radio

In this section, we focus on using all-spectrum cognitive radio for PDCNs to utilize all available spectrum in the area for improving the network performance. We consider a PDCN constructed by multiple PRUs where each PRU is a Cognitive Radio Base Station (CRBS). Each CRBS is equipped with multiple antennas to support different frequency bands available in the area. Based on the considered PDCN, we propose an adaptive topology control method. Our proposed method unites k non-overlapping minimum spanning trees to construct the topology for the use in routing. We provide an analysis on the relationship between k and the cognitive radio adaptability as well as the estimated routing computation time. We also provide an analysis how to select the value of k. Furthermore, extensive simulations are conducted to validate our analysis. Simulation results confirm the effectiveness of our proposal.

4.4.1 Motivation and Challenges of the Considered PDCNs Based on Cognitive Radio

Many research works have been conducted in the field of disaster response networks that which highlight the key requirements of disaster response networks including quality of service (QoS), robustness and reliability, coverage and mobility, rapid deployment, interoperability, spectrum agility, self-organization, and cost effectiveness [52–58]. Among the requirements, spectrum agility, which is the capability of operating in many different frequency bands, has not been well addressed in the existing works [52].

In order to fulfill the requirements of disaster response networks, which are also the requirements of large scale PDCNs, cognitive radio [59–61] should be considered because it has many advantages including heterogeneity, reconfigurability, self-organization, and interoperability with existing networks [62–65]. Particularly, the infrastructure in disaster areas could be destroyed or partially damaged, or can only operate intermittently, and thus, there will be a significant availability of spectrum for use by cognitive radio. The availability of spectrum depends on locations due to the difference in the degree of disaster effects. Furthermore, the available spectrum is also varying from time to time depending on the situations of the recovery process. Therefore, an effective and adaptive method that utilizes the available spectrum in the disaster affected area is required. In order to design such a method, we focus on the following issues.

- All-spectrum cognitive radio should be considered to utilize any available spectrum in the area.
- The availability of spectrum is varying due to the differences in time, location, and network operating.
- Only some places in the disaster area can have connectivity to the outside world, and thus, the method to route traffic in the area to such locations needs to be taken into account.

In order to effectively address these research issues, we consider a cognitive radio based PDCN as shown in Figure 4.6. Depending on the type of disasters, the scenarios in the affected areas will be different. For example, in Figure 4.6, both tsunami and earthquake occur. In the locations affected by the tsunami, the network base stations are destroyed. On the other hand, in earthquake affected areas, the infrastructure is damaged. After the disaster occurs, disaster victims cannot use network service due to the power outage and the lack of remaining network infrastructure. Therefore, many PRUs, which we refer to as Cognitive Radio Base

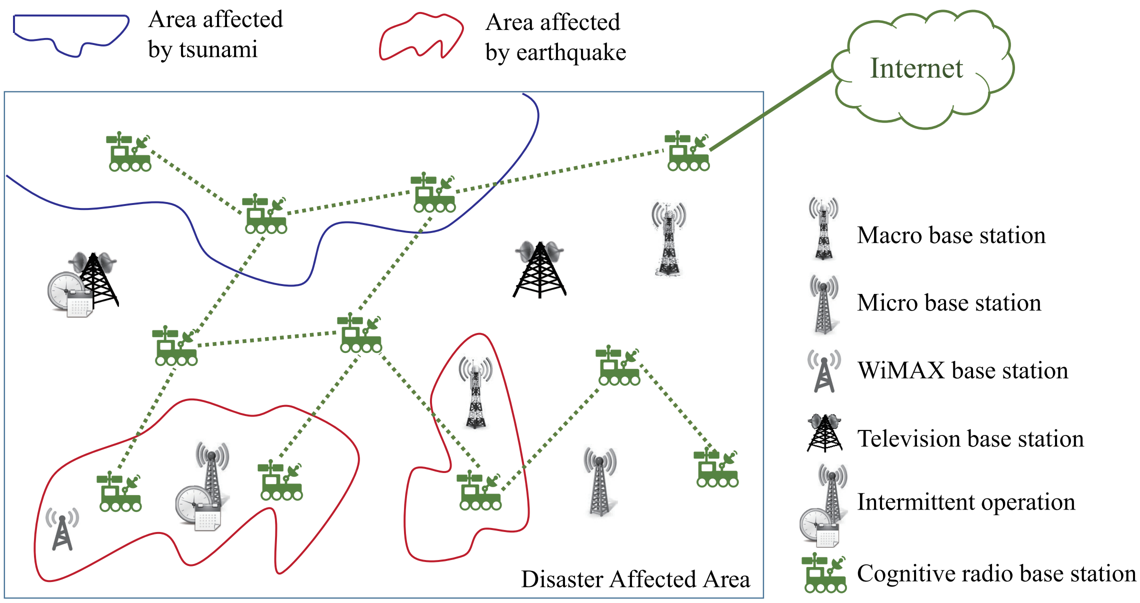

Figure 4.6: Considered large scale PDCN based on PRUs, where each PRU is a cognitive radio base station. ©2016 IEEE.

Stations (CRBSs), are deployed to the area to provide network communication services. Each CRBS is equipped with multiple antennas to support different frequency bands, such as cellular networks, WiMAX, television, and so forth. We assume that the CRBSs are agile and cost-efficient enough to be deployed with a relatively large amount in the disaster affected area.

However, there are many challenges that need to be resolved. We outline three main challenges for cognitive radio based PDCNs as follows.

Routing Unlike other types of networks, PDCNs have to face more difficulties due to the critical situation in disaster affected area. After a disaster occurs, many places in the area might be isolated in terms of the access to network services. Only a few locations can have connectivity to outside world, such as the locations located closely to a non-affected area, or the locations having facilities to connect to a network with very large coverage, e.g., satellite network [66,67] or wireless network in the sky [68]. Therefore, routing is very important to bring network connectivity and services to the whole area.

Adaptability This is always a challenge for cognitive radio networks. However, in the PDCNs scenarios, the challenge becomes even more critical due to the frequent change of available spectrum. In disaster areas, base stations and infrastructure can be inactive due to many reasons such as power outage, damage, safety shutdown, and so forth. It is not easy to predict when and how the infrastructure will recover because the situation is different case by case. Therefore, adaptability is one of the major challenges for designing a cognitive radio based PDCN that can adapt to different scenarios of disasters.

Computation Time The demand of using network service in disaster areas is always much higher than normal because the disaster victims will try to use the Internet to confirm the safety of their family, relatives, and friends, while the network infrastructure is usually damaged or destroyed. However, as mentioned above, only a few places in the area can have connectivity to outside area. Therefore, after a PDCN is deployed in the area, the routing computation time needs to be minimized to provide acceptable network services to users in the disaster area.

Furthermore, there is a trade-off relationship between cognitive radio adaptability and the routing computation time. If each CRBS has too many direct connections to other CRBSs in the area, the routing process will have a high computation time, causing a high delay in routing traffic. On the other hand, if each CRBS has too few neighbors, when the neighboring nodes cannot use the spectrum, the CRBS is unable to find the next hop to route its traffic, and thus, fails to adapt to the changing environment.

To overcome the challenges, we propose a topology control method to maximize the cognitive radio adaptability while considering the routing computation time.

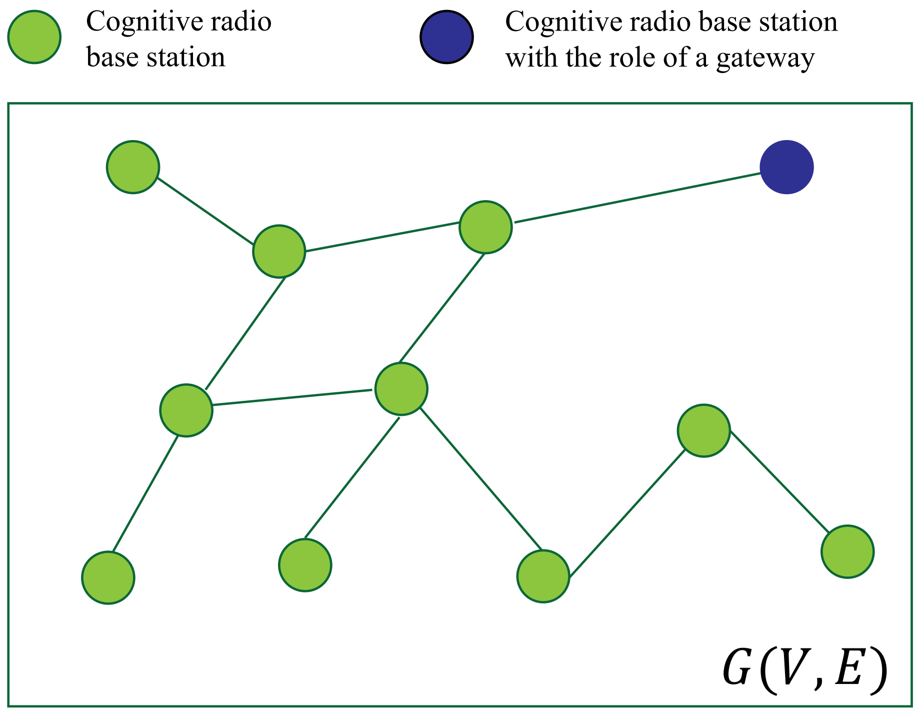

Figure 4.7: Modeled network of the considered PDCN based on cognitive radio base stations. ©2016 IEEE.

4.4.2 Considered Scenario

As shown in Figure 4.6, the considered PDCN is constructed by multiple CRBSs. Each CRBS is equipped with multiple antennas to support multiple frequency bands. The CRBSs are assumed to have the ability to switch between different antennas in order to adapt to the varying available spectrum in the area. Additionally, we assume that at a certain time, a central CRBS can be selected to carry out the topology formation task.

4.4.3 Network Model

For a cognitive radio based PDCN constructed by CRBSs, we define a graph $G(V, E)$, as shown in Figure 4.7, where V is the set of CRBSs and E is the set of links connecting the CRBSs. In this section, we use index number i to represent CRBS i

and a pair (i, j) to represent the link connecting CRBS i and CRBS j. The Euclidean distance between CRBS i and CRBS j is represented by d_{ij}.

Spectrum Availability at a Node

In the considered network, the central CRBS periodically senses the spectrum availability status and select the best frequency band for the PDCN to use for the next time period. We define ρ_i as the probability that the CRBS i can use the selected frequency band in its local area during the next time period.

Link Cost

The cost of the link (i, j), c_{ij}, is calculated base on ρ_i, ρ_j, and d_{ij} as follows:

$$c_{ij} = (1 - \rho_i \rho_j) d_{ij}. \tag{4.11}$$

Here, $(1 - \rho_i \rho_j)$ is the probability that at least one of the two CRBSs, i and j, cannot use the frequency band. In other words, $(1 - \rho_i \rho_j)$ is the probability that the link (i, j) will be disconnected during the next time period. d_{ij} is the distance between i and j. A longer distance between two CRBSs, the weaker the link connecting them. The reason behind the equation (4.11) is that by choosing the link, we accept the risk of having the link that might be broken or weaken due to the effect of spectrum availability and link distance. Link cost is higher when the values of ρ_i and ρ_j are smaller and/or d_{ij} is larger, and vice versa.

Neighbor Set

The set of neighbors of a CRBS i, $\mathcal{N}_i$, is defined as follows:

$$\mathcal{N}_i = \{j : j \in V, (i, j) \in E\}. \tag{4.12}$$

4.4.4 Metrics

In order to evaluate the performance of the considered PDCN, this research takes into account the following metrics.

Cognitive Radio Adaptability Index (CRAI)

We introduce CRAI of a CRBS as the index to measure the ability of the node in adapting to the change of available spectrum. CRAI of a node depends on the set of its neighbor nodes and the probability that each neighbor node can use the spectrum.

$$\mathcal{A}_i = \sum_{j \in \mathcal{N}_i} \rho_j, \tag{4.13}$$

where $\mathcal{A}_i$ is the CRAI of the CRBS i, and ρ_j is the probability that the CRBS j can use the spectrum at its local area.

Estimated Routing Computation Time

This metric estimates the computation time needed when the routing is carried out on the topology constructed after topology control process. It is directly affected by the number of nodes and links of the network. For example, if we use a routing algorithm having the complexity of $O(|E^*| + |V^*| \log |V^*|)$, we need to measure the absolute value of $|E^*| + |V^*| \log |V^*|$ to evaluate the computation time more precisely.

