國立臺灣大學資訊管理研究所碩士論文

指導教授：林永松　博士

無線網狀網路下考量端對端服務品質之出口閘道設施指定及路由演算法

Backhaul Assignment and Routing Algorithms with End-to-End QoS Constraints in Wireless Mesh Networks

研究生：曾勇誠　撰

中華民國九十五年十月

國立臺灣大學資訊管理研究所碩士論文

指導教授：林永松　博士

無線網狀網路下考量端對端服務品質之出口閘道設施指定及路由演算法

Backhaul Assignment and Routing Algorithms with End-to-End QoS Constraints in Wireless Mesh Networks

研究生：曾勇誠　撰

中華民國九十五年十月


國立臺灣大學
敦品勵學・愛國愛人

無線網狀網路下考量端對端服務品質之出口閘道設施指定及路由演算法

Backhaul Assignment and Routing Algorithms with End-to-End QoS Constraints in Wireless Mesh Networks

本論文係提交國立台灣大學
資訊管理學研究所作為完成碩士
學位所需條件之一部份

研究生：曾勇誠　撰

中華民國九十五年十月

國立臺灣大學
敦品勵學
愛國愛人

謝詞

本論文的完成，象徵人生中的一個里程碑，新的旅程將於此展開。首先感謝我的父母親：曾肇祿先生與吳梅蘭女士，謝謝你們對我的栽培與全力的支持，讓我有勇氣在脫離學校多年後重新拾起課本回到學校，完成我的碩士學位。

感謝我的恩師 林永松博士，謝謝您這兩年來給學生的指導與鼓勵。在老師的指導下，不僅使學生在知識研究上獲益良多，老師嚴謹的治學態度，更讓學生體悟到追求最佳化的那種契而不捨的精神。感謝口試委員呂俊賢博士、陳郁堂博士，對本篇論文提供諸多寶貴的意見，讓這篇論文能夠更加的完善，在此對各位老師致上最誠摯的謝意。

感謝博士班的演福學長與柏皓學長，在我研究的過程中諸多的協助，給了我許多的意見與啟發，使得我能更加順利的完成此論文。謝謝琳智、書平、孝澤、明源學長姐，感謝你們在我剛進實驗室的給我的指導與鼓勵。

感謝同門的中蓮、義倫、弘翕、文政，謝謝你們陪我渡過兩年最難忘且歡樂的研究生生活。感謝學弟妹雅芳、坤道、俊維、承賓、豈毅、翊恆、怡孜及其他更新進的學弟妹們，謝謝你們在我口試最後階段所給予的諸多協助。也要感謝我的妻子劉虹燕女士，謝謝你一路上的陪伴與相互扶持。最後感謝所有幫助過我的人、鼓勵過我的人。

曾勇誠　謹識
于台大資訊管理研究所

論文摘要

論文題目：無線網狀網路下考量端對端服務品質之出口閘道設施指定及路由演算法

作　　者：曾勇誠

指導教授：林永松　博士

無線網狀網路(WMN)是另一項可實現寬頻存取網際網路的「最後一哩(last mile)」技術。為了能在無線網狀網路中，提供多媒體應用服務，例如：視訊會議、網路電話(VoIP)，服務品質 (QoS)的保證將是至關重要的目標。這是因為多媒體應用對於延遲及延遲變異非常的敏感。如果能良好規劃網路及理想地部署網際網路閘道，每個行動用戶將可以享受到服務品質保證的多媒體應用服務。

在本研究中，我們針對網路服務提供者，在如何佈署出口閘道設施，及在滿足服務品質下如何安排路徑、分配頻寬等決策，提供一個解答。為了解決此問題，我們針對服務品質保證需求，包括端到端的平均延遲需求，以及端對端的延遲變異需求，提出一個數學模型。此演算法的基本方法為拉格蘭氏鬆弛法（Lagrangean Relaxation）及次梯度法（subgradient）。

關鍵字：無線網狀網路、出口閘道設施指定、考量服務品質之路由規劃、最佳化、拉格蘭日鬆弛法。

THESIS ABSTRACT

GRADUATE INSTITUTE OF INFORMATION MANAGEMENT

NATION TAIWAN UNIVERSITY

NAME：YEONG-CHENG TZENG

ADVISER：YEONG-SUNG LIN

Backhaul Assignment and Routing Algorithms with End-to-End QoS Constraints in Wireless Mesh Networks

Wireless mesh networks (WMNs) are an alternative technology for last-mile broadband Internet access. To enable multimedia applications such as video-conferencing and voice over IP (VoIP) in WMNs, the guarantees of Quality-of-Service (QoS) are very essential. This is because multimedia applications are very sensitive to delay and delay jitter. If the network is well designed and Internet gateways are optimally deployed, each mobile host can enjoy QoS-guaranteed multimedia applications.

In this thesis, we propose the solution to the network service providers' decisions on how many backhauls they should deploy and how they assign the paths and bandwidth for each mobile host with QoS guaranteed. To solve the problem, a mathematical model is proposed which focuses on generic QoS requirements, including end-to-end mean delay requirement and end-to-end delay jitter requirement for each mobile host. The basic approach to the algorithm is Lagrangean Relaxation and the subgradient method.

Keywords: Wireless Mesh Network, Backhaul Assignment, QoS Constrained Routing Assignment, Optimization, Lagrangean Relaxation Method.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Background

In the past few years, Wi-Fi networks have become increasingly popular. Under the present wireless network architecture, accessing the Internet through Access Points (APs) still has some limitations. First, it is expensive to deploy APs. This is because the cost of wired infrastructure overwhelms AP deployment costs. Second, mobile hosts need to be immediately close to APs within a short range in order to access the Internet.

For removing the above-mentioned shortcomings, a new promising technology Wireless Mesh Network (WMN) is proposed recently, which utilizes wireless multi-hop communication to access the Internet through a backhaul. The great advantage of WMNs is saving the expensive deployment cost of APs. Therefore, the deployment of WMNs is flexible and low-cost.

WMNs consist of several Transient Access Points (TAPs) and at least one backhaul. TAPs is responsible for admitting the connection requests of clients and relaying data traffic between TAPs, while backhaul, the egress of WMNs, connecting to internet with wired links. Under the WMN architecture, the data traffic of clients is conveyed to backhaul by wireless multi-hop communication through TAPs. Then clients' data traffic is transmitted to the Internet from the backhaul finally. Figure 1-1 shows the WMN architecture.

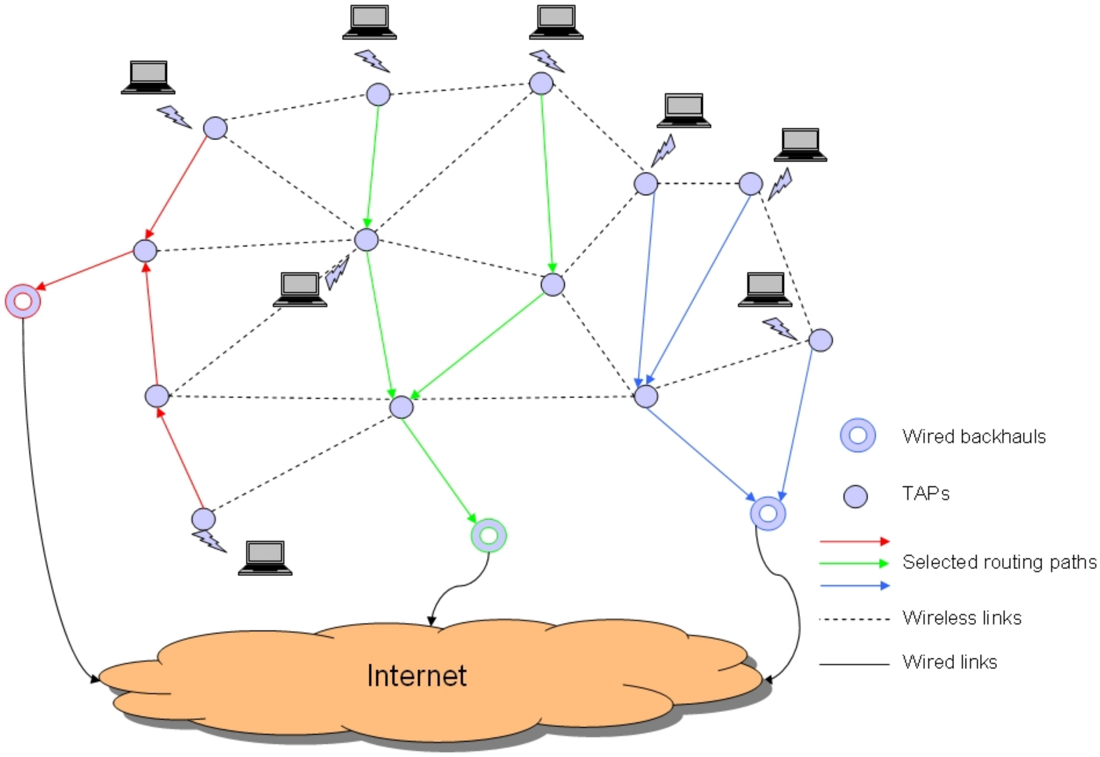

Figure 1-1 A mesh network constructed with a BS-oriented and ad hoc structure connects the wired network via some backhauls and covers a large area via wireless links.

The wireless multi-hop communication in WMNs has brought remarkable progress for wireless communication. However, the characteristics of WMN also cause some other problems at the same time. One of the most important issues is fairness. In WMN, many clients use the same backhaul to access the Internet, therefore the throughput a client can enjoy depending on how far is it away from the backhaul. Client from a longer hops path suffers lower throughput contrast to the shorter hops one. Therefore, the issue of how to fairly allocate resource in WMN becomes an important topic.

1.2 Motivation

The new technology of WMN seems to release Wi-Fi’s limitations. However, APs, as we called backhaul in WMNs, still take an important role of gateways to the Internet. Therefore, how to appropriate deploy APs, is still a problem of internet service providers.

In addition, to enable multimedia applications such as video-conferencing and voice over IP (VoIP) in WMNs, the guarantees of Quality-of-Service (QoS) are very essential. This is because multimedia applications are very sensitive to delay and delay jitter. If the network is well designed and Internet gateways are optimally deployed, each mobile host can enjoy QoS-guaranteed multimedia applications.

To enable a variety of applications in WMNs, many researchers are dedicated to develop new schemes that solve the problems as mentioned above, such as backhaul deployment, unfairness in wireless environment, and how to satisfy the QoS requirements in WMNs. This is also the goal of my work.

