Energy-Efficient Multicast Routing in Mobile Ad Hoc Networks

移動性 Ad Hoc 網路之低能耗群播路由演算法研究

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：傅琳智　撰

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謹以此篇論文獻給我親愛的家人和義堅

謝 詞

研究所兩年的求學生涯，隨著本篇論文的完成終將告一段落。首先要感謝的是影響我深遠的指導教授林永松老師，在整個論文撰寫的過程中，老師嚴謹的研究態度以及對網路最佳化領域的精闢見解，帶領我進入此殿堂，得以一窺其奧妙；在擔任老師助理期間，學習到許多待人處世的方法，感謝老師給我磨練的機會。我也非常感謝顏宏旭老師，從論文題目的構想啟發、方向擬定，到論文撰寫中遭遇到的各種疑難雜症，老師莫不給予我最大的協助，老師對研究的熱誠是我極力效法的學習典範。此外，口試期間，承蒙林盈達教授、趙啟超教授、呂俊賢教授對論文提供許多寶貴的意見與指正，予我受益良多，使得本論文得以更臻完善。

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感謝我的男朋友義堅陪伴我度過每一個艱苦奮鬥的日子，每當我遇到挫折時，你總是竭盡所能地給我安慰和鼓勵，讓我能夠鼓起勇氣、再接再厲。為了能替我分憂解勞，你不僅放下自己手邊的工作，全力以赴協助我解決難題，還不斷開導我以積極進取的態度迎接各種挑戰。你樂觀開朗的個性總讓我覺得，無論碰到任何困難，只要以不同的角度思考，一切陰霾都將成為過去。一路上義堅對我的細心呵護以及全力協助，使我能夠順利走過這最後的求學階段。

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當走過的路化成文字，記錄的是一份動人的回憶；當腳下的步伐實踐著文字，不禁感謝老天，自己是多麼幸運。最後，我要感謝過去所有曾經幫助過我，使我成長的人，謝謝您們。

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于台大資訊管理學研究所

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論 文 摘 要

論文題目：移動性 Ad Hoc 網路之低能耗群播路由演算法研究

作　　者：傳琳智　　　　　　　　　　　　　　　　　九十四年七月

指導教授：林永松、顏宏旭　博士

移動性的 Ad Hoc 網路使用無線傳播，是一個不需事先決定網路拓樸設計的網路。這種網路架構的特性使得它可以被快速的部署，並且不需依賴已存的基礎建設。值得注意的是在這顯著的特徵下，它適合使用在設計階段無法預測的網路架構的應用。

然而，在設計移動性的 Ad Hoc 網路存在很多關鍵的挑戰需要被解決。其中三個主要的挑戰是: 1) 缺乏集中式管理, 2) 節點的自主移動, 3) 所有通訊透過無線媒介傳播。

本篇論文我們著重在探討當每個節點受限於有限的電力資源，且整個路由的路徑是由每個自主移動的節點所組成的情況下，要如何以低能耗的路由決策，成功傳送資料給群播成員，在會因為節點移動而導致傳輸中斷，而需要重新作路由決策的網路拓樸。

不同於傳統設計的單層結構，我們同時考慮在有效的傳送半徑範圍內（網路連接性，屬實體層）以及群播樹的建立（路由功能，屬網路層），來做出低能耗的路由決策。我們將此問題設計成最佳化的數學模型，並且採用拉格蘭日鬆弛法（Lagrangian relaxation）為基礎的方法來處理此複雜的問題。

關鍵詞： 移動性的 Ad Hoc 網路，能源最佳化，移動性，數學最佳化，拉格蘭日鬆弛法。

THESIS ABSTRACT

Energy-Efficient Multicast Routing in Mobile Ad Hoc Networks

Lin-Chih Fu

MASTER DEGREE OF BUSINESS ADMINISTRATION

DEPARTMENT OF IMFORMATION MANAGEMENT

NATIONAL TAIWAN UNIVERSITY

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ADVISER: Dr. Frank Yeong-Sung Lin、Hong-Hsu Yen

The Mobile Ad Hoc Network (MANET) is an emerging network topology based on a radio propagation model. The network topology, which is neither fixed nor predetermined, can be rapidly deployed and does not need to rely on a pre-existing infrastructure. It is noteworthy that this salient feature makes it suitable for the network operations that, by their nature, are unpredictable during the design stage.