Average Node Degree

The degree of a node in a graph is calculated by the number of adjacent nodes. Therefore, the average node degree of the graph modeling the considered network, D, is calculated by the average number of neighbors per CRBS as follows:

$$D = \frac{1}{|V|} \sum_{i \in V} |\mathcal{N}_i|. \tag{4.14}$$

Average Number of Hops to Gateway

This metric is to estimate the number of hops from all CRBSs in the disaster area to the gateway CRBS in when the routing is conducted on the topology. The average number of hops to gateway, H, is calculated by the average number of hops in the resulted paths as follows:

$$H = \frac{1}{|V|} \sum_{i \in V} h_i, \tag{4.15}$$

where h_i is the smallest number of hops needed to route traffic from CRBS i to the gateway.

Utility

This metric can be considered as one of the most important metrics to evaluate the effectiveness of the network. We consider CRAI as the payoff we get after forming the topology, and the production of the average node degree and the average number of hops to the gateway as the estimated cost for routing conducted on the topology. The utility, $\mathcal{U}$, can be calculated as follows:

$$\mathcal{U} = \frac{\sum_{i \in V} \mathcal{A}_i}{D \times H}. \tag{4.16}$$

4.4.5 Proposed Adaptive Topology Control Method for Large Scale PDCNs Based on CRBSs

Our adaptive topology control method is carried out on the graph resulted by modeling the network composed of CRBSs. In our topology control method, the topology will be formed so that the redundant neighbors of each node, i.e., each CRBS, are removed before being used in routing. Therefore, we need to define which neighbor is redundant. The most straightforward consideration of a redundant neighbor of a node is that the neighbor will not be chosen to be the next hop in transmission, in

Procedure 5 Topology Formation

Input: $G(V, E)$, k.

Output: Topology for the routing, $G^*(V^*, E^*)$.

Calculate the cost of each link by using (4.11).
$G'(V', E') \leftarrow G(V, E)$
$V^* \leftarrow V'$
$E^* \leftarrow \emptyset$
for $i \leftarrow 1$ to k **do**
    Find the ith MST of $G'(V', E')$, $MST_i(V_i, E_i)$
    $E' \leftarrow E' \setminus E_i$
    $E^* \leftarrow E^* \cup E_i$
end for
return $G^*(V^*, E^*)$

any case. In order to carry out the process of removing redundant neighbors, we design a method to keep at least k neighbors for each node while the chosen neighbors have a high probability to be the next hop of the node in transmissions. k is a tuning factor that we can use to adjust the number of links in the topology. In order to keep the best neighbors of each node in terms of minimizing the total link cost, we extend the traditional minimum spanning tree (MST) algorithm [69] by using the equation (4.11) for calculating weights of links. Note that the traditional MST uses the only Euclidean distance between two nodes of a link as the link weight, we also consider the probability that each node can be used for transmissions. In order to guarantee that each node has at least k neighbors, we find k non-overlapping MSTs of the graph and combine them to construct the topology. As shown in Procedure 5, in each iteration i, the ith MST of the graph, $MST_i(V_i, E_i)$ is found. After that, the links in MST_i, E_i, are removed from the original graph and added to the topology. By doing this process, the MSTs are guaranteed to be non-overlapped.

The proposed method is considered "adaptive" because it uses the spectrum availability at the nodes to calculate weights of the links and cognitive radio adaptability index to calculate the utility. Aiming to maximize the utility, we can find the most suitable value of k, the tuning factor, to adapt to different network scenarios.

4.4.6 Analysis

Here, we analyze the relationship between k and the metrics introduced in subsection 4.4.4. Base on the analysis, we discuss the selection of the value of k that maximizes the performance of the proposal.

The Relationship Between k and Cognitive Radio Adaptability Index

Theorem 5. *Given a network $G(V, E)$ and the value of k. $G^*(V^*, E^*)$ is the topology resulted by applying Procedure 5 on $G(V, E)$. The average CRAI of the nodes in the topology $G^*(V^*, E^*)$ monotonically increases when the value of k increases.*

Proof. Based on (4.13), the average CRAI, $\mathcal{A}_{ave}$, of the nodes in the topology $G^*(V^*, E^*)$ is calculated as follows:

$$\mathcal{A}_{ave} = \frac{1}{|V^*|} \sum_{i \in V^*} \sum_{j \in \mathcal{N}_i} \rho_j. \tag{4.17}$$

As shown in Procedure 5, when k increases, $|V^*|$ does not change and always equals to $|V|$. The change in the constructed topology is only in E^*. The increase of k leads to the increase in the neighbors of each node i, $\mathcal{N}_i$. Thus, $\sum_{j \in \mathcal{N}_i} \rho_j$ increases, and finally, $\mathcal{A}_{ave}$ increases. ■

The Relationship Between k and the Routing Computation Time

Theorem 6. *Given a network $G(V, E)$ and the value of k. $G^*(V^*, E^*)$ is the topology resulted by applying Procedure 5 on $G(V, E)$. The computation time of routing conducted on G^* monotonically increases when the value of k increases.*

Proof. In Procedure 5, when k is increased by 1, the number of adjacent nodes for each node in the topology will be increased by at least 1. For routing based on the topology, each node needs to try with at least one more neighbor as the next hop. Hence, the routing computation time will qualitatively increase with the increase of k. The increase in computation time depends on the routing algorithm. For example, Dijkstra algorithm [70], the most well-known algorithm for finding shortest paths in graphs, has the complexity of $O(|E^*| + |V^*| \log |V^*|)$. In Procedure 5, when k increases, more links are added to E^* while V^* is kept the same. Therefore, the value of $|E^*| + |V^*| \log |V^*|$ monotonically increases when the value of k increases. ■

The Relationship Between k and the Average Number of Hops to Gateway

Theorem 7. *Given a network $G(V, E)$ and the value of k. $G^*(V^*, E^*)$ is the topology resulted by applying Procedure 5 on $G(V, E)$. If the shortest paths in terms of hop count are considered, the average number of hops from nodes on the topology $G^*(V^*, E^*)$ to the gateway monotonically decreases when the value of k increases.*

Proof. In Procedure 5, when k increases, more links are added to E^* while V^* is kept the same. Therefore, there will be more possible paths on the topology from any node to the gateway. When we consider shortest paths in terms of hop count, with the increase of k, the new shortest paths will have less hop count than before, or at least keep the same value. Therefore, the average number of hops from CRBSs to the gateway CRBS, H, monotonically decreases when the value of k increases. ■

Selecting the Value of k

As proven above, when k increases, the average CRAI increases, and thus, the total CRAI of the network, $\sum_{i \in V} \mathcal{A}_i$, also increases. Furthermore, the increase of k leads to the increase of the average node degree, D, and the decrease of the average number of hops to the gateway, H. Therefore, according to (4.16), there will be a value of k that maximizes the utility, $\mathcal{U}$. Note that in every specific network scenario, the value of k has an upper bound, which is the largest node degree in the modeled graph. Therefore, depending on the network scenario, the chosen value for the tuning factor, k, should be the value between 1 and the upper bound that maximizes the utility.

4.4.7 Performance Evaluation

In order to validate the analytical findings and evaluate the performance of the proposed method, we conducted extensive simulations. In this section, the simulation setup and the evaluation results are presented.

Simulation Setup

Table 4.2 presents the settings of our simulations. In the area of 10 km $\times$ 10 km, the CRBSs are randomly deployed. The number of CRBSs is set to three different values, 40, 60, and 80, in order to evaluate the effect of CRBS density on the performance of the proposal. The probability that a CRBS i can cognitively use the spectrum in its local area, ρ_i, is randomly assigned from 0.0 to 1.0. The transmission range of CRBSs is set to 3 km. 300 different network scenarios are generated to calculate the average results.

The Relationship Between k and CRAI

Figure 4.8 shows the relationship between the average CRAI and the value of k. The results demonstrate that when k increases, the average CRAI of the network also increases, which validates the conclusion of Theorem 5. The figure also shows the behavior of CRAI when the number of CRBSs changes. When k is small, e.g., k equals to 1 or 2, there is no significant change in the average CRAI when the number

Parameter	**Value**
Simulation area	10 km × 10 km
Number of CRBSs	40, 60, 80
ρ_i of CRBS i	0.0 - 1.0
Transmission range of CRBSs	3 km
Number of different scenarios	300

Table 4.2: Simulation settings for evaluating the proposed topology control method for PDCNs based on cognitive radio. ©2016 IEEE.

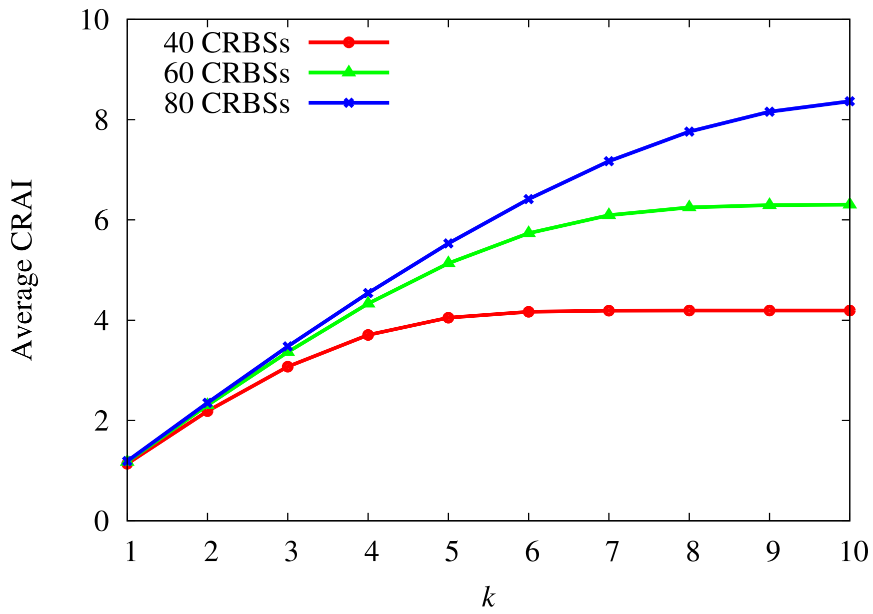

Figure 4.8: k versus the average CRAI. ©2016 IEEE.

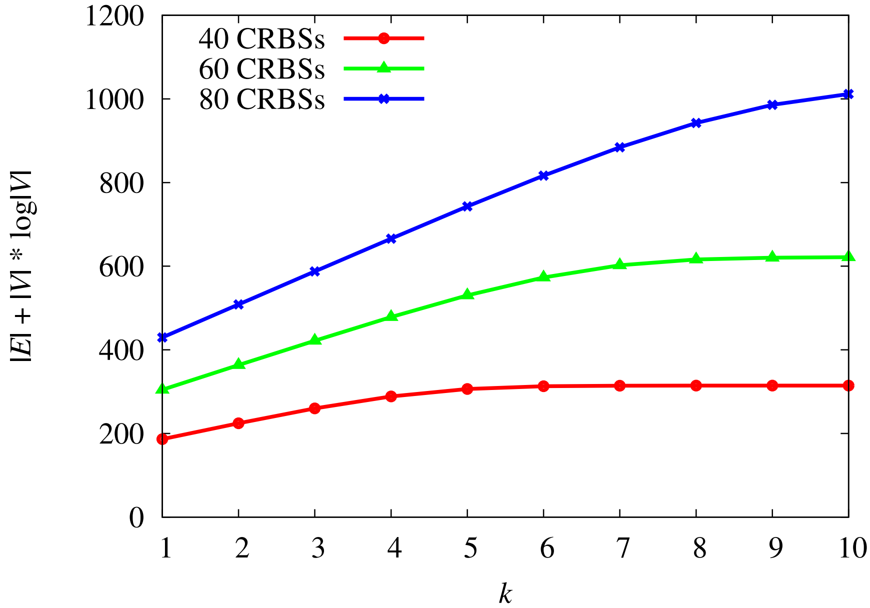

Figure 4.9: k versus the estimated routing computation time in case the Dijkstra algorithm is used for routing. ©2016 IEEE.

of CRBSs changes. However, when k becomes larger, i.e., more than 3, the effect of the number of CRBSs on the value of CRAI becomes more noticeable. The larger number of CRBSs, the higher value of CRAI. This is because the increase of k only makes changes to the topology if there are still links that can be further added to the topology.