1.3 Literature Survey

1.3.1 Wireless Mesh Networks

A WMN is a fully wireless network that employs multi-hop communications to forward traffic to wired Internet through backhauls. Different from flat ad hoc networks, a mesh network introduces a hierarchy in the network architecture with the implementation of dedicated nodes (called wireless routers) communicating among each other and providing wireless transport services to data traveling from users to either other users or access points (access points are special wireless routers with a high-bandwidth wired connection to the Internet backbone). The network of wireless routers forms a wireless backbone (tightly integrated into the mesh network), which provides multihop connectivity between nomadic users and wired gateways. The meshing among wireless routers and access points creates a wireless backhaul communication system, which provides each mobile user with a low-cost, high-bandwidth, and seamless multihop interconnection service with a limited number of Internet entry points and with other wireless mobile users. Roughly and generally speaking, backhaul is used to indicate the service of forwarding traffic from the originator node to an access point from which it can be distributed over an external network. Specifically in the mesh case, the traffic is originated in the users' devices, traverses the wireless backbone, and is distributed over the Internet network.

WMN has its own characteristics different from Wi-Fi or wired networks. We should redesign the routing protocols with respect to these characteristics [3] [4] [5][11][14].

1.3.2 End-to-end Performance

In [9][15], the authors propose a fairness scheme which includes the following issues:

1. Temporal fairness

   The authors allocate resource with respect to the channel access time which to ensure the fairness amount each data flows. The channel access time is fair, however the throughput is unfair. We can see the result in Table 1-1.

   In the scenario of Figure 1-1, the capacity of link C1, C2, and C3 is 20Mbps, 5Mbps, and 10Mbps respectively. With respect to throughput fairness, the throughput of flow(1,3), flow(1,2), TA(2), and TA(3) are the same and the delay time respect to each flow is 0.415s, 0.083s, 0.332s, 0.116s, and 0.167s. With respect to temporal fairness, the throughput of each flow is 1Mbps, 5 Mbps, 1.25 Mbps, 2.5 Mbps, and the channel access time are the same.

   In this example, system operators allocate the resource should consider throughput and temporal fairness.

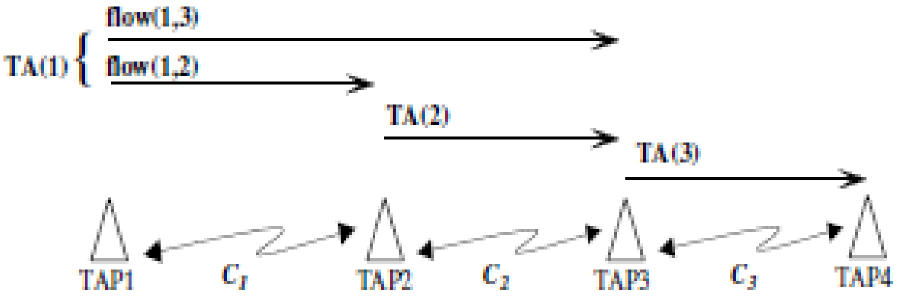

Figure 1-2 Example scenario for throughput comparison under different fairness constraints.

Table 1-1 Comparison of throughput of scenario depicted in Figure 1-2 for different fairness constraints.

Fairness Constrains		Flows				
		flow(1,3)	flow(1,2)	TA(2)	TA(3)	Total
Temporal	Throughput(Mbps)	1	5	1.25	2.5	9.75
	delay(sec.)	0.25	0.25	0.25	0.25	1
Spatial Bias & Throughput	Throughput(Mbps)	1.66	1.66	1.66	1.66	6.64
	Delay(sec.)	0.415	0.083	0.332	0.116	1
Spatial Bias & Temporal	Throughput(Mbps)	2.5	2.5	0.625	1.25	6.87
	delay(sec.)	5/8	1/8	1/8	1/8	1

2. Spatial bias fairness

In multi-hop communication environment, if we allocate the same resource to every flows. However, the flow with increasing hop counts, the resource allocated to this flow shared by more hops. Therefore, the performance is decreased. This is so called spatial bias. The authors propose that allocate the same channel time of fist link to each flows to remove the spatial bias. This ensure the throughput not be decreased with more hop counts.

However, in this way, the delay time is increased with hop count increasing. Clients far away from the backhaul experience longer delay time. We should allocate the resource with consideration for throughput and temporal fairness at the same time. Otherwise this work is based on chain topology, this may not be realistic.

1.4 Proposed Approach

We model the problem as linear integer mathematical programming problems. Then, heuristics are developed and the Lagrangean relaxation method is applied to solve the problems. We take the subgradient method with finding the extreme points to solve the Lagrangean relaxation.

1.5 Thesis Organization

The remainder of this thesis is organized as follows. A mathematical formulation for the Wireless Mesh Networks design problem is first shaped in Chapter 2. Chapter 3 presents the Lagrangean relaxation of the problem and the methods for solving the Lagrangean sub-problems. Chapter 4 describes how to get primal feasible solutions and its heuristics of each problem. Chapter 5 is the computational experiments for each problem. Finally, Chapter 6 is the summary of this thesis and also suggests some direction for the future works.

Chapter 2 Problem Formulation

2.1 Problem Description

The problem we addressed is to minimize the total cost of backhaul deployment in WMNs, while considering the end-to-end QoS requirements of each mobile host.

This problem to be solved is to decide how to deploy backhauls economically and how to assign mobile hosts to appropriate TAPs. Then, each source TAP is assigned an appropriate backhaul and a routing path with bandwidth allocation on each links of the selected path. In addition, the end-to-end QoS requirements of each mobile host should be considered.

We assume that the network topology including TAP set and mobile host set is known. The TAPs admit connection requests from mobile hosts and relay data traffic from other TAPs to associated backhauls. Each TAP is a candidate backhaul, too. Once a TAP is installed as a backhaul with a wireline, it integrates both functions of an access point and an egress of WMNs to the Internet. Then, the data traffic of mobile hosts is transmitted to the Internet via the backhauls finally.

To deploy the backhauls of entire network while considering end-to-end performance jointly is not an easy task. Under the goal of min cost of backhaul deployment, we should install backhauls as less as possible. However, less backhauls may not fulfil the end-to-end QoS requirements of all mobile hosts. More backhauls allow mobile hosts to enjoy good QoS, but the backhaul deployment may not be economical. Therefore, there implies a tradeoff between deployment cost and end-to-end QoS requirements. And it is the major difficulty of this problem. The summary of problem description is listed as below.

Table 2-1 Problem Description

Assumptions:

1. The backhauls integrate both functions of access and backhaul.
2. All flows are transmitted to Internet through backhauls.
3. There is no additional round trip time from the wired Internet.
4. Mobile hosts to TAPs and TAP to TAP transmission occurs on orthogonal channels.
5. The average delay and jitter from one MH to any TAPs can be formulated as a function of required data rate and link capacity.
6. The average delay and jitter from one TAP to another can be formulated as a function of link aggregate flow and capacity.

Given:

1. The set of all TAPs - also the set of candidate backhauls.
2. The set of all backhaul configurations.
3. The cost of backhaul installation and configuration.
4. The set of all candidate paths from each TAP to reach backhauls.
5. The set of all mobile hosts.
6. The required data rate of each mobile host.
7. The QoS requirements including end-to-end mean delay and delay jitter.

Objective:

To minimize the total cost of backhaul deployment.

Subject to:

1. Backhaul assignment constraints
2. Routing constraints
3. Link constraints
4. Mobile host constraints
5. Capacity constraints
6. QoS constraints

To determine:

1. Backhaul deployment and configuration
2. Routing assignment of each O-D pairs
3. The source TAP assignment of each mobile host
4. Bandwidth allocation on each link

2.2 Notation

The notations listed bellow is the given parameters and the decision variables of our formulation shown in Table 2-2 and Table 2-3:

Table 2-2 Notation of Given Parameters

Notation	Description
V	The set of TAP*s* which is also the set of candidate backhauls, where $v \in V$.
K	The set of backhaul configurations, where $k \in K$.
c_b	The fixed cost to install candidate backhaul b into a backhaul.
P_{bs}	The set of paths from original TAP s to destination TAP b, where $p \in P_{bs}$.
δ_{puv}	The indication function, which denote link uv on path p.
C_{uv}(packets/sec)	The capacity of link uv.
$\overline{C_s}$ (packets/sec)	The nodal capacity of TAP s.
$\overline{\overline{C_s}}$ (packets/sec)	The air-interface capacity of TAP s.
$\Phi_b\left(k\right)$	The cost of building the wired line on backhaul b, which is a function of backhaul configuration k.
$Q_b\left(k\right)$	The capacity of the wired line on backhaul b, which is a function of backhaul configuration k.
$F_{uv}(f_{uv},C_{uv})$	The average delay on link uv, which is a function of aggregate flow f_{uv} and link capacity C_{uv}.
$M_{uv}(f_{uv},C_{uv})$	The delay jitter on link uv, which is a function of aggregate

	flow f_{uv} and link capacity C_{uv}.
T	The end-to-end delay requirement.
J	The end-to-end jitter requirement.
N	The set of mobile hosts, where $n \in N$.
θ_n (packets/sec)	The data rate required to be transmitted of mobile host n.
r_{ns}(packets/sec)	The link capacity from mobile host n to TAP s.
$\overline{F}_{ns}\left(\theta_n, r_{ns}\right)$	The average delay from mobile host n to source TAP s, which is a function of required data rate θ_n and link capacity r_{ns}.
$\overline{M}_{ns}\left(\theta_n, r_{ns}\right)$	The delay jitter from mobile host n to source TAP s, which is a function of required data rate θ_n and link capacity r_{ns}.
M_1	An arbitrarily large number.
M_2	An arbitrarily large number.
M_3	An arbitrarily large number.

Table 2-3 Notation of Decision Variables

Notation	Description
η_{bk}	1 if TAP b is selected to be a backhaul with configuration k; otherwise 0.
z_{bs}	1 if TAP s connects to the wired network via backhaul b; otherwise 0.
x_p	1 if path p from TAP s to TAP b is selected; otherwise 0.
y_{suv}	1 if link uv is on the path adopted by TAP s; otherwise 0.
κ_{ns}	1 if mobile host n associates to TAP s; otherwise 0.
a_s (packets/sec)	The data rate required to be transmitted of TAP s.
γ_{suv}	The bandwidth allocation of TAP s on link uv.

f_{uv}	The aggregate flow on link *uv*.