However, a lot of critical challenges in the design and operation of MANET need to be solved. The three main challenges come from: 1) the lack of a centralized entity, 2) the possibility of platform movements, 3) the fact that all the communication is carried over the wireless medium.

The issues we address here are 1) a node operates on limited battery resources, and 2) multi-hop routing paths are used over constantly changing network environments due to node mobility. Hence, efficient utilization of routing packets and immediate recovery of route breaks are critical in routing and multicasting protocols in MANET.

Our approach to energy-efficient communication departs from the traditional layered

structure in that we jointly address the issues of transmitted power levels (a network connectivity function, related to the Physical layer) and multicast tree formulation (a routing function, associated with the Network layer).

We model the problem as a linear integer mathematical programming problem. In addition, we propose a set of heuristic solution procedures based on Lagrangian relaxation methods to solve the complicated problem.

Keywords: MANET, Energy-Efficient, Mobility, Mathematical Optimization, Lagrangian Relaxation Method.

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Chapter 1 Introduction

1.1 Background

In general, there are two major models for wireless networking namely single-hop and multi-hop. The single-hop model [24], based on the cellular network model, provides one-hop wireless connectivity between mobile hosts and static nodes known as Base Stations (BS). This type of network relies on a fixed backbone infrastructure, which interconnects all base stations by high-speed wired links.

On the other hand, the multi-hop model requires neither a fixed nor a predetermined network topology. Ad-hoc networks [6] [9] are comprised of a homogeneous mobile stations connected by wireless links. In ad hoc networks, some stations are assigned a transmission radius, and the overall power assignment determines the transmission graph, as shown in Figure 1-1. Since all stations operate on limited energy, they form a multi-hop wireless network, which is the most popular scenario.

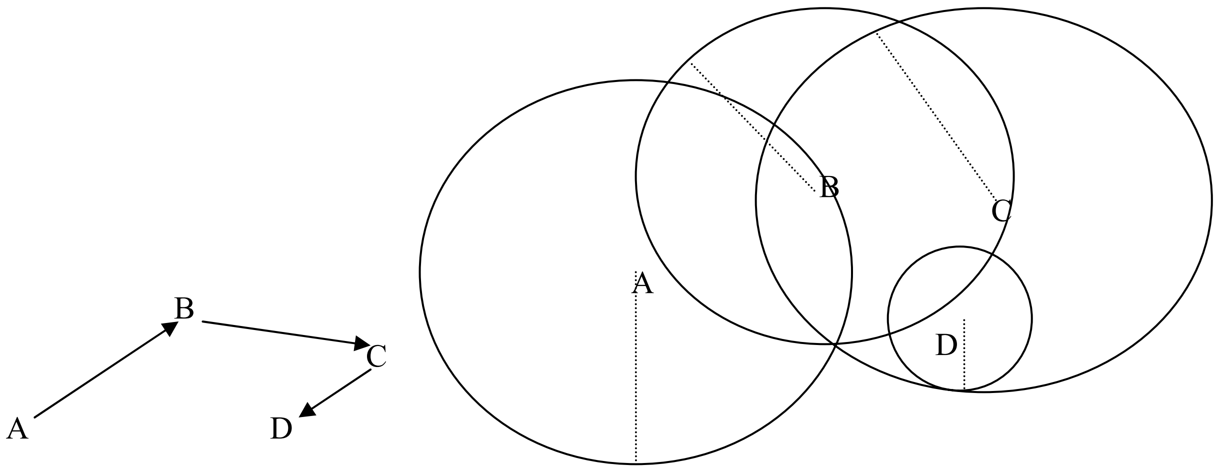


Figure 1-1 A range assignment and its corresponding directed transmission graph

This network architecture can be rapidly deployed and does not need to rely on a pre-existing infrastructure. It is noteworthy that this salient feature makes it suitable for the network operations, which by their nature are unpredictable during the design stage. In addition, advances in wireless technology have led to various important applications, especially in mobile ad hoc networks (MANET), such as the military or emergency use [25].