The Relationship Between k and the Estimated Routing Computation Time

In order to estimate the computation time of routing with the resulted topology, we evaluate the computation time of finding shortest paths on the topology by using Dijkstra algorithm. Dijkstra algorithm on a graph $G(V, E)$ can be implemented with the computation time of $O(|E| + |V| \log |V|)$. Figure 4.9 demonstrates the absolute value of $|E| + |V| \log |V|$ with the topology resulted by using our simulations. The results show that when k increases, the computation time also increases. This

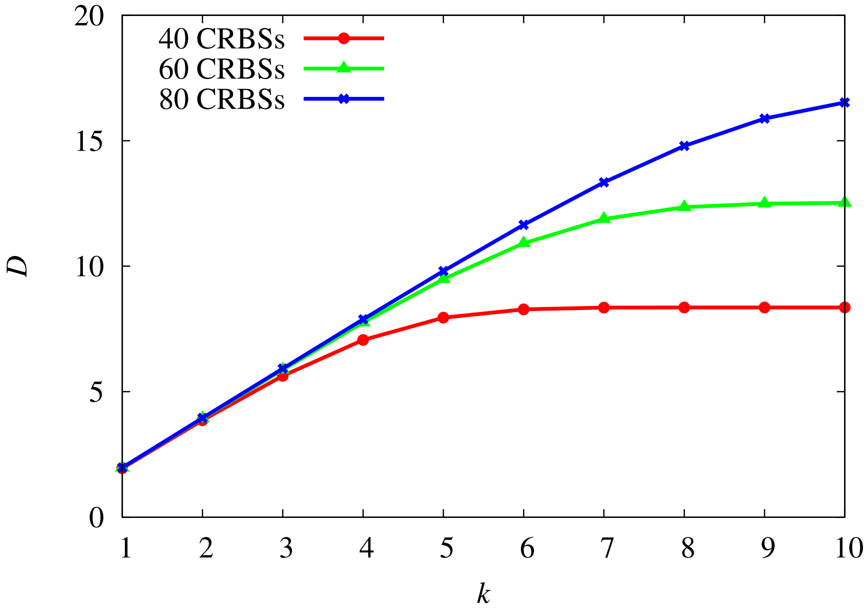

Figure 4.10: k versus the average node degree, D. ©2016 IEEE.

proves the conclusion in Theorem 6. The figure also shows that larger number of CRBSs leads to larger computation time. It is reasonable because a higher density of network nodes cause the increase in the number of each node's neighbors.

k with the Average Node Degree and the Average Number of Hops to Gateway

Figures 4.10 and 4.11 show that when k increases, the average node degree, D, increases while the average number of hops to gateway, H, decreases. Therefore, Theorem 7 is also validated. Since D can be considered as the average number of tries that a node needs to do to find the next hop, and H is the average number of hops required to relay a packet from a source to the gateway, $D \times H$ can be the approximate number of tries needed for finding routes to the gateway. Therefore, we also find the relationship between $D \times H$ with k, as shown in Figure 4.12, in order to approximately evaluate the cost of routing process on the resulted topology.

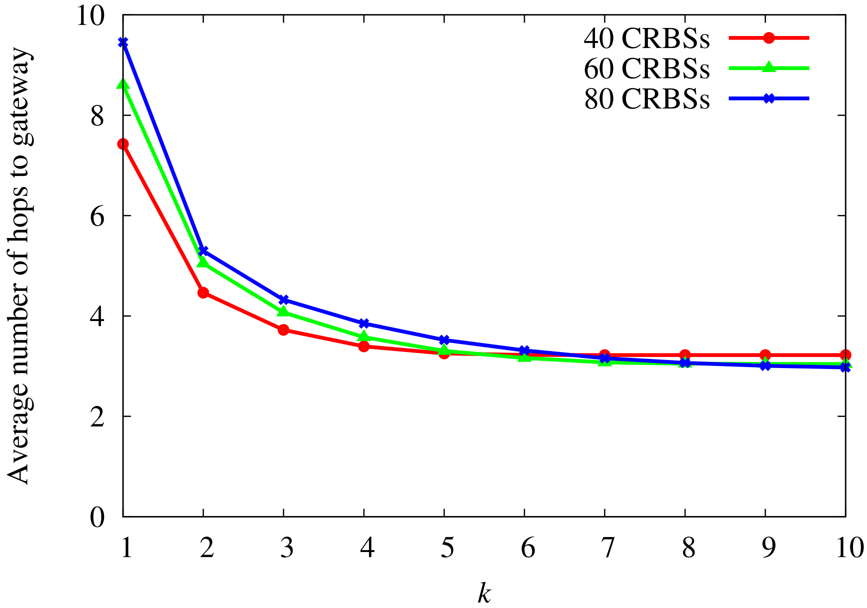

Figure 4.11: k versus the average number of hops to gateway, H. ©2016 IEEE.

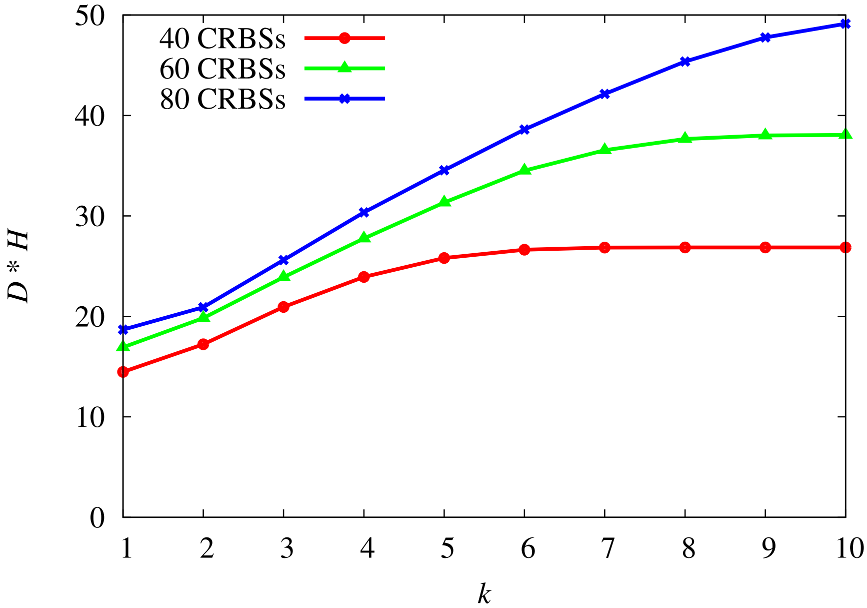

Figure 4.12: k versus $D \times H$. ©2016 IEEE.

The results show that $D \times H$ increases with the increase of k and becomes larger with larger number of CRBSs. This is reasonable because a larger value of k and/or a larger number of CRBSs will make the network more complex, and thus, more difficult for routing.

The Relationship Between k and the Utility

The relationship between k and the utility, $\mathcal{U}$, is presented in Figure 4.13, with different network scenarios. Figures 4.13(a) and 4.13(b) demonstrate an example of having different optimal values of k for maximizing the utility when the network scenario is generated randomly with different seeds. It shows that the optimal value of k does exist but might be different depending on network scenarios. Figure 4.13(c) illustrates the distribution of the optimal values of k and the optimal points when 300 different scenarios are simulated with different number of CRBSs. The figure shows that when the number of CRBSs becomes higher, the optimal values of k tends to become larger. However, the figure also demonstrates that even with the same number of CRBSs, the optimal values of k can be different with different scenarios.

4.5 Summary

In this chapter, we introduced two adaptive topology control methods for different scales of PDCNs to adapt to the changes in available resources at the disaster site. With small scale PDCNs, we utilized cooperative communications to improve the capacity in the backbone network composed of the portable APs. With large scale PDCNs, we utilized cognitive radio to exploit available resources in the area.

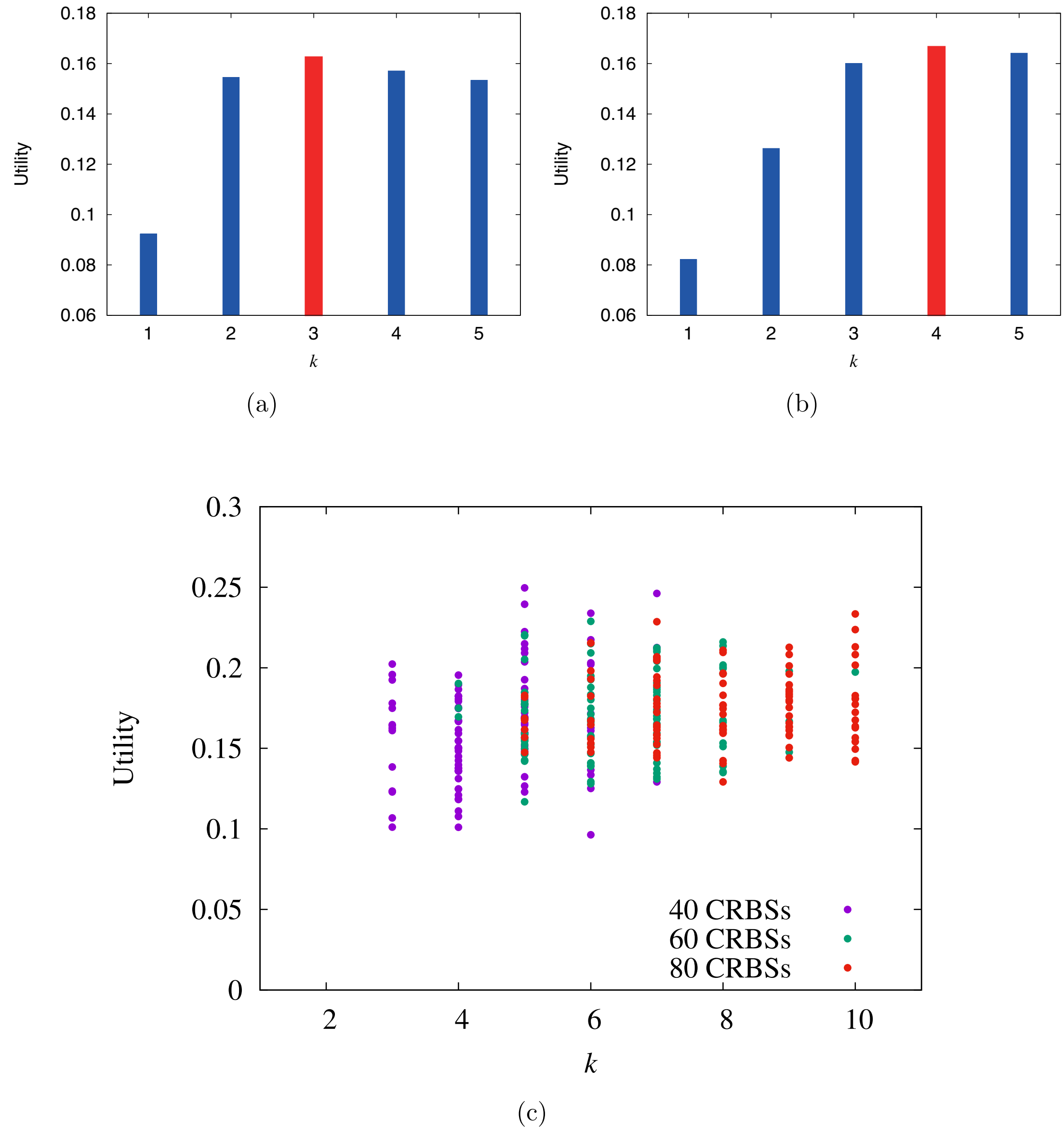

Figure 4.13: Different network scenarios lead to different optimal values of k, for example, optimal k equals to 3 in (a) and 4 in (b). (c) The distribution of optimal values of k with different network scenarios and different number of CRBSs. ©2016 IEEE.

Adaptive topology control for small scale PDCNs based on cooperative communications

With small scale PDCNs, we addressed the problem that the low capacity in the backbone network constructed by APs cannot satisfy the high demand from the users in the APs' local networks. Our proposed method utilizes cooperative communications to gain the throughput of inter-AP links. The proposal aims to find k best non-overlapping paths, in terms of throughput gain, via cooperative agents to connect any pair of APs. We provided an analysis on the effect of k on cooperative throughput gain, cooperative computation time, and cooperative throughput gain speed, which is considered as the utility. We also proved that there is a value of k that maximizes the utility, and thus, optimizes the trade-off relationship between throughput gain and computation time. Extensive simulations were conducted and their results demonstrated that the proposed algorithm can help to maximize the throughput gain while maintaining the computation time within a reasonable level.