2.3 Problem Formulation

Optimization Problem:

Objective function (IP):

$$\min \sum_{b\in V}\sum_{k\in K}\left(c_b+\Phi_b\left(k\right)\right)\eta_{bk} \qquad \text{(IP)}$$

subject to:

$$\sum_{b\in V}\sum_{k\in K}Q_b\left(k\right)\cdot\eta_{bk} \ge \sum_{n\in N}\theta_n \qquad \text{(IP 1)}$$

$$\sum_{k\in K}\eta_{bk} = 0 \ or \ 1 \qquad \forall b\in V \qquad \text{(IP 2)}$$

$$z_{bs} \le \sum_{k\in K}\eta_{bk} \qquad \forall b,s\in V \qquad \text{(IP 3)}$$

$$\sum_{b\in V}z_{bs} = 1 \qquad \forall s\in V \qquad \text{(IP 4)}$$

$$z_{bs} \le \sum_{p\in P_{bs}}x_p \qquad \forall b,s\in V \qquad \text{(IP 5)}$$

$$\sum_{b\in V}\sum_{p\in P_{bs}}x_p = 1 \qquad \forall s\in V \qquad \text{(IP 6)}$$

$$\sum_{b\in V}\sum_{p\in P_{bs}}x_p\delta_{puv} \le y_{suv} \qquad \forall s,u,v\in V \qquad \text{(IP 7)}$$

$$\sum_{s\in V}\sum_{v\in V}y_{suv} \ge 1-\sum_{k\in K}\eta_{uk} \qquad \forall u\in V \qquad \text{(IP 8)}$$

$$\sum_{s\in V}\sum_{v\in V}y_{suv} \le M_1\left(1-\sum_{k\in K}\eta_{uk}\right) \qquad \forall u\in V \qquad \text{(IP 9)}$$

$$\sum_{s\in V}\sum_{u\in V}y_{suv} \ge \sum_{k\in K}\eta_{vk} \qquad \forall v\in V \qquad \text{(IP 10)}$$

$$\sum_{s\in V}\sum_{u\in V}y_{suv} \le \left|V\right|-1 \qquad \forall v\in V \qquad \text{(IP 11)}$$

$$\sum_{s\in V}\kappa_{ns} = 1 \qquad \forall n\in N \qquad \text{(IP 12)}$$

$$\sum_{n\in N}\theta_n\kappa_{ns} \le \overline{\overline{C_s}} \qquad \forall s\in V \qquad \text{(IP 13)}$$

$$\sum_{n\in N}\theta_n\kappa_{ns} \le a_s \qquad \forall s\in V \tag{IP 14}$$

$$0 \le a_s \le \overline{\overline{C_s}} \qquad \forall s\in V \tag{IP 15}$$

$$\sum_{s\in V} a_s \ge \sum_{n\in N}\theta_n \qquad \forall s\in V \tag{IP 16}$$

$$a_s - M_2(1-y_{suv}) \le \gamma_{suv} \qquad \forall s,u,v\in V \tag{IP 17}$$

$$\gamma_{suv} \le a_s \qquad \forall s,u,v\in V \tag{IP 18}$$

$$\sum_{s\in V}\gamma_{suv} \le f_{uv} \qquad \forall u,v\in V \tag{IP 19}$$

$$0 \le f_{uv} \le C_{uv} \qquad \forall u,v\in V \tag{IP 20}$$

$$0 \le \gamma_{suv} \le C_{uv} \qquad \forall s,u,v\in V \tag{IP 21}$$

$$\sum_{s\in V}\sum_{u\in V}\gamma_{suv} \le \overline{C}_v \qquad \forall v\in V \tag{IP 22}$$

$$\sum_{s}\sum_{u}\gamma_{sub} + a_b - M_3\left(1-\sum_{k\in K}\eta_{bk}\right) \le \sum_{k\in K} Q_b(k)\eta_{bk} \quad \forall b\in V \tag{IP 23}$$

$$\sum_{u\in V}\sum_{v\in V} y_{suv}F_{uv}\left(f_{uv},C_{uv}\right) + \kappa_{ns}\overline{F}_{ns}\left(\theta_n,r_{ns}\right) \le T \quad \forall n\in N, s\in V \tag{IP 24}$$

$$\sum_{u\in V}\sum_{v\in V} y_{suv}M_{uv}\left(f_{uv},C_{uv}\right) + \kappa_{ns}\overline{M}_{ns}\left(\theta_n,r_{ns}\right) \le J \quad \forall n\in N, s\in V \tag{IP 25}$$

$$\eta_{bk} = 0 \text{ or } 1 \qquad \forall b\in V, k\in K \tag{IP 26}$$

$$z_{bs} = 0 \text{ or } 1 \qquad \forall b,s\in V \tag{IP 27}$$

$$x_p = 0 \text{ or } 1 \qquad \forall p\in P_{bs}\ \ b,s\in V \tag{IP 28}$$

$$y_{suv} = 0 \text{ or } 1 \qquad \forall s,u,v\in V \tag{IP 29}$$

$$\kappa_{ns} = 0 \text{ or } 1 \qquad \forall n\in N, s\in V . \tag{IP 30}$$

Explanation of the objective function:

The main objective of this problem is to minimize the cost of backhaul deployment that includes installation cost of upgrading existing TAPs to backhauls and wireline cost of leasing wirelines on backhauls to the Internet.

Explanation of constraints:

1) **Backhaul assignment constraints:**

   Constraint (1) confines that the total wireline capacity on backhauls should be equal to or large than the total data rate required to be transmitted of all mobile hosts. Therefore, all incoming flows from mobile hosts can be transmitted to the Internet via backhauls.

   Constraint (2) confines that each candidate backhaul select exactly only one configuration or none.

   Constraint (3) confines that a candidate backhaul should be installed as a backhaul firstly, then other TAPs can be assigned to this candidate backhaul.

2) **Routing constraints:**

   Constraint (4) confines that each TAP *s* must select a candidate backhaul *b* as an egress.

   Constraint (5) confines that once TAP *s* selects candidate backhaul *b* as an egress, there must paths exist from TAP *s* to candidate backhaul *b*.

   Constraint (6) confines that each TAP s select exactly one candidate backhaul as egress, and exactly one routing path to the selected egress.

   Constraint (7) confines that once the path *p* is selected and the link *uv* is on the path, then the decision variable y_{suv} must be equal to 1.

3) **Link constraints:**

   Constraint (8) and (9) are two complementary constraints which confine that each TAP, except the backhauls, has at least one out-going link.

   Constraint (10) and (11) are two complementary constraints which confine that the backhauls has at least one in-coming link.

4) Mobile host constraints:

Constraint (12) confines that each mobile host is assigned to exactly one TAP.

Constraint (13) confines that the total incoming data rate from mobile hosts admitted by TAP *s* should not large its the air-interface capacity $\overline{\overline{C}}_s$.

Constraint (14) confines the total incoming data rate from mobile hosts admitted by TAP *s* should not large than the data rate required to be transmitted of TAP *s*.

Constraint (15) confines the boundries of data rate required to be transmitted of each TAP.

Constraint (16) confines that the total data rate required to be transmitted of all TAPs should be equal to or large than the total data rate required to be transmitted of all mobile hosts.

5) Link capacity constraints:

Constraint (17) and (18) are two complementary constraints which confine that the bandwidth allocation of TAP *s* on link *uv* should be equal to the data rate required to be transmitted of TAP *s* if link *uv* is on the selected path of TAP *s*. Otherwise, the bandwidth allocation of TAP *s* on link *uv* should be 0.

Constraint (19) confines that total bandwidth allocation of all TAPs on link *uv* should not large than the aggregate flow on link *uv*.

Constraint (20) confines the boundries of aggregate flow on link *uv*.

Constraint (21) confines the boundries of bandwidth allocation of TAP *s* on link *uv*.

6) Nodal capacity constraints

Constraint (22) confines that each TAP's total incoming data flow from others TAPs should not be large than its nodal capacity.

Constraint (23) confines that total incoming flow of all backhauls should not be large than total wireline capacities.

7) QoS constraints

Constraint (24) confines the end-to-end average delay should be no longer than maximum allowable end-to-end average delay requirement.

Constraint (25) confines the end-to-end delay jitter should be no longer than maximum allowable end-to-end delay jitter requirement.

For simplification, we take MM1 model to calculate the intra-TAP mean delay. And we compute the delay from moble host to TAP by the formulation proposed in [13]. We assume the delay time is exponential distribution. Therefore, the delay jitter is the square of the mean dealy.

8) The Integer Constraints:

Constraints (26), (27), (28), (29), and (30) are the integer constraints of decision variables.

Chapter 3 Solution Approach

3.1 Introduction to the Lagrangean Relaxation Method

In the 1970s, Lagrange Relaxation was first introduced for solving large scale integer programming. Because it is flexible and provides good solutions to these problems, it has become a wildly used tool for dealing with optimization problems, such as integer programming problems and even nonlinear programming problems.

Many difficult problems can be viewed as easy problems complicated by a relative small set of side constraints. By adopting Lagrange Relaxation, the original hard problem becomes an easier Lagrangean problem after dualizing the set of tangled constraints with fixed multiplier to the objective function. This new problem can be further divided into several mutually independent subproblems with its own constraints. Therefore, we only need to solve each subproblem optimally in some well-know algorithms within a smaller space [7][8].

The overall procedure to solve the network design problem is shown as in Figure 1-3. They are composed of two procedures, Lagrangean relaxation and subgradient optimization procedure. The Lagrangean relaxation of the primal problem is developed first which provides lower bound on the optimal solutions, since we relax some constraints of the original problem. Then, we use the boundary to design a heuristic approach to get a primal feasible solution. To solve the original problem optimally and minimize the gap between the primal problem and the Lagrangean Relaxation problem, we improve the lower bound by solving the sub-problems optimally and using the subgradient method to adjust the multipliers at each iteration.

Then subgradient optimization procedure is used for further improving these solutions by updating the Lagrangean multipliers.