However, a lot of pedantic challenges will need to be solved [10], [25]. Two such issues of which we are already aware are that node operates on limited battery resource, and multi-hop routing paths are used over constantly changing network environments due to node mobility. Hence, efficient utilization of routing packets and immediate recovery of route breaks are critical in routing and multicasting protocols in MANET.

In the real world, the problem is that the network needs to find the most reliable way to transmit time critical information to multicast members in a highly dynamic and limited energy resource environment, such as the military or emergency services.

Nodes in flat networks transmit at a significantly lower power than the transmission power of the cluster heads in the hierarchical networks [6]. This has several implications: First, the battery power of the nodes in ad-hoc networks is preserved. Second, the wireless spectrum can be better reused, leading to more network capacity. Third, larger degree of low probability of interception/ low probability of detection can be achieved, resulting in a more secure network operation. Fourth, there is no “single point of failure” which occurred in the cluster heads. According to above analysis, we choose a flat configuration as our research target.

1.2 Motivation

Minimum energy broadcast tree problem has been proven a NP-complete problem [17]. Though many protocols and algorithms have been proposed, most of them are not well suited to the salient features of mobile ad hoc networks.

Some researchers propose the heuristic algorithm (Broadcast Incremental Power) to construct the minimum-power tree for static ad hoc wireless networks [26] [13] [12]. This algorithm exploits the broadcast nature of the wireless communication environment, and addresses the need for energy-efficient operation.

We then wonder how to evaluate team optimization of cooperating systems (TOCS) to determine the best team of broadcast trees. In [20] [19], by using viability lemma, the authors propose models allowing for optimization of both the static and dynamic energy constrained wireless broadcasting.

Further, some researchers present more accurate mathematical analytic methodologies, like integer programming models [7], which is possible to judge the quality of the solutions with respect to the optimal. Although optimal solutions can be obtained for fixed wireless networks (i.e.: nodes in the networks are fixed.), this is not a suitable way for analyzing the mobile ad hoc networks.

However, we need to find other researches which address on the issue of the property of mobility in ad hoc networks. In [15], ODMRP provides a method of mobility prediction, which adapts the network topology refresh interval to the mobility patterns. In addition, applied the mobility prediction, we can have a new point to select a more stable route. In [4]

[16], there are several mobility models that mimic mobile nodes' behaviors. Changes in speed and direction must occur in reasonable time slots. While we try to make efficient routing decision, we must choose representative mobility model which can simulate the movements in realistic situation in MANET.

To enable a variety of applications in MANET, many researchers are actively engaged in developing schemes that fulfill the requirements of energy-efficient and dynamic changes in network topology. This is also the goal of my work.

1.3 Literature Survey

1.3.1 Minimal power consumption in wireless networks

In wired models, as long as there is a link connecting two nodes, the reception is ensured over that link. Besides, the cost of Node *i*'s transmission to Node *j* and Node *k* would be sum of the two single transmission costs from the relay node *i* to the individual nodes *j, k*. Note that wired networks can be viewed as link-based, so that the broadcasting problem can be formulated as well-known minimum-cost spanning tree (MST) problem. This formulation is based on the existence of a cost associated with each link in the network.

$$MST\ \text{: minimize} \sum_{\mathrm{i}} \sum_{j} C_{ij} X_{ij}\ ,\ \mathrm{i} \neq \mathrm{j}$$

Wireless, unlike wired networks, inherently reaches several modes with a single transmission, as shown in Figure 1-2. With omni-directional antenna, all nodes which are in the range of the relay node's transmission radius receive the packet without additional cost. With the property of wireless broadcast advantage, we calculate the transmission cost based on the "node-based" nature of wireless communication.

$$MPB\text{: minimize} \sum_{\mathrm{i}} \max{}_{\mathrm{j}}(C_{ij} X_{ij})\ ,\ \mathrm{i} \neq \mathrm{j}$$