Adaptive topology control for large scale PDCNs based on cognitive radio

With large scale PDCNs, we focused on all-spectrum cognitive radio based PDCNs to fulfill the spectrum agility requirement. The considered PDCN is constructed by CRBSs, deployed in the disaster affected area. Each CRBS is equipped with multiple antennas to support different frequency bands available in the area. All CRBSs in the network route their traffic to the gateway CRBS having connectivity to the outside area. On the considered PDCN, we proposed an adaptive topology control method that unites k non-overlapping MSTs on the original network to construct the topology. An analysis on the relationship between k and the cognitive radio adaptability as well as the computation time of routing process was provided. Additionally, extensive simulations were conducted to verify our analysis and the simulation results demonstrated the effectiveness of our proposal.

Chapter 5

Post-Disaster Communication Network Application Performance Enhancement

5.1 Introduction

In this chapter, we focus on the applications of the PDCNs based on PRUs. Among the possible applications of PDCNs, safety confirmation can be considered as one of the most important services. With an embedded image database, a single PRU can provide the safety confirmation application that allows users to search for the images that look similar to the people they are looking for. However, a network with multiple PRUs may increase the image searching time of the safety confirmation application because the image databases are distributed and the capacity of the backbone wireless network constructed by connecting the PRUs is also limited. Therefore, in this chapter, we introduce a safety confirmation method that guarantees the minimum searching time of users. The method includes four phases, namely resizing and storing images, broadcasting small-size images, routing, and deciding image size to deliver to users. Based on mathematical analysis using the absorbing Markov chain, we estimate the expected searching time for each different size of images and choose the most appropriate size.

This chapter will discuss the applications of PDCNs based on multiple PRUs, introduce our proposed method for the safety confirmation application using image database, and present our proposed Markov-based analysis to optimize the performance of the application.

Some parts of the content in this chapter are presented in the following paper, which was written by the author of this dissertation.

- T. Ngo, H. Nishiyama, N. Kato, T. Sakano, and A. Takahara,"An Efficient Safety Confirmation Method Using Image Database in Multiple-MDRU-Based Disaster Recovery Network," *IEEE Systems Journal*, Accepted.

5.2 Applications of PDCNs Based on Multiple PRUs and Relevant Research Works

In recent years, industrial organizations working on the PDCNs based on PRUs have focused on developing the compact size of the PRUs. For example, AT&T and NTT have developed van-type PRUs, which make the multiple PRUs based PDCNs practical. In the PDCNs consisting of multiple PRUs, the PRUs should not work individually. This is because there may be only a few PRUs that have a connection to the outside area. The other PRUs need to rely on those to communicate with the outside world. Also, depending on PRUs, the available resources such as energy, spectrum, devices, and so forth, might be different. Therefore, each PRUs should corporate with others to provide better services in overall. Furthermore, the deployment of PRUs in disaster area should be taken into account. In [71], the authors provided a performance evaluation of multiple PRUs based wireless mesh network by using computer-based simulations. The results show that different deployment of PRUs might significantly affect the overall performance of the PDCN composed by the PRUs. In addition, when the multiple PRUs are used to construct a wireless network, routing is one of the most important research issues. Some existing approaches focus on improving spectrum efficiency [24, 72] while some others aim to improve energy efficiency [73, 74]. In order to consider both spectrum and energy efficiencies, the multiple PRUs based PDCNs can utilize the spectrum and energy-efficient routing approach introduced in [75].

Regarding the applications of PDCNs based on multiple PRUs, text messages, Voice over IP calls, and multimedia delivery are the main services which can be provided. In order to provide multimedia services, many research issues have been considered in the literature. Different multimedia applications and target networks need different approaches for solving the issues. Zhou and Chao focus on the security issue of multimedia service in Internet of Things [76]. They design a security framework using the classification of multimedia traffic. They also provide the design rule and strategy that take into account the trade-off relationship between system flexibility and efficiency to make the architecture more efficient. On the other hand, the authors of [77] focus on the delay-sensitive multimedia applications for resource-limited heterogeneous networks. By considering the multimedia forensics, network adaptation, and scheduling, they propose a method for allocating the available network resources to fulfill the requirements of multimedia forensics service while satisfying the application's delay constraints.

In this work, we focus on the disaster relief application using the image database installed in the PRUs and aim to provide a safety confirmation application for people in/outside the disaster areas. The routing method proposed in [75] and the traditional approaches for resizing and compressing images such as those in [78–80] are utilized. The proposed algorithm is based on an analysis using absorbing Markov chain, which is widely used in many different fields [81–86].

5.3 A Typical PDCN Application Example: Safety Confirmation Application Using Image Database

5.3.1 Image Database and the Safety Confirmation Application Using a Single PRU

The demand for safety confirmation always becomes significantly high after the occurrence of any disaster. However, if the cellular network infrastructure is damaged by the disaster, people will not be able to make calls or send messages to others. In that case, if the PDCN can provide the safety confirmation application using image database stored at the PRU, it will be very useful for users. In fact, the works in [2, 21] have considered using image database in their disaster recovery network, where each PRU is equipped with an image database to provide image-based applications for the PDCN.

The basic application of the image database is to provide a means of uploading and downloading photos for people who are able to connect to the PRU. Users in the disaster affected area can upload photos of people, infrastructure, evacuation centers, and so forth, to the image storage. Government and people from the outside area later can browse the photos and achieve the updated information of the disaster area.

The image storage equipped with the PRU also offers a useful application, which is the safety confirmation application as illustrated in Figure 5.1. The application mainly focuses on the photos of people. Together with uploading the photos, the other information such as name, gender, age, residing location, and so forth can be registered. There is a database to store the photos and information uploaded to the PRU. Any user having access to the PRU can do carry out the registration. For instance, rescuers can take the photos of the disaster victims and register them to the database. Evacuees can directly register their photos and their personal information

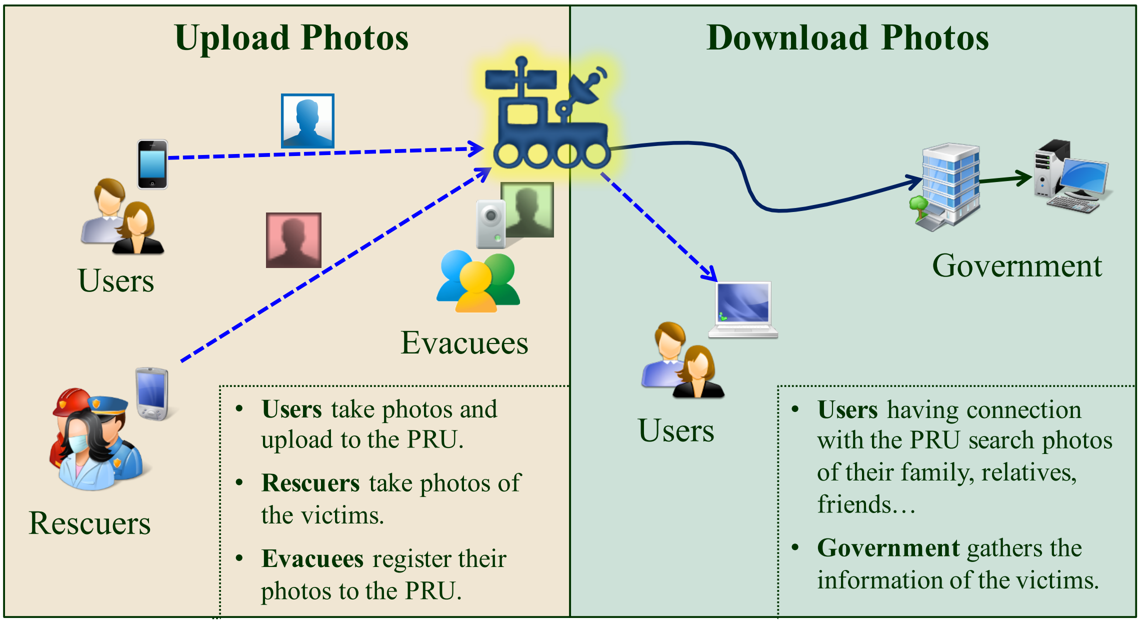

Figure 5.1: Safety confirmation application using image database in a single PRU based PDCN. ©2015 IEEE.

to the PRU. The image searching functionality can be provided by the PRU using the image database. By using this application, people from the outside area are able to search the photos of their family, relatives, friends, and so forth, who are in the disaster area. The government can also use this application to gather the updated information of the victims and evacuees in the disaster area to make an appropriate decision for supporting the people and managing the situation.

5.3.2 Challenges of Safety Confirmation Application in Multiple PRUs Scenario

The main challenges for the safety confirmation application in the multiple PRUs scenario are illustrated in Figure 5.2. The most important challenge is that, unlike the single PRU scenario, the image databases are distributed among the PRUs in the multiple PRUs based PDCN. For example, in the figure, some rescuers can upload photos to the PRU number 1 while some evacuees register their photos to

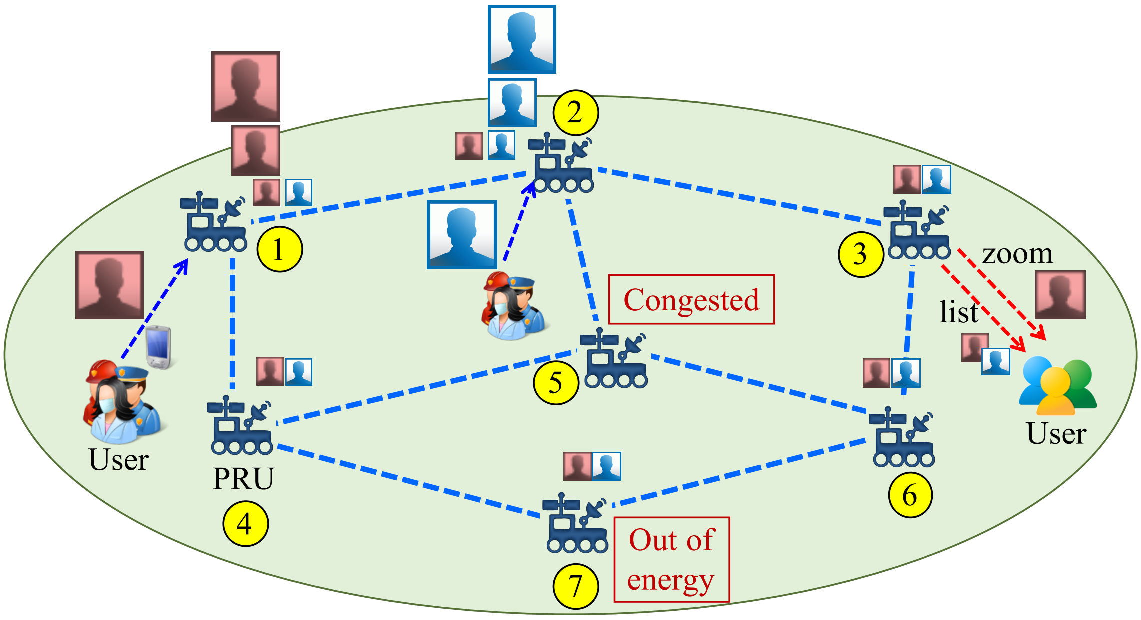

Figure 5.2: Challenges of the safety confirmation application using image database in the multiple PRUs scenario: synchronization of distributed image databases, congestion, lack of energy, routing, etc. ©2015 IEEE.

the PRU number 2. Therefore, we first need to solve the problem of synchronization among such individual databases. Furthermore, during the synchronization of the databases, there may be many issues, such as congestions (like the PRU number 5) or PRUs running out of energy (like that of PRU number 7). Those issues need to be taken into account in the routing method for the backbone network comprising only PRUs.

5.3.3 Envisioned Solution for Safety Confirmation Application in Multiple PRUs Scenario

In order to come up with a solution for the above-mentioned challenges, we need to learn about the characteristics of the application. The first characteristic that could be deducted is that images are different from other types of data especially when the data is not adequately provided. With other types of data such as binary files, if the data is not enough, e.g., some bits are missing, there might be corruption in opening the files and we cannot achieve any information from them. However, we still can get some information from low-resolution images even though they do not have all the data of the original ones. For example, we at least can differentiate the types of images, i.e., images of people or landscape or others. Moreover, if an image is a photo of a person, we can recognize the gender of the person, the approximate age, the hairstyle, and so forth. We can even see whether we know this person or not if the resolution is not too low. The higher the resolution is, the better the correctness of the recognition will be. In other words, low-resolution images can still be recognized by people but only causes the probability of errors in recognizing. On the other hand, high-resolution images usually need larger spaces in the storage and require more time to be transferred in the network.