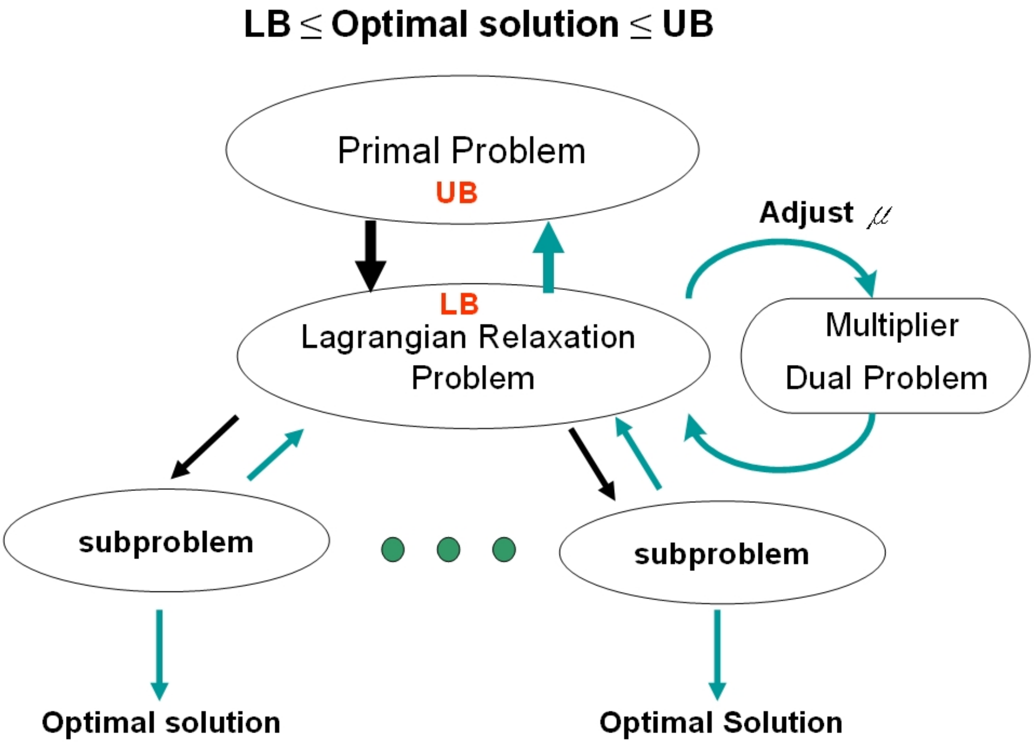

Figure 3-1 Lagrangean Relaxation illustration

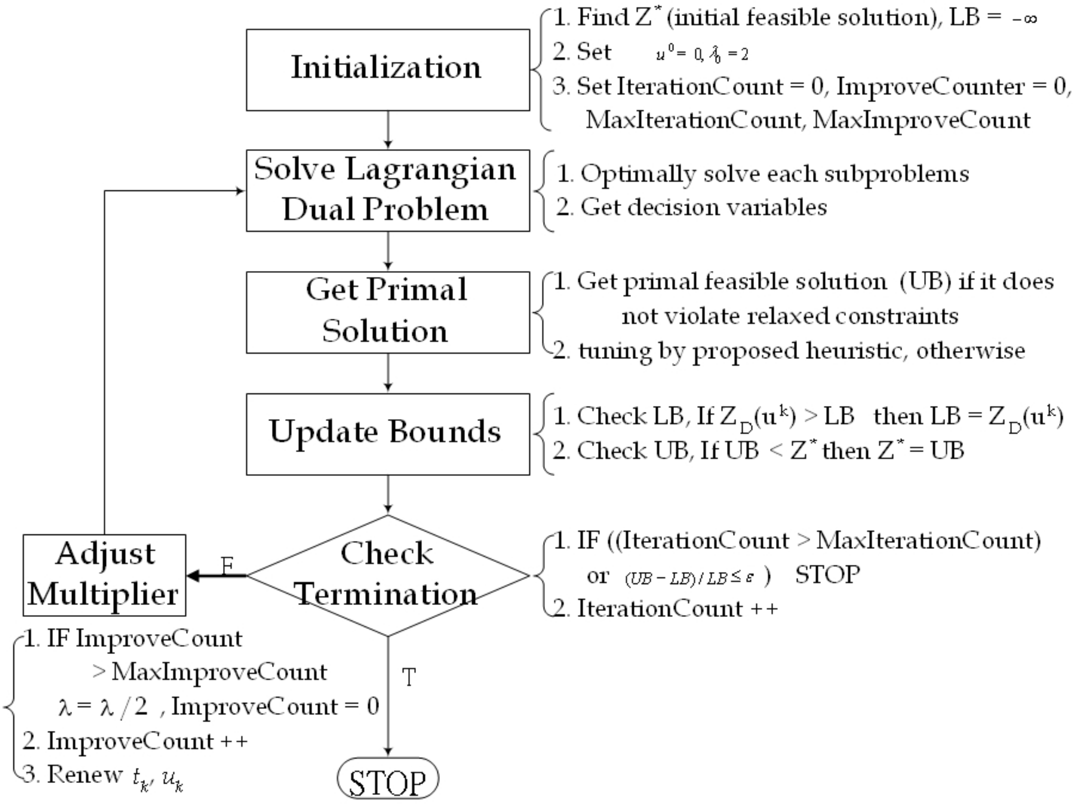

Figure 3-2 Lagrangean relaxation procedures

3.2 Lagrangean Relaxation

We relax Constraints (1), (3), (5), (7), (8), (9), (10), (13), (14), (17), (18), (19), (23), (24), and (25) and multiply them by the multiplier vectors respectively, which adds to the objective function as follows:

Optimization Problem (LR):

$$Z_{LR}\left(\mu^1,\mu^2_{bs},\mu^3_{bs},\mu^4_{suv},\mu^5_u,\mu^6_u,\mu^7_v,\mu^8_s,\mu^9_s,\mu^{10}_{suv},\mu^{11}_{suv},\mu^{12}_{uv},\mu^{13}_b,\mu^{14}_{ns},\mu^{15}_{ns}\right)=$$

$$\min\sum_{b\in V}\sum_{k\in K}\left(c_b+\Phi_b\left(k\right)\right)\eta_{bk}$$

$$+\mu^1\left[\sum_{n\in N}\theta_n-\sum_{b\in V}\sum_{k\in K}Q_b\left(k\right)\cdot\eta_{bk}\right]$$

$$+\sum_{b\in V}\sum_{s\in V}\mu^2_{bs}\left[z_{bs}-\sum_{k\in K}\eta_{bk}\right]$$

$$+\sum_{b\in V}\sum_{s\in V}\mu^3_{bs}\left[z_{bs}-\sum_{p\in P_{bs}}x_p\right]$$

$$+\sum_{s\in V}\sum_{u\in V}\sum_{v\in V}\mu^4_{suv}\left[\sum_{b\in V}\sum_{p\in P_{bs}}x_p\delta_{puv}-y_{suv}\right]$$

$$+\sum_{u\in V}\mu^5_u\left[1-\sum_{k\in K}\eta_{uk}-\sum_{s\in V}\sum_{v\in V}y_{suv}\right]$$

$$+\sum_{u\in V}\mu^6_u\left[\sum_{s\in V}\sum_{v\in V}y_{suv}-M_1\left(1-\sum_{k\in K}\eta_{uk}\right)\right]$$

$$+\sum_{v\in V}\mu^7_v\left[\sum_{k\in K}\eta_{vk}-\sum_{s\in V}\sum_{u\in V}y_{suv}\right]$$

$$+\sum_{s\in V}\mu^8_s\left[\sum_{n\in N}\theta_n\kappa_{ns}-\overline{\overline{C}}_s\right]$$

$$+\sum_{s\in V}\mu^9_s\left[\sum_{n\in N}\theta_n\kappa_{ns}-a_s\right]$$

$$+\sum_{s\in V}\sum_{u\in V}\sum_{v\in V}\mu^{10}_{suv}\left[a_s-M_2(1-y_{suv})-\gamma_{suv}\right]$$

$$+\sum_{s\in V}\sum_{u\in V}\sum_{v\in V}\mu_{suv}^{11}\left[\gamma_{suv}-a_s\right]$$

$$+\sum_{u\in V}\sum_{v\in V}\mu_{uv}^{12}\left[\sum_{s\in V}\gamma_{suv}-f_{uv}\right]$$

$$+\sum_{b\in V}\mu_{b}^{13}\left[\sum_{s}\sum_{u}\gamma_{sub}+a_b-M_3\left(1-\sum_{k\in K}\eta_{bk}\right)-\sum_{k\in K}Q_b\left(k\right)\eta_{bk}\right]$$

$$+\sum_{n\in N}\sum_{s\in V}\mu_{ns}^{14}\left[\sum_{u\in V}\sum_{v\in V}y_{suv}F_{uv}\left(f_{uv},C_{uv}\right)+\kappa_{ns}\overline{F}_{ns}\left(\theta_n,r_{ns}\right)-T\right]$$

$$+\sum_{n\in N}\sum_{s\in V}\mu_{ns}^{15}\left[\sum_{u\in V}\sum_{v\in V}y_{suv}M_{uv}\left(f_{uv},C_{uv}\right)+\kappa_{ns}\overline{M}_{ns}\left(\theta_n,r_{ns}\right)-J\right]$$

(LR)

subject to:

$$\sum_{k\in K}\eta_{bk}=0\ or\ 1 \qquad \forall b\in V \qquad \text{(IP 2)}$$

$$\sum_{b\in V}z_{bs}=1 \qquad \forall s\in V \qquad \text{(IP 4)}$$

$$\sum_{b\in V}\sum_{p\in P_{bs}}x_p=1 \qquad \forall s\in V \qquad \text{(IP 6)}$$

$$\sum_{s\in V}\sum_{u\in V}y_{suv}\le\left|V\right|-1 \qquad \forall v\in V \qquad \text{(IP 11)}$$

$$\sum_{s\in V}\kappa_{ns}=1 \qquad \forall n\in N \qquad \text{(IP 12)}$$

$$0\le a_s\le\overline{\overline{C_s}} \qquad \forall s\in V \qquad \text{(IP 15)}$$

$$\sum_{s\in V}a_s\ge\sum_{n\in N}\theta_n \qquad \forall s\in V \qquad \text{(IP 16)}$$

$$0\le f_{uv}\le C_{uv} \qquad \forall u,v\in V \qquad \text{(IP 20)}$$

$$0\le\gamma_{suv}\le C_{uv} \qquad \forall s,u,v\in V \qquad \text{(IP 21)}$$

$$\sum_{s\in V}\sum_{u\in V}\gamma_{suv}\le\overline{C}_v \qquad \forall v\in V \qquad \text{(IP 22)}$$

$$\eta_{bk}=0\ or\ 1 \qquad \forall b\in V,k\in K \qquad \text{(IP 26)}$$

$$z_{bs}=0\ or\ 1 \qquad \forall b,s\in V \qquad \text{(IP 27)}$$

$$x_p=0\ or\ 1 \qquad \forall p\in P_{bs}\ \ b,s\in V \qquad \text{(IP 28)}$$

$$y_{suv} = 0 \ or \ 1 \qquad \forall s, u, v \in V \qquad \text{(IP 29)}$$

$$\kappa_{ns} = 0 \ or \ 1 \qquad \forall n \in N, s \in V \ . \qquad \text{(IP 30)}$$

where $\mu^{1}, \mu_{bs}^{2}, \mu_{bs}^{3}, \mu_{suv}^{4}, \mu_{u}^{5}, \mu_{u}^{6}, \mu_{v}^{7}, \mu_{s}^{8}, \mu_{s}^{9}, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_{b}^{13}, \mu_{ns}^{14}$, and μ_{ns}^{15} are the vectors of non-negative Lagrangean multipliers. To solve the LR, we decompose the problem into the following six mutually independent and easily solvable optimization subproblems.

3.2.1 Subproblem 1 (related to decision variable η_{bk})

Objective function:

$$Z_{sub3.1}\left(\mu^1, \mu_{bs}^2, \mu_b^5, \mu_b^6, \mu_b^7, \mu_b^{13}\right)$$

$$= \min \sum_{b\in V}\sum_{k\in K}\Big[c_b + \Phi_b(k) - Q_b(k)\mu^1 - \sum_{s\in V}\mu_{bs}^2 - \mu_b^5 + M_1\mu_b^6 + \mu_b^7$$

$$+\left(M_3 - Q_b(k)\right)\mu_b^{13}\Big]\eta_{bk} \qquad \text{(SUB 3.1)}$$

subject to:

$$\sum_{k\in K}\eta_{bk} = 0 \; or \; 1 \qquad \forall b \in V \qquad \text{(IP 2)}$$

$$\eta_{bk} = 0 \; or \; 1 \qquad \forall b \in V, k \in K. \qquad \text{(IP 26)}$$

(SUB 3.1) can be further decomposed into |*V*| independent subproblems. For each candidate backhaul *b*,

$$\min \sum_{k\in K}\Big[c_b + \Phi_b(k) - Q_b(k)\mu^1 - \sum_{s\in V}\mu_{bs}^2 - \mu_b^5 + M_1\mu_b^6 + \mu_b^7 + \left(M_3 - Q_b(k)\right)\mu_b^{13}\Big]\eta_{bk}$$

(SUB 3.1.1)

Subject to:

$$\sum_{k\in K}\eta_{bk} = 0 \; or \; 1 \qquad \forall b \in V \qquad \text{(IP 2)}$$

$$\eta_{bk} = 0 \; or \; 1 \qquad \forall b \in V, k \in K. \qquad \text{(IP 26)}$$

For each (SUB 3.1.1), we calculate the coefficient $\left(c_b + \Phi_b(k) - Q_b(k)\mu^1 - \sum_{s\in V}\mu_{bs}^2 - \mu_b^5 + M_1\mu_b^6 + \mu_b^7 + \left(M_3 - Q_b(k)\right)\mu_b^{13}\right)$ of η_{bk} for each configuration *k*. Then we find the smallest coefficient for all configuration *k* of candidate bachhaul *b*. If the smallest coefficient is negative then set the corresponding η_{bk} to be 1 and the others to be 0, otherwise set all configuration *k* to be 0.

3.2.2 Subproblem 2 (related to decision variable z_{bs})

Objective function:

$$Z_{sub3.2}\left(\mu_{bs}^{2},\mu_{bs}^{3}\right)$$

$$=\min\sum_{s\in V}\sum_{b\in V}\left[\mu_{bs}^{2}+\mu_{bs}^{3}\right]z_{bs} \qquad \text{(SUB 3.2)}$$

subject to:

$$\sum_{b\in V} z_{bs}=1 \qquad \forall s\in V \qquad \text{(IP 4)}$$

$$z_{bs}=0 \ or \ 1 \qquad \forall b,s\in V. \qquad \text{(IP 27)}$$

This problem can be further decomposed into $|V|$ independent subproblems. For each source TAP s,

$$\min\sum_{b\in V}\left[\mu_{bs}^{2}+\mu_{bs}^{3}\right]z_{bs} \qquad \text{(SUB 3.2.1)}$$

Subject to:

$$\sum_{b\in V} z_{bs}=1 \qquad \forall s\in V \qquad \text{(IP 4)}$$

$$z_{bs}=0 \ or \ 1 \qquad \forall b,s\in V. \qquad \text{(IP 27)}$$

The algorithm to solve the decomposed subproblem is stated as follows:

Step 1: Compute the coefficient $\left(\mu_{bs}^{2}+\mu_{bs}^{3}\right)$ of z_{bs} for each candidate backhaul b, and sort it in ascending order.

Step 2: Select the first order coefficient and assign the corresponding decision variable z_{bs} to 1 and others to 0.

3.2.3 Subproblem 3 (related to decision variable x_p)

Objective function:

$$Z_{sub3.3}\left(\mu_{bs}^{3},\mu_{suv}^{4}\right)$$

$$=\min\sum_{s\in V}\sum_{b\in V}\sum_{p\in P_{bs}}\left[-\mu_{bs}^{3}+\sum_{u\in V}\sum_{v\in V}\mu_{suv}^{4}\delta_{puv}\right]x_p \qquad \text{(SUB 3.3)}$$

subject to:

$$\sum_{b\in B}\sum_{p\in P_{bs}}x_p=1 \qquad \forall s\in V \qquad (4)$$

$$x_p=0\ or\ 1 \qquad \forall p\in P_{bs},b\in B,s\in V. \qquad (28)$$

This problem can be further decomposed into |*V*| independent shortest path problems with non-negative arc weights. Each shortest path problem can be easily solved by the Dijkstra's algorithm. If the coefficient of x_p is negative, then set x_p to 1, otherwise 0.

3.2.4 Subproblem 4 (related to decision variable a_s)

Objective function:

$$Z_{sub3.4}\left(\mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_s^{13}\right)$$

$$= \min \sum_{s\in V}\left[-\mu_s^9 + \sum_{u\in V}\sum_{v\in V}\mu_{suv}^{10} - \sum_{u\in V}\sum_{v\in V}\mu_{suv}^{11} + \mu_s^{13}\right]a_s \qquad \text{(SUB 3.4)}$$

subject to:

$$0 \le a_s \le \overline{\overline{C_s}} \qquad \forall s \in V \qquad \text{(IP 15)}$$

$$\sum_{s\in V} a_s \ge \sum_{n\in N}\theta_n \qquad \forall s \in V. \qquad \text{(IP 16)}$$

The proposed algorithm for solving (SUB 3.4) is described as follows:

Step 1: Reset all a_s to 0.

Step 2: For each TAP s, we compute the coefficient

$$\left(-\mu_s^9 + \sum_{u\in V}\sum_{v\in V}\mu_{suv}^{10} - \sum_{u\in V}\sum_{v\in V}\mu_{suv}^{11} + \mu_s^{13}\right) \text{ for each } a_s.$$

Step 3: Find the unset a_s with smallest coefficient. If found, then set it to $\overline{\overline{C_s}}$, else stop.

Step 4: Repeat step 3 until the total data rate required to be transmitted of all TAPs is equal to or large than the total incoming flow of all mobile hosts.

3.2.5 Subproblem 5 (related to decision variable γ_{suv})

Objective function:

$$Z_{sub3.5}\left(\mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_{v}^{13}\right)$$

$$= \min \sum_{s\in V}\sum_{u\in V}\sum_{v\in V}\left[-\mu_{suv}^{10} + \mu_{suv}^{11} + \mu_{uv}^{12} + \mu_{v}^{13}\right]\gamma_{suv} \qquad \text{(SUB 3.5)}$$

subject to:

$$0 \le \gamma_{suv} \le C_{uv} \qquad \forall s,u,v \in V \qquad \text{(IP 21)}$$

$$\sum_{s\in V}\sum_{u\in V}\gamma_{suv} \le \overline{C}_v \qquad \forall v \in V. \qquad \text{(IP 22)}$$

This problem can be further decomposed into $|V|$ independent subproblems. For each source TAP *v*,

$$\min \sum_{s\in V}\sum_{u\in V}\left[-\mu_{suv}^{10} + \mu_{suv}^{11} + \mu_{uv}^{12} + \mu_{v}^{13}\right]\gamma_{suv} \qquad \text{(SUB 3.5.1)}$$

$$0 \le \gamma_{suv} \le C_{uv} \qquad \forall s,u,v \in V \qquad \text{(IP 21)}$$

$$\sum_{s\in V}\sum_{u\in V}\gamma_{suv} \le \overline{C}_v \qquad \forall v \in V. \qquad \text{(IP 22)}$$

The proposed algorithm for solving (SUB 3.5.1) is described as follows:

Step 1: For each TAP *v*, we compute the coefficient $\left(-\mu_{suv}^{10} + \mu_{suv}^{11} + \mu_{uv}^{12} + \mu_{v}^{13}\right)$ for each γ_{suv}.

Step 2: For all incoming links of TAP *v*, we find the smallest coefficient. If the total incoming flow of TAP *v* does not exceed the nodal capacity $\overline{C}_v$ and the smallest coefficient is negative then we set the corresponding γ_{suv} to 1. Repeat step 2 for all TAP *v*.

Step 3: Set the other incoming flow γ_{suv} to 0.

3.2.6 Subproblem 6 (related to decision variable y_{suv} and f_{uv})

Objective function:

$$Z_{sub3.6}\left(\mu_{suv}^{4},\mu_{u}^{5},\mu_{u}^{6},\mu_{v}^{7},\mu_{suv}^{10},\mu_{ns}^{14},\mu_{ns}^{15},\mu_{uv}^{12}\right)$$

$$\begin{aligned}&=\min\sum_{u\in V}\sum_{v\in V}\left[\sum_{s\in V}\left(-\mu_{suv}^{4}-\mu_{u}^{5}+\mu_{u}^{6}-\mu_{v}^{7}+M_{2}\mu_{suv}^{10}+\sum_{n\in N}\mu_{ns}^{14}F_{uv}\left(f_{uv},C_{uv}\right)\right.\right.\\&\qquad\left.\left.+\sum_{n\in N}\mu_{ns}^{15}M_{uv}\left(f_{uv},C_{uv}\right)\right)y_{suv}-\mu_{uv}^{12}f_{uv}\right]\end{aligned}\tag{SUB 3.6}$$

subject to:

$$\sum_{s\in V}\sum_{u\in V}y_{suv}\le\left|V\right|-1 \qquad \forall v\in V \tag{IP 11}$$

$$0\le f_{uv}\le C_{uv} \qquad \forall u,v\in V \tag{IP 20}$$

$$y_{suv}=0\ or\ 1 \qquad \forall s,u,v\in V\ . \tag{IP 29}$$

This subproblem is complicated due to the coupling of y_{suv} and f_{uv}. It can be further decomposed into $\left|V\times V\right|$ independent subproblems. For each link uv,

$$\begin{aligned}&\min\left[\sum_{s\in V}\left(-\mu_{suv}^{4}-\mu_{u}^{5}+\mu_{u}^{6}-\mu_{v}^{7}+M_{2}\mu_{suv}^{10}+\sum_{n\in N}\mu_{ns}^{14}F_{uv}\left(f_{uv},C_{uv}\right)+\sum_{n\in N}\mu_{ns}^{15}M_{uv}\left(f_{uv},C_{uv}\right)\right)y_{suv}\right.\\&\qquad\left.-\mu_{uv}^{12}f_{uv}\right]\end{aligned}\tag{SUB 3.6.1}$$

Subject to:

$$\sum_{s\in V}\sum_{u\in V}y_{suv}\le\left|V\right|-1 \qquad \forall v\in V \tag{IP 11}$$

$$0\le f_{uv}\le C_{uv} \qquad \forall u,v\in V \tag{IP 20}$$

$$y_{suv}=0\ or\ 1 \qquad \forall s,u,v\in V. \tag{IP 29}$$

For each (SUB 3.6.1) can be solved analytically [2][6] by the algorithm stated as follows:

Step 1: Solve $y_{suv}(f_{uv}) = -\sum_{b \in V} \mu_{suv}^{3} - \mu_{u}^{4} + \mu_{u}^{5} - \mu_{v}^{6} + M_{2}\mu_{suv}^{7} + \mu_{s}^{10} F_{uv}\left(f_{uv}, C_{uv}\right)$ $+\mu_{s}^{11} M_{uv}\left(f_{uv}, C_{uv}\right) = 0$ for each TAP *s*, call them the break points of f_{uv}.