Consequently, the major issue here is that the images in high-resolution may result in congestion in the network while low-resolution images may lead to user recognition errors. However, if we can create different copies of images with different sizes beforehand to be used in different situations. Given a network situation, an optimal image size can be decided to make recognition correct in the shortest possible time. That is the key idea of our proposed method for the safety confirmation application. The use of this application can be explained via the following scenario. After a disaster, a person from the outside area tries to find any information about his/her father, who is in the disaster affected area. However, due to the effect of the disaster, cellular network infrastructure in the area has been damaged and the power outage occurred, and thus, the person cannot contact to his/her father. After the PRUs arrive at the disaster area, they construct a multiple PRUs based PDCN, which has a connection to the outside area. The evacuees and the rescuers are then able to upload photos of people in the disaster area to any of the PRUs via the wireless connection to the PDCN based on PRUs. Figure 5.3 illustrates the typical

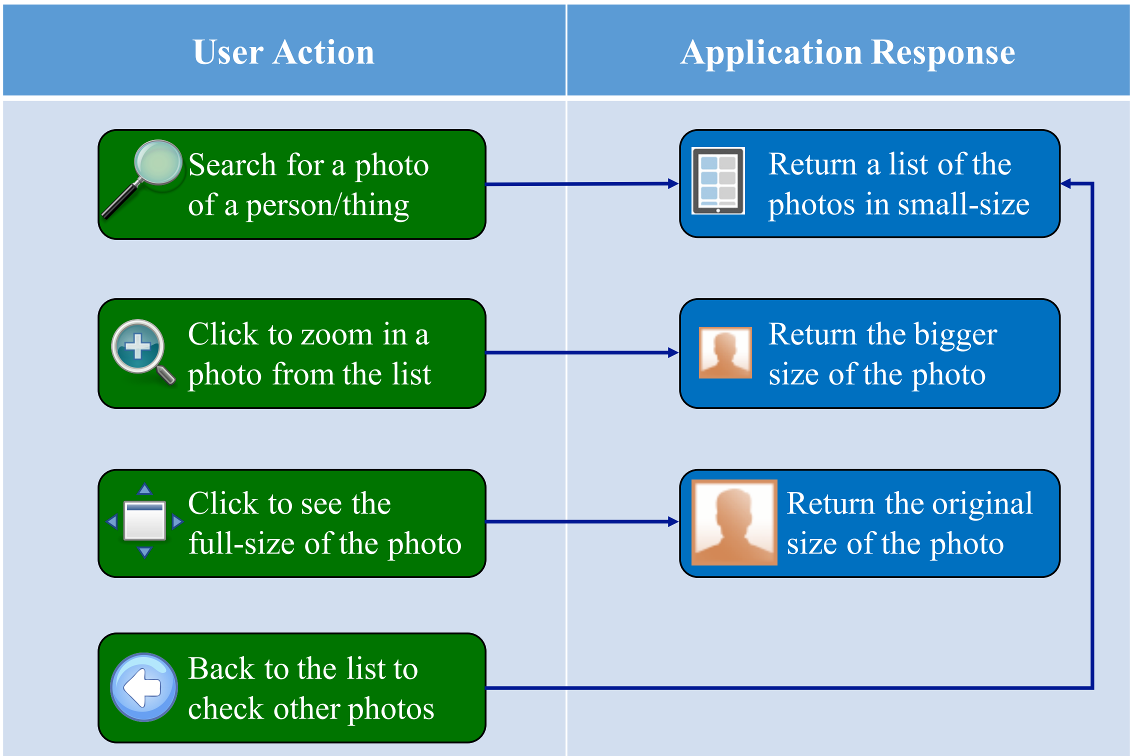

Figure 5.3: Typical user actions and responses of the safety confirmation application.

user actions and responses of the safety confirmation application based on the image database. By using the application, the person can explore all the images stored in the database of any PRU. Additionally, he/she can also filter the images by name, gender, age, and so forth. After the list of images is displayed on his/her device, the person can select any image that looks similar to his/her father. A bigger size of that image will be downloaded to the person's device to help him/her see the image in a better resolution. If the downloaded resolution is still not enough, there is an option to view the original size of the image. The person can repeat the above steps again until he/she finds a photo of his/her father or until there is no more similar image to explore. Note that all the photos shown to the user in the application should be from the storage of any PRU in the PDCN. The transmission of photos inside the PDCN should be transparent to users.

5.4 Proposed Performance Optimization Method for the Safety Confirmation Application

In this section, we present in detail our proposed method for the image searching application in the multiple PRUs based PDCN. The proposed method has four phases: resize and storing images, broadcasting small-size images, routing in the backbone network, and deciding image size to deliver to the users. Among them, the last phase can be considered as the core contribution of this work.

5.4.1 Resizing and Storing Images

This phase is demonstrated in Figure 5.4. After an image is uploaded to the PRU, different copies of the image with different sizes will be created automatically. The reason behind this redundancy is that, in a disaster scenario, the system throughput of the network is more critical than the size of the image storage. It is also due to the trade-off relationship between the resolution of the delivered images and the downloading speed of those images. On one hand, if only the large size of the images are used, delivery speed might be affected due to the significantly high traffic load causing congestions in the network. On the other hand, if only images in small size are used, the speed might be guaranteed but the quality of the downloaded images will be low. Therefore, depending on the network situation, different sizes of the image should be used to deliver to users. Another advantage of creating and storing different sizes of the images beforehand is that the processing time can be reduced when other users explore the images using the application.

In fact, in order to create the database storing different copies of images with different sizes, we need to take into account the image resizing techniques. However, in the scope of this work, we do not propose a new method of image resizing or compressing. Instead, we assume that any traditional approaches can be utilized.

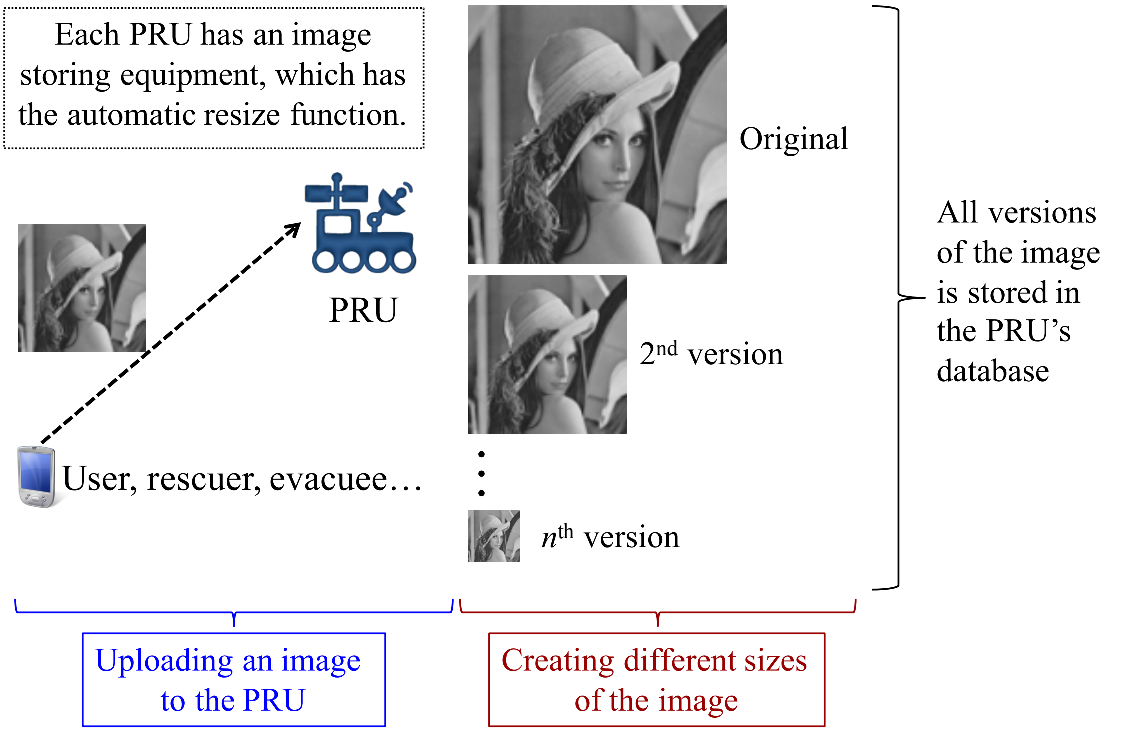

Figure 5.4: Resizing and storing images uploaded to the PRU. ©2015 IEEE.

5.4.2 Broadcasting Small-Size Images to Other PRUs

When a user uploads images to the system, the images are uploaded to the closest PRU, which we will be referring to as the "local PRU". After the images are copied and stored in different sizes, the copies are also stored in that local PRU. After resizing and storing the images, the smallest copy of each image is broadcasted together with the additional information of the person in the image such as name, age, gender, and so forth. By doing this way, the image storage in each PRU will have all versions of the images that are directly uploaded from its local users and all small-size images uploaded to other PRUs. Therefore, whenever users want to see the list of images, the local PRU can promptly response the list of all images in small size. When a user wants to see an image in a bigger size, the PRU having the original version of the image will deliver it to the user through the PDCN.

5.4.3 Routing in Backbone Network

Since the image transmission among the PRUs in the PDCN is required, the routing in the backbone network is necessary regardless of the image size, either small-size images for broadcasting or large-size images for individual requests. In this work, we assume that any existing routing method can be used for this phase. In fact, the method introduced in Chapter 3 can also be used in this proposed method to find the best routing paths among PRUs in terms of spectrum-energy efficiency. Note that the routing phase is not considered as the main contribution in this proposal. This phase is presented here in order to help readers thoroughly understand all phases of our proposed method.

5.4.4 Deciding Image Size for Delivering to Users

When a user search for an image using the safety confirmation application, a list of images in small sizes will be responded to the user. When the user clicks on an image in the list, a larger size of the image will be downloaded so that the user can see it more clearly. However, deciding the size of the image for responding to the user is a research issue here. If the size of the image is too big while the network condition is not good, it may cause the congestion in the network, which leads to long time needed for the user to verify whether this image is relevant or not. On the other hand, if the size of the image is too small, there is a high probability that the user still need to see a bigger size (or even the original image) for verification. In that case, the total time for confirming the image might be even more than only returning the original image to the user for preview.

In this work, we aim to minimize the *searching time*, which is the total time for users to find out whether there is an image relevant to the person of the users' interest. Depending on network condition, appropriate image size should be chosen to deliver images to users so that users can find the relevant images in the shortest possible time. This task requires the updated information of the network condition. Therefore, each PRU needs to periodically check its connections with neighboring PRUs and broadcasts the information to other PRUs. Since this information can be stored in a few packets and the number of PRUs in an area is usually not too large, this information sharing step is much smaller than delivering an image in the system. Therefore, the overhead caused by sharing the local information of the PRUs can be considered negligible. By doing this process, each PRU can know the updated situation of the backbone network. When a user starts using the image searching application, the local PRU checks the condition of its local network and, beforehand decide the appropriate size of the bigger-size images that are delivered when requested. When the user clicks on any small image in the list, the local PRU will send a request, which includes the calculated size and the ID of the image, to the PRU having the original image in its storage.