Step 2: Sorting these break points and denoted as $f_{uv}^{1}, f_{uv}^{2}, \ldots, f_{uv}^{n}$.

Step 3: At each interval, $f_{uv}^{i} \le f_{uv} \le f_{uv}^{i+1}$, $y_{suv}\left(f_{uv}\right)$ is 1 if $-\sum_{b \in V} \mu_{suv}^{3} - \mu_{u}^{4} + \mu_{u}^{5}$ $-\mu_{v}^{6} + M_{2}\mu_{suv}^{7} + \mu_{s}^{10} F_{uv}\left(f_{uv}, C_{uv}\right) + \mu_{s}^{11} M_{uv}\left(f_{uv}, C_{uv}\right) \le 0$ and otherwise 0.

Step 4: Within the interval, $f_{uv}^{i} \le f_{uv} \le f_{uv}^{i+1}$, we can take calculus to find the local minimal.

Step 5: The global minimum point can be found by comparing these local minimum points.

3.2.7 Subproblem 7 (related to decision variable κ_{ns})

Objective function:

$$Z_{sub3.6}\left(\mu_s^8, \mu_s^9, \mu_{ns}^{14}, \mu_{ns}^{15}\right)$$

$$= \min \sum_{n\in N}\sum_{s\in V}\left[\theta_n\mu_s^8 + \theta_n\mu_s^9 + \mu_{ns}^{14}\overline{F}_{ns}\left(\theta_n, r_{ns}\right) + \mu_{ns}^{15}\overline{M}_{ns}\left(\theta_n, r_{ns}\right)\right]\kappa_{ns} \qquad \text{(SUB 3.7)}$$

subject to:

$$\sum_{s\in V}\kappa_{ns} = 1 \qquad \forall n \in N \qquad \text{(IP 12)}$$

$$\kappa_{ns} = 0 \ or \ 1 \qquad \forall n \in N, s \in V. \qquad \text{(IP 30)}$$

This problem can be further decomposed into |*N*| independent subproblems. For each mobile host *n*,

$$\min \sum_{s\in V}\left[\theta_n\mu_s^8 + \theta_n\mu_s^9 + \mu_{ns}^{14}\overline{F}_{ns}\left(\theta_n, r_{ns}\right) + \mu_{ns}^{15}\overline{M}_{ns}\left(\theta_n, r_{ns}\right)\right]\kappa_{ns} \qquad \text{(SUB 3.7.1)}$$

Subject to:

$$\sum_{s\in V}\kappa_{ns} = 1 \qquad \forall n \in N \qquad \text{(IP 12)}$$

$$\kappa_{ns} = 0 \ or \ 1 \qquad \forall n \in N, s \in V. \qquad \text{(IP 30)}$$

The algorithm to solve the decomposed subproblem is stated as follows:

Step 1: Compute the coefficient $\left(\theta_n\mu_s^8 + \theta_n\mu_s^9 + \mu_{ns}^{14}\overline{F}_{ns}\left(\theta_n, r_{ns}\right) + \mu_{ns}^{15}\overline{M}_{ns}\left(\theta_n, r_{ns}\right)\right)$ of κ_{ns} for each TAP *s*.

Step 2: Find the smallest coefficient, then set the corresponding decision variable κ_{ns} to 1 and others to 0.

3.3 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem, for any $\mu^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15} \geq 0$, the objective value of $Z_{LR}\left(\mu^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15}\right)$ is a lower bound of Z_{IP}. Based in problem (LR), the following dual problem (D) is then constructed to calculate the tightest lower bound.

Dual Problem (D):

$$Z_D = \max Z_D\left(\mu^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15}\right)$$

subject to:

$$\mu^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15} \geq 0 .$$

There are several methods to solve the dual problem (D). One of the most popular methods is the subgradient method which employed here. Let the vector *g* be a subgradient of $Z_D\left(\mu^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15}\right)$. Then, in iteration *k* of the subgradient optimization procedure, the multiplier vector $\pi^k = \left({}^1, \mu_{bs}^2, \mu_{bs}^3, \mu_{suv}^4, \mu_u^5, \mu_u^6, \mu_v^7, \mu_s^8, \mu_s^9, \mu_{suv}^{10}, \mu_{suv}^{11}, \mu_{uv}^{12}, \mu_b^{13}, \mu_{ns}^{14}, \mu_{ns}^{15}\right)$ is updated by $\pi^{k+1} = \pi^k + t^k g^k$. The step size t^k is determined by $t^k = \lambda \frac{\left(Z_{IP}^h - Z_{D1}\left(\pi_k\right)\right)}{\left\|g^k\right\|^2}$. Z_{IP}^h is the primal objective function value for a heuristic solution (an upper bound on Z_{IP}) and λ is a constant where $0 \leq \lambda \leq 2$.

Chapter 4 Getting Primal Feasible Solution

4.1 Lagrangean Relaxation Results

By applying Lagrangean Relaxation method and the subgradient method to solve the complex problem, we can get a theoretical lower bound of the primal problem and some hints to get a feasible solution to the primal problem. Because some difficult constraints of the primal problem are relaxed by using Lagrangean Relaxation method, we can not guarantee that the consolidated result of the Lagrangean Relaxation problem is feasible to the primal problem. We have to ensure that it is a feasible solution, which is satisfied with all constraints of the primal problem, if not, we have to make some modifications.

4.2 Getting Primal Heuristic

We take the major decision variable, η_{bk}, into consideration. Accorading to η_{bk}, we can obtain which TAPs should be installed as backhauls in each Lagrangean Relaxation iteration. We count the frequency that each TAP should be installed as a backhaul iteration by iteration. Because the maximal data rate that a backhaul can process limits to the sum of its nodal capacity and air-interface capacity. And the total maximal processing data rate of all backhauls should not be less than the total data rate required to be transmitted of all mobile hosts. Therefore, we pick up TAPs to be installed as backhauls with frequency in ascending order, until all backhauls' maximal processing data rate do not less than the total data rate request from mobile hosts.

After initiate the backhaul deployment, we should assign mobile hosts to appropriate TAPs. Therefore, we can obtain the data rate required to be transmitted of each TAP. Then, we run routing heuristic for TAPs to decide backhaul assignment and routing paths selection. Besides, the initiated backhaul deployment may not be feasible. Thus we propose add backhaul heuristic to get the feasible solution.

Table 4-1 Getting Primal Heuristic Algorithm

```
Step1: Initiate backhaul deployment according to decision variable $\eta_{bk}$.
Step2: Run Assign_Mobile_Host_Heuristic.
Step3: Run Routing_Heuristic.
Step4: Go to step 5 if all TAPs can route to associated backhauls without violating end-to-end QoS requirements.
Step4.1: Run Add_Backhaul_Heuristic.
Step4.2: Go back to step 2.
Step5: Calculate total cost of backhaul deployment.
```

4.2.1 Assign Mobile Host Heuristic

By decision variable κ_{ns}, we can decide how to assign mobile hosts to associated TAPs. Some TAPs may violate the air-interface capacity due to admit too many mobile hosts. For getting feasible solutions, the mobile host assignment should be adjusted.

If a mobile within the access range of a TAP and a backhaul at the same time, the mobile host should try to access the backhaul first. Therefor, the mobile host can get into the Internet via the backhaul directly and doest not experience the poor performace of wireless multi-hot transmition. We describe the detail procedures as in Table 4-2.

Table 4-2 Assign Mobile Host Heuristic Algorithm

Step1: Initiate mobile host assignement according to variable κ_{ns}.

Step2: Find a TAP that violates the air-interface capacity most seriously. If not found, Stop.

Step3: For each mobile host, we try to reassign to another TAP and calculate the coefficient of κ_{ns}. Then, we find the mobile host with smallest coefficient and reassign to the relative TAP. Repeat step 3 until this TAP does not violate air-interface capacity.

Step4: Repat step 2 and 3 until all TAP do not violate air-interface capacity.

Step5: For each backhaul, we reassign the nearby mobile hosts with smallest coefficient κ_{ns} of to the backhaul one at a time until cannot admit one mobile host without violating the air-interface capacity.

4.2.2 Routing Heuristic

The basic idea of routing heuristic is that if the end-to-end QoS performance of one TAP is close to its QoS requirements, this TAP should route first. This means the TAP with tightest QoS has less flexibility in routing path selection. In the following, we show the detail procedures in Table 4-3.

Table 4-3 Routing Heuristic Algorithm

Step1: Set the arc weight for each link to be the coefficient of variable x_p. and run Dijkstra’s algorithm to get the shortest path from each TAP.

Step2: Choose a path with the tighest QoS performance.

Step3: Repeat step 1 and 2 until all TAP have a path to a backhaul.

4.2.3 Add Backhaul Heuristic

The basic idea of this heuristic is that if a TAP locate at the place that many traffic flows may pass through, this TAP is at a proper location for installed as a backhaul. This means many other TAPs’ data flow can reach to this TAP. We denote the times of reaching by other TAPs as “reachability”. Therefore, we calculate each TAP’s reachability, then we pick the highest reachability value for backhaul deploy. We show the detail procedures in Table 4-4.

Table 4-4 Add Backhaul Heuristic Algorithm

Step1: Initiate all TAPs’ reachability counter to zero.

Step2: Find a TAP that admits data flow from mobile hosts but not be assigned to any backhaul. If a TAP without assigned backhaul found, we run Dijkstra’s algorithm to get the shortest path tree and check end-to-end QoS from root to any other TAP on this tree. Then, we increase reachability counter of the TAP without violating end-to-end QoS requirements. Repeat step 2 until all TAPs are assigned to associated backhauls.

Step3: Select the TAP of highest reachability counter, and installed it as a backhaul.

Chapter 5 Computational Experiments

In this chapter, we conduct several computational experiments to examine how good of the quality of our solution approach. In the mean time, for the purpose of evaluating the solution quality, we implement three simple algorithms for comparison.

5.1 Experiment Environment

The computational experiments program has been written in C an using a Pentium IV 3GHz, 1024MB, Windows 2000 Server Pack4 environment. Table 5-1 shows the general parameters and test platform for the experiments.

Table 5-1 Parameters of Lagrangean Relaxation based algorithm

Number of iterations	2000
Improvement counter	40
Begin to get primal feasible solution	1
Initial upper bound	0
Initial scalar of step size	2
Stopping step size	10^{-6}

5.2 Simple Algorithms and Metrics

We implement Random Algorithm as Simple Algorithm 1 (SA1) and Greedy Algorithm as Simple Alogrithm 2 (SA2). SA1 deploy backhaul and decide the sequence of paths selection randomly, while SA2 chooses mininum deployment cost backhaul and minimum data flow first. We also implement Simple Algorithm 3 (SA3) which chooses minimum usage of network resources first and use the same deploy backhaul manner as LR in order to conserve the righteousness for comparison with different sequence of paths selection.

We denot the dual solution as “Zdu” and Lagrangean-based heuristic as “ZIP”. We use two metrics – “Gap” and “Improvement Ratio” to evaluate our solution quality. Where Gap is calculated by $\left|\frac{ZIP-Zdu}{Zdu}\right|*100\%$ and Improvement Ratio is calculated by $\left|\frac{SA-LR}{LR}\right|*100\%$.

5.3 Experiment Scenarios

In order to test the solution quality of our algorithm, we design several scenarios with different feature.

1. Grid Network with Different Number of TAPs
2. Random Network with Different Number of TAPs
3. Hexagonal Network with Different Number of TAPs
4. Random Network with Different Data Flow

5.4 Grid Network with Different Number of TAPs

Table 5-2 Experiment Result of Grid Network with Different Number of TAPs

Number of TAPs	Lower Bound (LB)	Upper Bound (UB)	Gap (%)	SA1	Imp Ratio	SA2	Imp Ratio	SA3	Imp Ratio
9	36.9883	42	13.5451	67	36.3276	58	25.4514	47	10.6383
16	57.9986	73	25.865	148	50.5513	102.25	25.7326	85.5	14.5687
25	88.8848	115	29.3808	242.75	52.4429	150.75	23.3527	140	17.3277
36	127.9923	165.5	29.3046	382.25	56.1835	235.25	29.4524	195.5	14.6658
49	174.1973	227	30.3122	499.25	54.5026	340	32.8883	252	9.5064
64	227.5465	294.5	29.424	705.75	58.2366	489.25	38.517	334.5	11.7779
81	287.963	378	31.2668	893.25	57.6308	626.5	38.54	430.5	12.1793

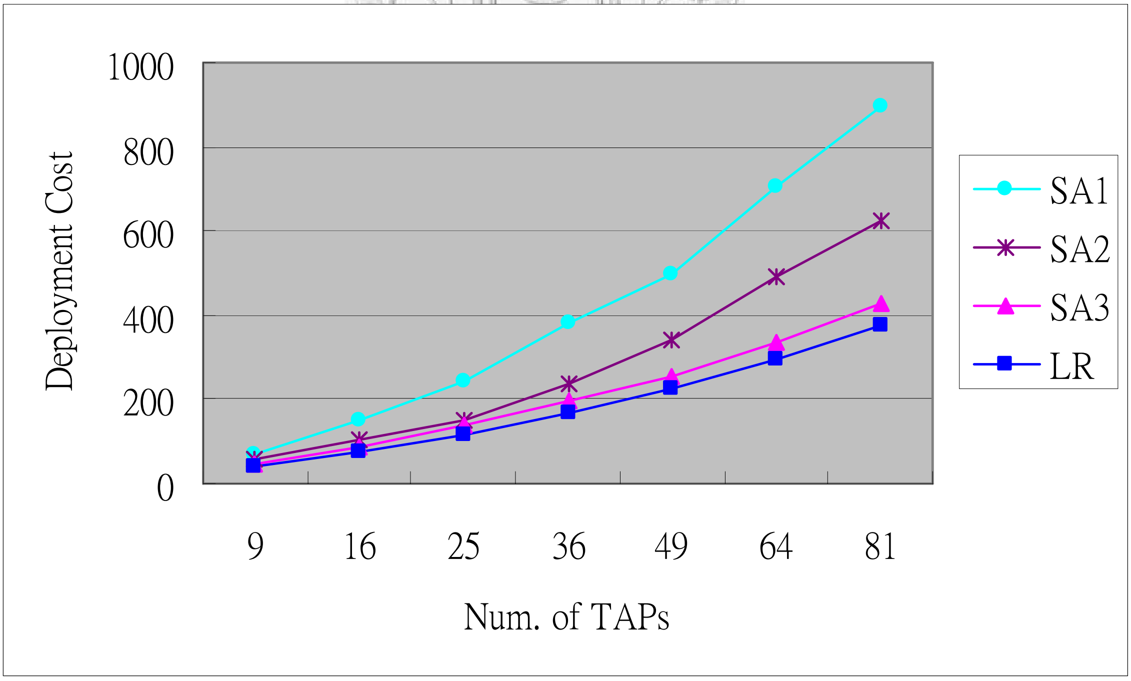

Figure 5-1 Deployment Cost of Grid Network with Different Number of TAPs

5.5 Random Network with Different Number of TAPs

Table 5-3 Experiment Result of Random Network with Different Number of TAPs

Number of TAPs	Lower Bound (LB)	Upper Bound (UB)	Gap (%)	SA1	Imp Ratio	SA2	Imp Ratio	SA3	Imp Ratio
9	36.9967	37.75	2.0358	65.75	42.0311	49	22.9166	40	4.6875
16	57.9756	69	19.0158	130.75	46.6676	100.75	29.7079	81.25	14.3443
25	88.8375	108.75	22.4133	255.5	57.1153	149.75	26.6139	122.25	11.0261
36	127.9523	158.75	24.0696	412.75	61.0547	239.25	32.9324	182.75	12.9864
49	174.1718	212.5	22.0059	556	60.989	304.75	27.4739	240.25	11.0291
64	225.443	275.5	22.2522	794.5	64.414	436.25	36.0423	312.5	11.7484
81	286.2353	363.5	27.0045	890.75	58.3753	499.75	27.2184	428.5	15.0948

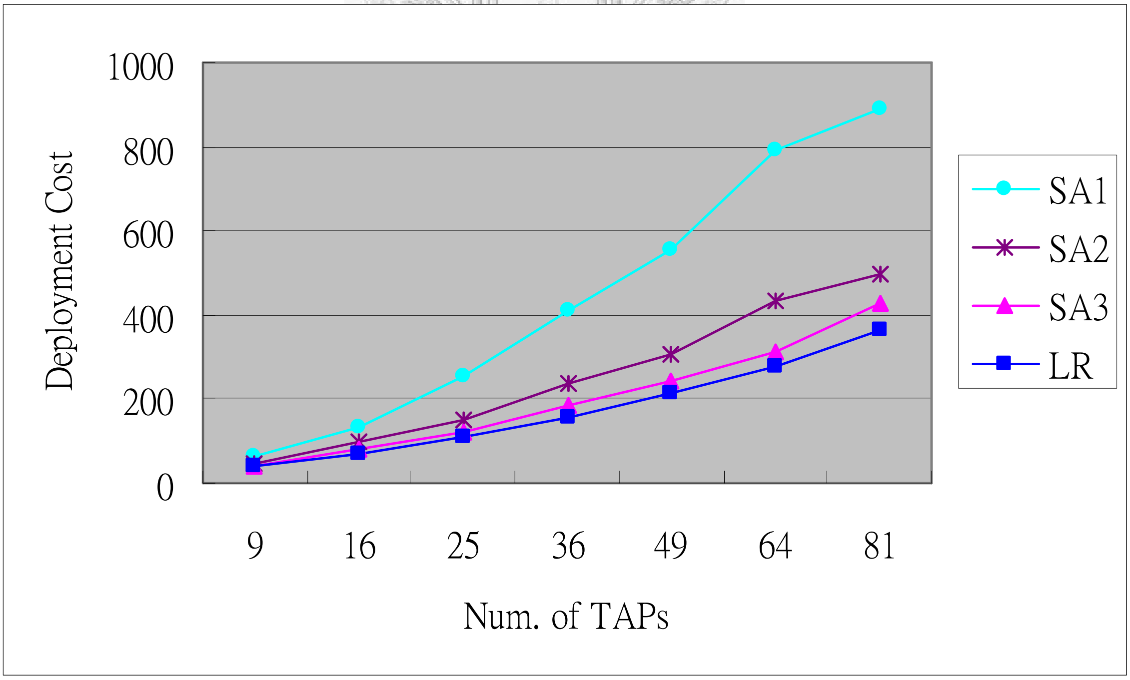

Figure 5-2 Deployment Cost of Random Network with Different Number of TAPs

5.6 Hexgonal Network with Different Number of TAPs

Table 5-4 Experiment Result of Hexgonal Network with Different Number of TAPs

Number of TAPs	Lower Bound (LB)	Upper Bound (UB)	Gap (%)	SA1	Imp Ratio	SA2	Imp Ratio	SA3	Imp Ratio
7	30.9747	31	0.0816	41.5	25.2694	41	24.3902	31	0
19	67.2586	79.5	18.1986	149.5	46.3668	112.5	28.7871	92	13.1828
37	131.5258	158.5	20.5088	305.25	47.6052	229.25	30.473	186	14.7594
61	216.851	265.5	22.4345	526.5	48.5793	372.75	26.3505	295.5	9.9916
91	323.499	405.5	25.3483	768.75	46.6027	635.25	35.5417	440.5	7.9184