The state diagram presented in Figure 5.5 demonstrates the possible actions of users when using the image searching application and the physical meanings of the transitions between states. The actions include focusing on a small image, viewing a larger size of the image, see the original size of the image, and finish (deciding whether there is a relevant image or not). As shown in this figure, after receiving the list of small images, the user will focus on the first image. If the image looks similar to the image the user wants to find, he/she may want to zoom into the image to confirm. If the bigger size image is still not clear enough, the user may want to see the original size of the image. If this image is the one that user is looking for, the searching process finishes. Otherwise, the user will move on to the next image and do the same process until the target image is found. In the Figure 5.6, the names of states are replaced by symbols and the transitions between states are represented by probability. F_i, B_i, and O_i stand for focusing on the image i, viewing a larger size of the image i, and viewing the original image i, respectively. P_s is the

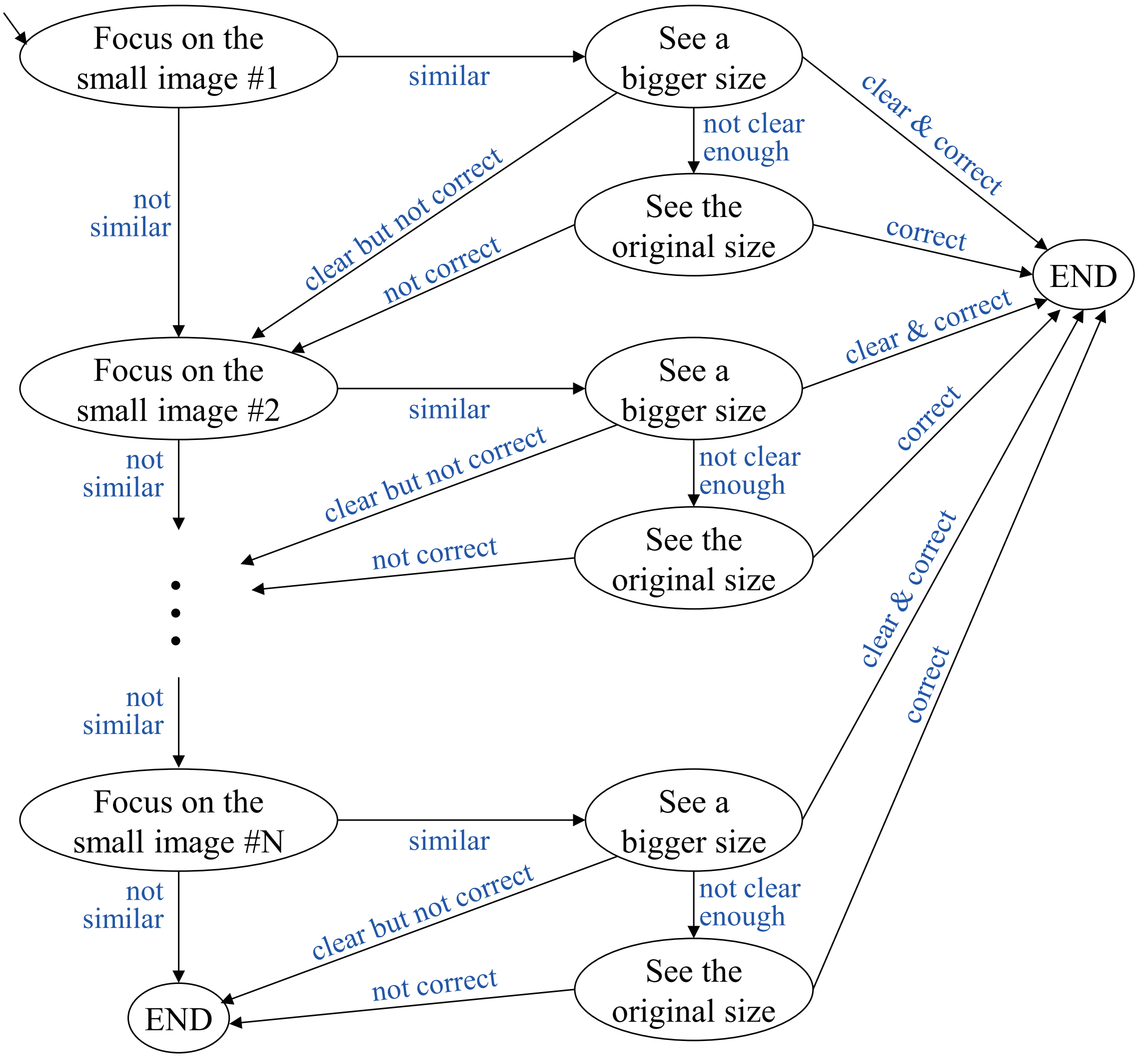

Figure 5.5: State diagram presenting the flow of user actions after downloading the list of images. ©2015 IEEE.

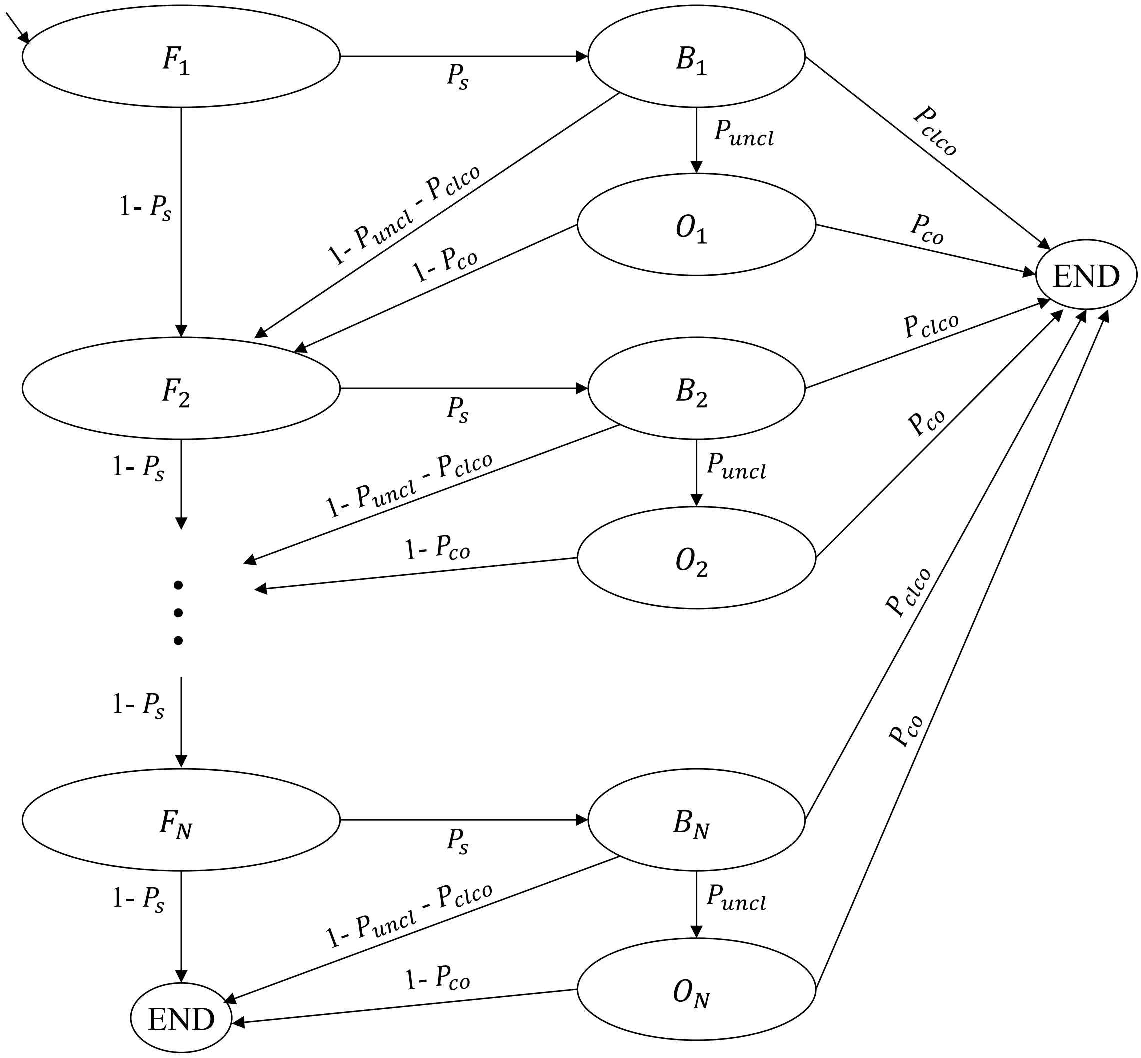

Figure 5.6: Transition diagram presenting the flow of user actions after downloading the list of images. ©2015 IEEE.

probability that a small image in the list looks similar to the one the user wants to find. P_{co} is the probability that the image is what the user is looking for. P_{uncl} is the probability that the large image responded to the user is not clear enough. P_{clco} is the probability that the large image responded to the user is clear and is what the user is looking for. The diagrams demonstrate a Markov chain, which we proved to be an *absorbing Markov chain* (see Section 5.5). With different sizes of the images, the time to finish each action and the value of the transition probabilities can be different. By calculating the expected number of periods the chain spends in each state and estimating the time necessary for each corresponding action, the expected time until absorption (until the user find the answer whether there is any relevant image or not) can be calculated. Therefore, given the network condition, the probabilities presenting transitions between user actions, and the time to finish each action, we can calculate the expected searching time corresponding each image size. The most appropriate image size can be chosen so that the searching time of users is minimized. In Section 5.5, the analysis we use to calculate the expected searching time will be presented in detail.

5.4.5 Input Parameters for the Proposed Method

In this sub-section, we discuss the input parameters that are required to carry out the proposed method. As introduced above, F, B, and O are used to denote the user actions: focusing on an image, viewing a larger size, and viewing the original size of the image, respectively. The time required for these user actions, $T(F)$, $T(B)$, and $T(O)$, are the given input parameters of our method. They can be calculated based on the statistics of user behaviors and the size of the image. However, in the scope of this work, we do not propose a method to calculate these values. Instead, we consider them as the given parameters.

Regarding the probability values, P_{co} can be simply calculated as:

$$P_{co} = \begin{cases} \frac{1}{N}, & \text{if the target image is in the database,} \\ 0, & \text{otherwise,} \end{cases} \tag{5.1}$$

where N is the number of images in the database. P_s and P_{uncl} depend on the type of images in the database and the size of the images. For example, a person in an ID photo can be clearly seen even though the size of the photo is small. In contrast, in order to recognize a person in a photo of a group, a large copy of the photo is needed. Therefore, the different sets of images may lead to different values of P_s and P_{uncl}. The method to calculate P_s and P_{uncl} is out of the scope of this work and they are considered as a given parameters for our proposed method. With the given P_{uncl} and the P_{co} calculated in (5.1), P_{clco} can be calculated as follows:

$$P_{clco} = (1 - P_{uncl})P_{co}. \tag{5.2}$$

Section 5.5 will introduce how the input parameters are used in our proposed method.

5.5 Markov-based Analysis on the Expected Image Searching Time

This section provides the analysis that we base our proposal on. In this section, we first show that the Markov chain used in our proposed method is an absorbing chain. After that, we use the characteristics of an absorbing chain to estimate the expected searching time of users. The expected searching time can be calculated by using this analysis, and thus, the most appropriate size of images can be decided so that the total searching time is minimized.

5.5.1 Prove that the Markov Chain Used in the Proposed Method is an Absorbing Markov Chain

The definition of absorbing Markov chain in [82] expressed that a chain is called an absorbing chain if it satisfies two following conditions. First, it needs to have at least one absorbing state, which does not have any probability of transitioning to other states. Second, each non-absorbing state is able to transit to some absorbing states (either directly or in multiple steps). As shown in Figures 5.5 and 5.6, the state and transition diagrams are presented as a Markov chain having "END" is the only one absorbing state. Note that for the simplicity in drawing the diagrams, the absorbing state "END" is represented by two "END" states in Figures 5.5 and 5.6. On the other hand, it is possible for each state in the chain to transition to "END" by one or more steps. Therefore, the chain presented in Figures 5.5 and 5.6 is an absorbing Markov chain.

5.5.2 Estimate the Expected Searching Time by Using the Characteristics of an Absorbing Markov Chain

The transition matrix of Markov chain used in the proposed method can be presented as Figure 5.7. Let M be the transition matrix. As demonstrated in this figure, M can be written in the "canonical" form as follows:

$$M = \begin{bmatrix} Q & R \\ 0 & I \end{bmatrix}. \tag{5.3}$$

Here, Q is a sub-matrix that represents the probabilities of the transitions from non-absorbing to non-absorbing states, R is a sub-matrix representing the transition probabilities from non-absorbing to absorbing states, 0 is the sub-matrix of zeros, and I is an identity matrix.

Q R 0 I

	F_1	F_2	F_3	$\cdots$	F_N	B_1	B_2	$\cdots$	B_N	O_1	O_2	$\cdots$	O_N	END
F_1	0	$1-P_s$	0	$\cdots$	0	P_s	0	$\cdots$	0	0	0	$\cdots$	0	0
F_2	0	0	$1-P_s$	$\cdots$	0	0	P_s	$\cdots$	0	0	0	$\cdots$	0	0
F_3	0	0	0	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	0	0
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
F_N	0	0	0	$\cdots$	0	0	0	$\cdots$	P_s	0	0	$\cdots$	0	$1-P_s$
B_1	0	$1-P_{uncl}-P_{clco}$	0	$\cdots$	0	0	0	$\cdots$	0	P_{uncl}		$\cdots$		P_{clco}
B_2	0	0	$1-P_{uncl}-P_{clco}$	$\cdots$	0	0	0	$\cdots$	0	0	P_{uncl}	$\cdots$		P_{clco}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
B_N	0	0	0	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	P_{uncl}	$1-P_{uncl}$
O_1	0	$1-P_{co}$	0	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	0	P_{co}
O_2	0	0	$1-P_{co}$	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	0	P_{co}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
O_N	0	0	0	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	0	1
END	0	0	0	$\cdots$	0	0	0	$\cdots$	0	0	0	$\cdots$	0	1

Figure 5.7: Transition matrix of the absorbing Markov chain in the proposed method. ©2015 IEEE.

As an absorbing Markov chain, M has the following characteristic.

$$M^2 = \begin{bmatrix} Q & R \\ 0 & I \end{bmatrix} \begin{bmatrix} Q & R \\ 0 & I \end{bmatrix} = \begin{bmatrix} Q^2 & R + QR \\ 0 & I \end{bmatrix} \tag{5.4}$$

$$M^3 = \begin{bmatrix} Q^3 & R + QR + Q^2R \\ 0 & I \end{bmatrix} \tag{5.5}$$

$$\vdots$$

$$M^n = \begin{bmatrix} Q^n & (I + Q + Q^2 + \ldots + Q^{n-1})R \\ 0 & I \end{bmatrix} \tag{5.6}$$

Since $Q^{\infty} \rightarrow 0$ as $n \rightarrow \infty$, and

$$I + Q + Q^2 + ... = (I - Q)^{-1}, \tag{5.7}$$

which is called the fundamental matrix for the absorbing chain, we have:

$$M^{\infty} = \begin{bmatrix} 0 & (I - Q)^{-1}R \\ 0 & I \end{bmatrix}. \tag{5.8}$$

Let $\hat{F}$ be the fundamental matrix,

$$\hat{F} = (I - Q)^{-1}, \tag{5.9}$$

we have:

$$M^{\infty} = \begin{bmatrix} 0 & \hat{F}R \\ 0 & I \end{bmatrix}. \tag{5.10}$$

As proven in [85], in the fundamental matrix $\hat{F}$, any element $\hat{F}(i, j)$ is the expected number of periods that the chain spends in the jth non-absorbing state, given that the chain began in the ith non-absorbing state. In the state diagram of the proposed method, the chain begins at F_1, the first non-absorbing state. Let N be the number of images in the list downloaded by users. Following the index in Figure 5.7, the number of periods spent on each state F_i, B_i, and O_i are

$$V(F_i) = \hat{F}(1, i), \tag{5.11}$$

$$V(B_i) = \hat{F}(1, i + N), \tag{5.12}$$

and

$$V(O_i) = \hat{F}(1, i + 2 \times N), \tag{5.13}$$

respectively. Let $T(F_i)$, $T(B_i)$, and $T(O_i)$ be the time required for each user action F_i, B_i, and O_i, respectively, the expected searching time, Θ, can be calculated as

Procedure 6 Deciding the Image Size for Delivering to User

Input: Throughput of the backbone network among PRUs, throughput of each local PRU network, number of images in the list responded to the user (N), the list of image sizes (S), and functions to calculate input parameters mentioned in Section 5.4.5.

Output: The most appropriate image size of the bigger image that should be delivered to the user.

1: Calculate the time required for user actions $T(F_i)$, $T(B_i)$, and $T(O_i)$ according to the size of image i using the given functions.
2: Calculate P_{co} using (5.1).
3: Calculate P_s and P_{uncl} for different image sizes using the given functions.
4: Calculate P_{clco} for different image sizes using (5.2).
5: **for all** image size $s \in S$ **do**
6:     Estimate the expected number of periods spent on each action, $V(F_i)$, $V(B_i)$, and $V(O_i)$, for any i, $1 \leq i \leq N$, using (5.11), (5.12), and (5.13).
7:     Calculate the expected searching time, Θ, using (5.14).
8: **end for**
9: **return** the image size that minimizes the value of Θ.

follows:

$$\Theta = \sum_{i=1}^{N} V(F_i) \times T(F_i) + \sum_{i=1}^{N} V(B_i) \times T(B_i) + \sum_{i=1}^{N} V(O_i) \times T(O_i). \quad (5.14)$$

5.5.3 Decide the Image Size for Delivering to User

Different image sizes lead to different values of P_s, P_{co}, P_{uncl}, and P_{clco}. As a result, the transition matrix changed with image sizes. And thus, the number of periods spent on each state $T(F_i)$, $T(B_i)$, and $T(O_i)$ will be different. Furthermore, given the throughput of the backbone network and the local PRU networks, different image sizes also lead to different values of the time required for each user action, $T(F_i)$, $T(B_i)$, and $T(O_i)$. Therefore, in order to find the most appropriate size of

Parameter	Value
Number of images (N)	20, 100, 400
Original image size	4096 kB
Sizes of the image copies	16 - 4096 kB
Average speed of backbone network	256 kbps
Average speed of local PRU network	64 kbps
$T(F_i)$	2.0 ms
$T(B_i)$	2.5 - 640 ms
$T(O_i)$	640 ms
P_{co}	$1/N$
P_s	$3 \times P_{co}$

Table 5.1: Simulation settings for evaluating proposed method. ©2015 IEEE.

images, the expected searching time, Θ, can be calculated for all image sizes. After that, the image size that minimizes the value of Θ will be chosen. As presented in Procedure 6, the proposed method can decide the most appropriate image size by using the results of this analysis.

5.6 Performance Evaluation

In this section, we evaluate the performance of our proposed method and verify the analytical findings in Section 5.5. Extensive computer-based simulations using MATLAB are conducted to find the evaluation results. In Table 4.2, the simulation settings and parameters are summarized. There are two main experiments carried out for our evaluation. On one hand, the first experiment is to verify the relationship between the expected searching time and image size, with a different number of images in the list responded to the user. On the other hand, the second experiment is to illustrate the existence of the optimal image size that minimizes the expected searching time. Also in the second experiment, we evaluate how much improvement the proposed method can provide comparing to the system that does not use our proposal. Furthermore, the effect of the input parameter P_{uncl} on the minimum expected searching time is presented in this section.

5.6.1 The Relationship Between Expected Searching Time and Image Size

Regarding the settings for the first experiment, there are five levels of image size, which are 16, 64, 256, 1024, and 4096 kilobytes (kB). The original size of the images uploaded to any PRU is 4096 kB. After an image is uploaded to any PRU, different copies of the image with the size of 16, 64, 256, and 1024 kB are created and stored in the local PRU's database. Then, the smallest copy (16 kB) is broadcasted to any other PRU. In the first experiment, we suppose that there is a user using the image searching application and the local PRU has to calculate the most appropriate size of the bigger image that should be responded to the user. The speeds of the backbone network and the local PRU network are supposed to be 256 and 64 kilobits per second (kbps), respectively. The number of images in the list responded to a user, N, is set to three different values, 20, 100, and 400 for three different scenarios. Suppose there is an image in the databases of the PRUs that a user is looking for, the probability that an image is the relevant one is $P_{co} = 1/N$. The probability that a small photo in the list looks similar to the targeted one, P_s, is set to be three times bigger than P_{co}. With different image sizes, the probability that the user thinks that the image is not clear enough, P_{uncl}, is also different. In the first experiment, P_{uncl}

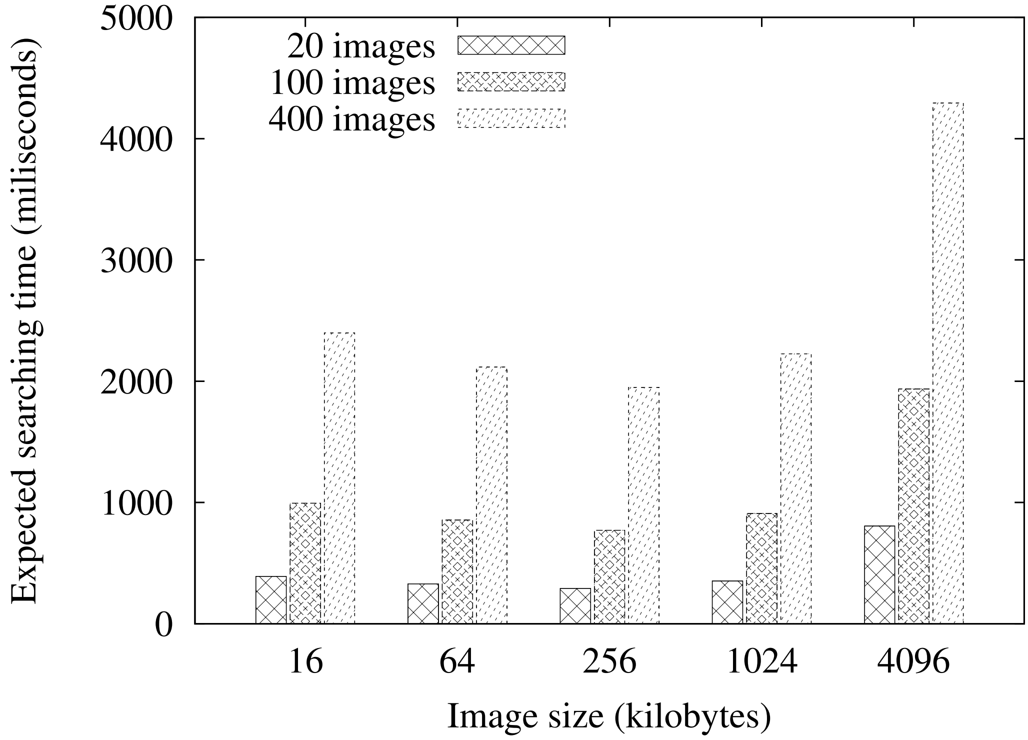

Figure 5.8: Expected searching time versus image size with different number of images in the list. ©2015 IEEE.

is set to 0.5, 0.4, 0.3, 0.2, and 0.1 for the image size of 16, 64, 256, 1024, and 4096 kB, respectively. Figure 5.8 shows the simulation results of the first experiment. As demonstrated in the figure, with the current settings of the experiment, the image size of 256 kB leads to the smallest value of the expected searching time. Furthermore, it clearly demonstrates that the higher number of images in the list responded to the user in the first step leads to a much higher expected searching time. Therefore, if the user can effectively use the filter function with name, gender, age, and so forth, the searching time will be significantly decreased.

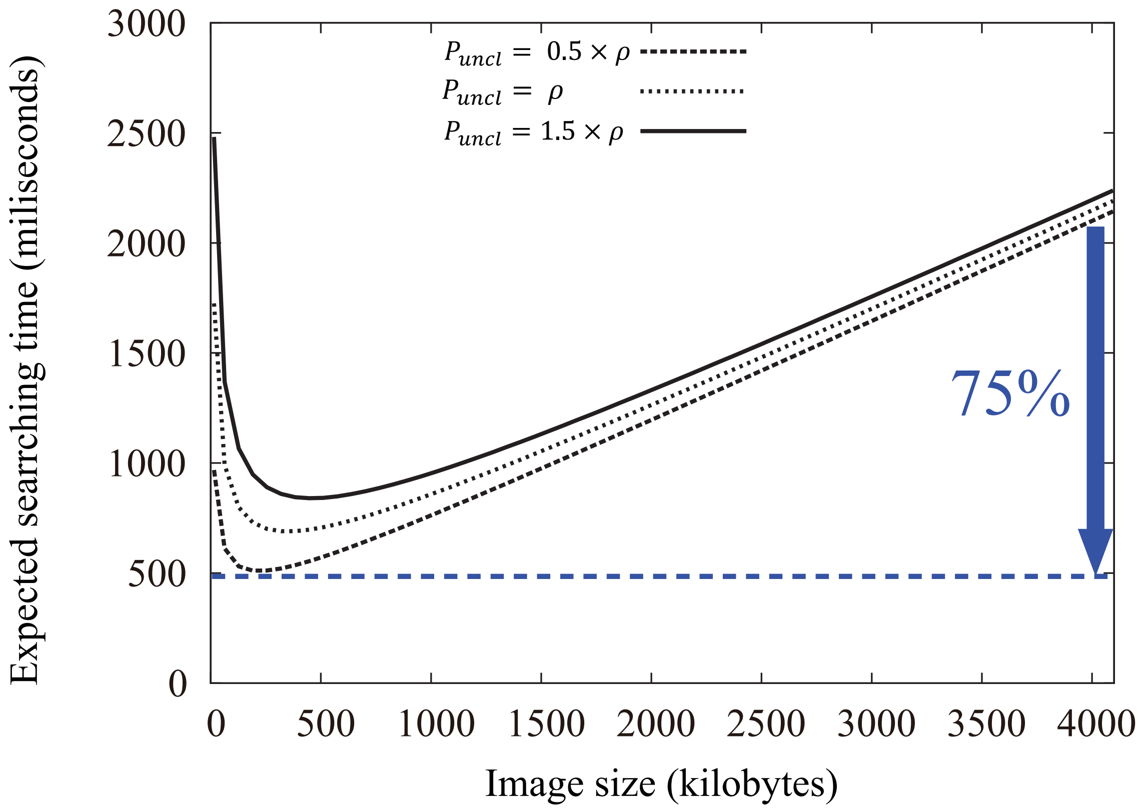

Figure 5.9: Expected searching time versus image size with different number of images in the list.