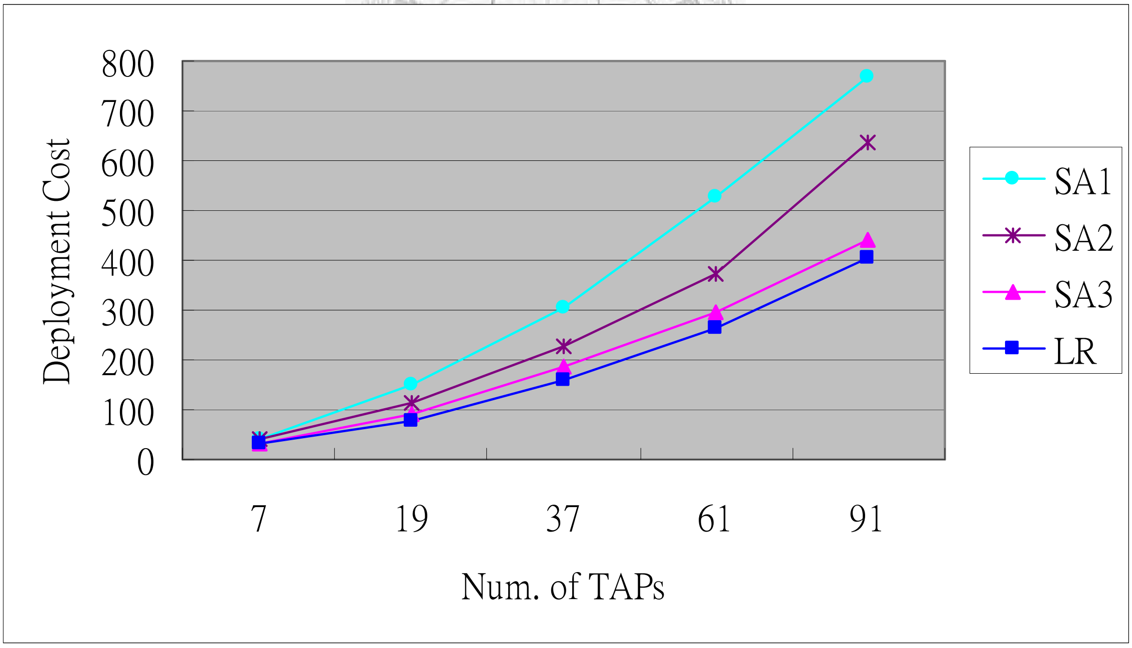

Figure 5-3 Deployment Cost of Hexgonal Network with Different Number of TAPs

5.7 Random Network with Different Data Flow

Table 5-5 Experiment Result of Random Network with Different Data Flow (49 TAPs)

Data Flow (λ)	Lower Bound (LB)	Upper Bound (UB)	Gap (%)	SA1	Imp Ratio	SA2	Imp Ratio	SA3	Imp Ratio
0.25	46.71955	71.25	52.5033	250.5	59.3537	121.75	34.9322	76.25	5.8769
0.5	87.1013	115.75	32.8912	303.5	57.2032	177.75	31.9331	146	20.6103
0.75	130.638	168.75	29.1737	442	60.1972	262.25	33.3969	202.5	16.4802
1	174.1718	212.5	22.0059	556	60.989	304.75	27.4739	240.25	11.0291
1.25	217.6515	269.75	23.9376	573.75	51.1592	372.75	27.2771	306.5	12.0139
1.5	261.1	314	20.2613	657	51.1485	443.75	29.0983	355.5	11.5836
1.75	304.6685	355.25	16.6023	683.25	47.3988	479.25	25.6663	428.5	16.7172

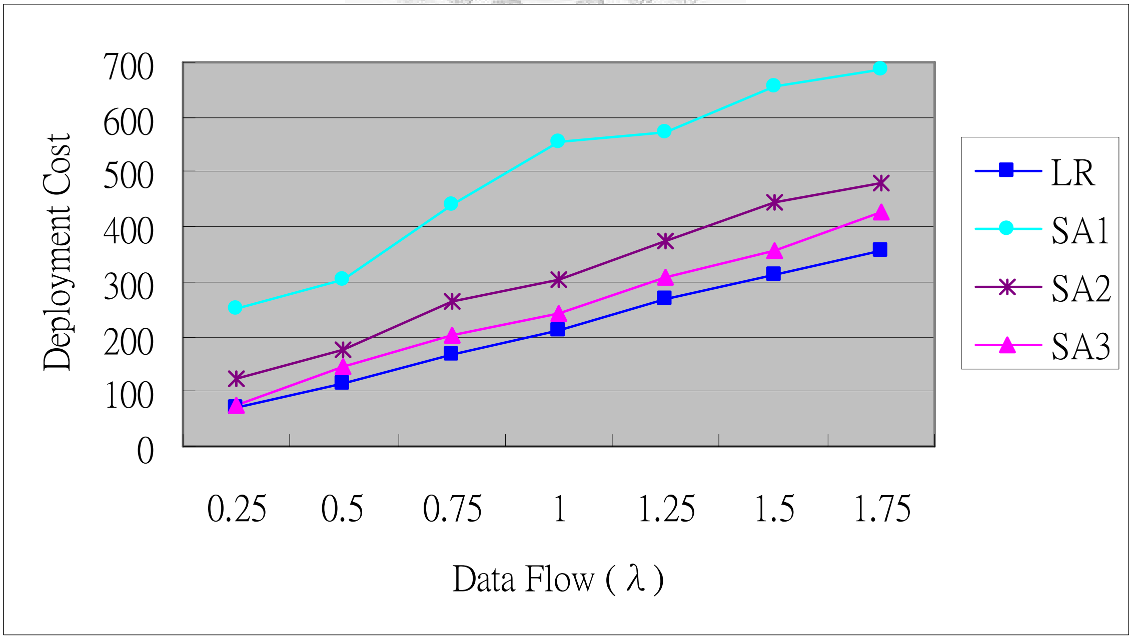

Figure 5-4 Deployment Cost of Random Network with Different Data Flow (49 TAPs)

5.8 Experiment Discussion

According to the experiment results, we can find that the cost of backhaul deployment increases with the number of TAPs and mobile hosts. And the Lagrangean Relaxation based algorithm always outperforms other simple algorithms.

Lagrangean Relaxation based algorithm and SA3 adopt the concept of reachbility to deploy the backhauls. We can see these two algorithms performs well eminently by comparison with random deploy maner adopted by SA 1 and greedy deploy manner adopted by SA2. Therefore, we can take this deploy manner to deploy backhaul economically and effectively.

Alghough Lagrangean Relaxation based algorithm and SA3 use the same deploy manner, Lagrangean Relaxation based algorithm performs better than SA3. According this, we discover that the sequence of routing path selection has impact to the experimental outcomes. This because the TAPs routing previously consume part of network resources and the following TAPs restricted to less network resources. Therefore, the more previous TAP has more flexiable in paths selection.

Chapter 6 Conclusion

6.1 Summary

In this thesis, we emphasize on a problem of backhaul deployment while considering the end-to-end QoS constraints in wireless mesh networks. In chapter, we formulate this problem as an integer programming problem, where the objective is to minimize the total cost of backhaul deployment. In chapter 3 and 4, we develop a Lagrangean Relaxation based heuristic to solve this problem. In chapter 5, we take serials of experiments to evaluate the quality of our solution approach. As shown in the results of chapter 5, our approach performs well in grid, random, and hexagonal network.

The contribution of this thesis can be described as follows:

1. We propose a mathematical formulation and a optimization based algorithm with jointly considering backhaul deployment and QoS routing in a wireless mesh network.
2. Our Lagrangean Relaxation based solutions have significant improvement than other intentional algorithms.

6.2 Future Work

Although we take both backhaul deployment and end-to-end QoS into consideration, there are still extensions we can make progress in the future studies.

First, in the experimental results we can see the sequence of paths selection imapce our results. We could derive more heuristic solutions to in order to decide the sequence of paths selection in the end-to-end QoS routing problem.

Second, in the backhaul deployment problem we assign source TAP to appropriate backhaul implies clustering. In the backhaul deployment problem, we can derive cluster-based solution approachs.

Finally, the mobility of mobile hosts should be taken into consideration. That will be more suitable for the reality.

References

[1] B. Li. “End-to End Fair Bandwidth Allocation in Multi-hop Wireless Ad Hoc Networks”, *Proc. IEEE ICDCS 2005*, Columbia, OH, June 2005.

[2] H. H. Yen and F. Y. S. Lin, “Near-Optimal Delay Constrained Routing in Virtual Circuit Networks”, *Proc. IEEE Infocom 2001*, Anchorage, Alaska USA , April 2001.

[3] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless Mesh Networks: A Survey”, *Elsevier Computer Networks*, vol. 47, no. 4, pp. 445–487, March 2005.

[4] J. Jun and M. Sichitiu, “The Nominal Capacity of Wireless Mesh Networks”, *IEEE Wireless Communications*, vol. 10, no. 5, pp. 8-14, October 2003.

[5] J. Padhye, R. Draves, and B. Zill, “Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks”, *Proc. ACM MOBICOM 2004*, Philadelphia, PA, September 2004.

[6] K. T. Cheng and F. Y. S. Lin, “Minimax End-to-end Delay Routing and Capacity Assignment for Virtual Circuit Networks”, *Proc. IEEE Globecom*, pp. 2134-2138, 1995.

[7] M. Fisher, “Optimal Solution of Scheduling Problems Using Lagrange Multipliers: Part I.”, *Operations Res.*, vol. 21, pp. 1114-1128, 1973.

[8] M. Fisher, “The Lagrangean Relaxation Method for Solving Integer Programming Problems”, *Management Science,* vol. 27, pp. 1-18, 1981.

[9] N. B. Salem and J. P. Hubaux, “A Fair Scheduling for Wireless Mesh Networks”, *Proc. IEEE WiMesh 2005*, Santa Clara, CA, September 2005.

[10] P. De, A. Raniwala, S. Sharma, and T.C. Chiueh, “Design Considerations for a Multihop Wireless Network Testbed”, *IEEE Communications Magazine*, vol. 43,

no. 10, pp. 102-109, October 2005.

[11] R. Bruno, M. Conti, and E. Gregori, “Mesh Networks: Commodity Multihop Ad Hoc Networks”, *IEEE Communications Magazine*, vol. 43, no. 3, pp. 123–131, March 2005.

[12] R. Karrer, A. Sabharwal, and E. Knightly, “Enabling Large-scale Wireless Broadband: The Case for TAPs”, *Proc. ACM HotNets-II*, Cambridge, MA, November 2003.

[13] S. T. Sheu and J. H. Chen, “MR^{2}RP: The Multi-Rate and Multi-Range Routing Protocol for Ad Hoc Wireless Networks”, *Proc. IEEE ISCC 2002*, Italy, July 2002.

[14] T. J. Tsai and J. W. Chen, “IEEE 802.11 MAC Protocol over Wireless Mesh Networks: Problems and Perspectives”, *Proc. IEEE AINA 2005*, Taiwan, R.O.C., March 2005.

[15] V. Gambiroza, B. Sadeghi, and E. Knightly, “End-to-End Performance and Fairness in Multihop Wireless Backhaul Networks”, *Proc. ACM MOBICOM 2004*, Philadelphia, PA, September 2004.

簡歷

姓名：曾勇誠

出生地：臺灣省臺北縣

出生日：中華民國六十六年八月二十九日

學歷：八十四年九月至八十八年六月

私立中原大學資訊管理學系

九十三年九月至九十五年十月

國立臺灣大學資訊管理學研究所