5.6.2 The Existence of the Optimal Image Size that Minimizes the Expected Searching Time

In order to see the optimal image size more clearly, we do not set the levels of image sizes in the second experiment. Instead, we suppose ρ is a function of image size that represents the P_{uncl}. ρ can be any given function. For example, in this experiment, we set $\rho = \sqrt{\frac{2.5}{t_s}}$, where t_s is the time needed to open an image with the size s. The experiment is carried out with $P_{uncl} = 0.5 \times \rho$, $P_{uncl} = \rho$, and $P_{uncl} = 1.5 \times \rho$, respectively. Figure 5.9 demonstrates the results of the second experiment. The results show that the minimum of the expected searching time does exist regardless of the value of P_{uncl}. These results confirm the existence of the optimal image size.

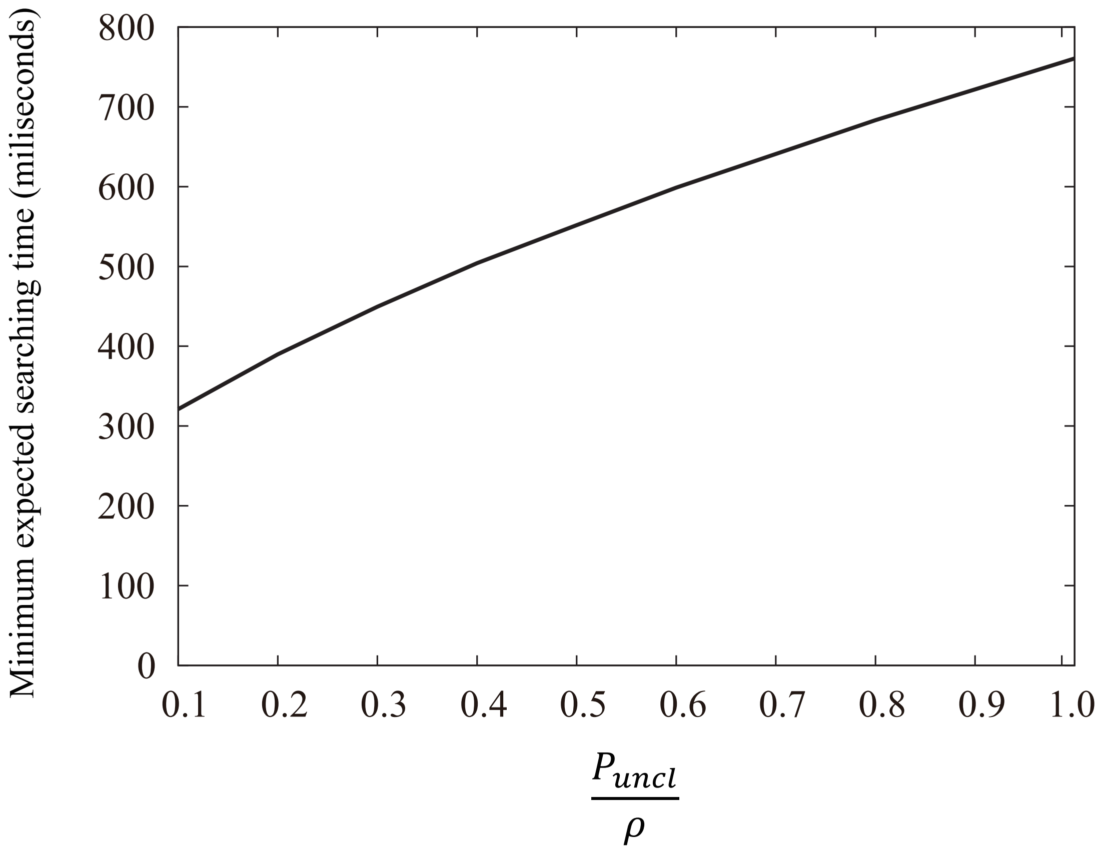

Figure 5.10: The minimum expected searching time versus the ratio $\frac{P_{uncl}}{\rho}$. ©2015 IEEE.

We also investigate the trend of the optimal image size when the quality of the images is varied, which leads to the change of P_{uncl}. In order to evaluate the effect of P_{uncl} on the value of the minimum expected searching time, we conduct the same experiment but with the ratio $\frac{P_{uncl}}{\rho}$ varied from 0.1 to 1.0. Figure 5.10 shows the trend of the minimum expected searching time when P_{uncl} changes. As shown in this figure, when P_{uncl} increases, the minimum expected searching time also increases. Note that a high value of P_{uncl} implies that the images are not clear enough or in a low-resolution. Therefore, the results are reasonable because people need more time to recognize the details in a low-quality image.

5.6.3 The Improvement of the Proposed Method

As presented in Figure 5.9, there is the big gap between the value of the expected searching time at the image size of 4096 kB and the minimum point. Note that in the system without our proposed method, the images are not resized and copied to different versions. In other words, only the original size of images (4096 kB in this experiment) are stored in the databases and will be responded to users when requested. In contrast, our proposed method stores different copies of images with different sizes and only respond images with an appropriate size. As shown in the figure, the proposed method can reduce the searching time by approximately 75 percent. These results validate the effectiveness of our proposal.

5.7 Summary

In this chapter, we proposed a safety confirmation method which includes four phases, i.e., resizing and storing images, broadcasting small-size images, routing, and deciding image size to deliver to users. The objective of our method is to minimize the searching time of users. We estimated the expected searching time for each different size of images and choose the most appropriate image size based on a mathematical analysis using the absorbing Markov chain. Extensive computer-based simulations were conducted to verify the findings of our analysis. Furthermore, the simulation results proved the existence of the optimal image size that minimizes the searching time. The results also demonstrated the effectiveness of our proposed method.

Chapter 6

Conclusion

6.1 Summary and Discussion

In this thesis, we focused on PDCNs, which are deployed in disaster affected areas where the network infrastructure can be damaged or even destroyed. We identified three main challenging issues that PDCNs need to address and also discussed the corresponding requirements. Firstly, due to the emergency situations after disasters, the portability and prompt deployment of a PDCN is required in order to quickly provide the network services in the disaster affected areas. Secondly, because of the high demand from users and limited capacity of the remaining infrastructure, PDCNs need to focus on efficiency inside the system in order to provide a high performance, especially in throughput and delay. Finally, due to the variety of post-disaster scenarios, PDCNs need to adapt to different situations and utilize the remaining resources effectively. Our considered network scenarios and assumptions, in this thesis, are similar to those in the MDRU-based disaster recovery network [2]. We focused on the PDCNs based on PRU(s) and attempted to propose the methods to address the above-mentioned challenges. The contents of the chapters in this thesis can be summarized as follows.

Chapter 1 The background, objectives, and main contributions of this thesis were introduced.

Chapter 2 In this chapter, we provided an overview of PDCNs and the existing PDCNs that consider using PRUs. The related works in disaster response/recovery networks were also discussed in this chapter. Furthermore, we identified throughput and delay as the main requirements that PDCNs need to take into account.

Chapter 3 In this chapter, we pointed out the requirements of spectrum and energy efficiencies in PDCNs based on PRUs. However, the current works in literature only consider the problems of spectrum efficiency and energy efficiency separately, despite the fact that they are conflicting objectives. Hence, we proposed a method to improve the utilization of both spectrum and energy resources. The proposal consists of two phases, namely, topology formation and transmission division. The topology formation phase constructs a topology composed of APs and links that belong to the top k spectrum-efficient disjoint paths. The resulting topology is used by the transmission division phase to split the transmissions from sender APs to the PRU. Through analyses, we proved that there exists a value of k such that the spectrum-energy efficiency of a given topology is maximized. Our experimental results confirmed our analytical findings.

Chapter 4 In this chapter, we proposed two topology control methods for different scales of PDCNs. On one hand, for a small scale PDCN based on a single PRU, we suggested using cooperative communications and proposed a topology control cooperative method, that optimally decides the number of cooperative agents in order to maximize the throughput gain while guaranteeing a reasonable cooperative computation time. We provided an analysis on the effect of k on the throughput gain, the cooperative computation time, and the utility, throughput gain speed. The analysis was validated by using simulations. On the other hand, for a large scale PDCN which is based on multiple PRUs, we considered PRUs as Cognitive Radio Base Stations (CRBSs) that are equipped with multiple antennas to utilize all available spectrum in the area. We proposed an adaptive topology control method that aims to maximize the cognitive radio adaptability while guaranteeing the routing computation time. Also, we proved that there is a value of k for a given network that optimally solves the trade-off relationship between cognitive radio adaptability and the routing computation time. Additionally, extensive simulations were conducted to verify our analysis.

Chapter 5 In this chapter, we proposed a method for safety confirmation application which includes four phases, i.e., resizing and storing images, broadcasting small-size images, routing, and deciding the image size to deliver to users. The objective of our method is to minimize the image searching time of users. We estimated the expected searching time for each different size of images and chose the most appropriate image size based on a mathematical analysis using an absorbing Markov chain. Extensive computer-based simulations were conducted to verify the findings of our analysis. Furthermore, the simulation results proved the existence of the optimal image size that minimizes the searching time. The results also demonstrated the effectiveness of our proposed method.

6.2 Future Directions

In this thesis, we aimed at improving the throughput and delay of PDCNs based on PRUs in three different aspects, i.e., *efficiency*, *adaptiveness*, and *application*. For each aspect, we provided the possible extensions as follows.

Regarding the *efficiency*, we proposed a method that considers both spectrum and energy constraints and aims to maximize the utilization of those resources.

Currently, energy constraints are the remaining energy at the portable APs. In fact, the APs can also have energy harvesting functionality. The consideration of using expected energy which can be harvested in the next time period can be an extension of this work.

Regarding the *adaptiveness*, we proposed two topology control methods for different deployment scales of PDCNs. In the proposed method for small scale PDCNs using cooperative communications, we assumed that the topology of the backbone network is decided beforehand and does not change during the process. However, a dynamic topology formation of the backbone network can be an extension of this proposal. In the proposed method for large scale PDCNs using cognitive radio, we stated that any routing method can be used on top of the constructed topology. If a novel distributed adaptive routing was added to the current method, it would be a completely adaptive routing method for PDCNs using cognitive radio.

Regarding the *application*, we proposed a method for the safety confirmation application using the distributed image databases onboard the PRUs in the large scale PDCNs. Currently, the performance optimization using the absorbing Markov chain is specific for only this application. A possible extension of this work can be a model that can enhance the performance of different applications with different network usage characteristics. Furthermore, since the images used in the safety confirmation application are generally human photos, the special characteristics of human photos should be considered in the image resizing task. If such an image resize technique is included in the proposed method, it can produce recognizable copies of the images while keeping the size as small as possible. As a result, the image searching time can be reduced even more.

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Awards

- **Best Paper Award** in the 2016 IEEE International Conference on Communications (ICC 2016) for the paper entitled "GHAR: Graph-based Hybrid Adaptive Routing for Cognitive Radio Based Disaster Response Networks"
- **Best Paper Award** in the 2016 IEEE 83rd Vehicular Technology Conference (VTC2016-Spring) for the paper entitled "A Novel Graph-based Topology Control Cooperative Algorithm for Maximizing Throughput of Disaster Recovery Networks"
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