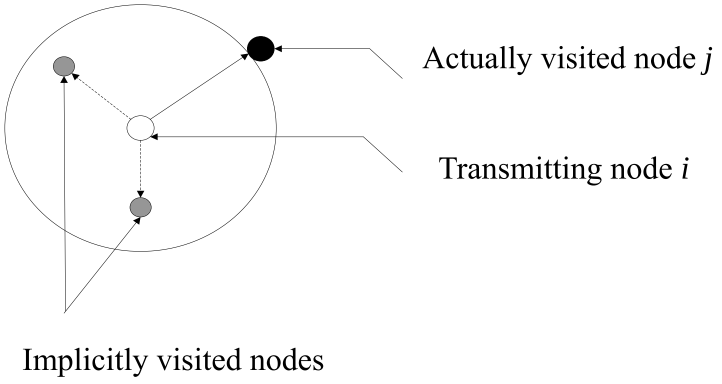


Figure 1-2 wireless broadcast advantages [7]

1.3.2 Gauss-Markov mobility model

It is noteworthy that a mobile user's future location and velocity are likely to be correlated with its past and current location and velocity. In an attempt to coincide the phenomenon, we choose Gauss-Markov mobility model [4] to mimic realistic movement of the mobile user. The reason we choose is that Gauss distribution is a normal distribution, and the memory nature of Gauss-Markov mobility model makes it suitable to predict the oncoming location and velocity of the mobile node. Furthermore, the Gauss-Markov mobility model represents a wide range of user mobility patterns, including, as its two extreme cases, the random-walk and the constant velocity fluid-flow models.

Gauss-Markov mobility model [16] was designed to adapt to different levels of randomness via tuning parameter α . We define a discrete version of the mobile velocity with $v_n = v(n\Delta t)$ and the memory level $\alpha = e^{-\beta \Delta t}$. $\beta \geq 0$ determines the degree of memory .

By tuning the memory level α , we can vary the randomness of mobile's movements.
The velocity can be expressed as follows:

$$v_n = \alpha v_{n-1} + (1-\alpha)\mu + \sigma\sqrt{1-\alpha^2}\, w_{n-1}$$

Besides, the parameter set (α, μ, σ) can be tuned such that the Gauss-Markov model can duplicate the mobile movements of the most popular mobility models:

1) The random-walk model -has no memory, can't represent the time correlation in a mobile's velocity.

It can be represented by $v_n^{(RW)} = \overline{\mu}^{(RW)} + \overline{\sigma}^{(RW)} \odot W_n^{(RW)}$, where $\overline{\mu}^{(RW)}$ is a vector of velocities, $\overline{\sigma}^{(RW)}$ is a vector of velocity standard deviations, and $\{W_n^{(RW)}\}$ is a vector of uncorrelated Gaussian processes with zero mean and unit variance.

The Gauss-Markov model has the parameters $\{\overline{\alpha} = 0,\ \overline{\mu} = \overline{\mu}^{(RW)},\ \overline{\sigma} = \overline{\sigma}^{(rw)}\}$.

2) The fluid-flow model -has constant velocity in all dimensions

It can be represented by $v_n^{(FF)} = C^{(FF)}$, where $C^{(FF)}$ is a vector of constant velocities. The Gauss-Markov model has the parameters $\{\overline{\alpha} = 1,\ v_0 = C^{(FF)}\}$, $\{\overline{\alpha} = 0,\ \overline{\mu} = C^{(FF)},\ \overline{\sigma} = 0\}$, $\{\overline{\mu} = C^{(FF)},\ \overline{\sigma} = 0, v_0 = C^{(FF)}\}$ to generate movement patterns the same as the fluid-flow model.

3) The random Waypoint model- is the most prevalent mobility model in mobile ad hoc network simulations. In this model, a mobile cycle contains constant velocity and motionless. In each cycle, it randomly selects a destination, moves toward the destination at a randomly selected velocity until it reaches the destination, stays at the destination for a randomly chosen amount of time. The movement of a mobile under this model consists of segments of fluid-flow with various level of velocity.

As shown in the Figure 1-3, the Gauss-Markov model can eliminate the sudden stops and sharp turns encountered in the Random Walk mobility model by allowing past velocities (and directions) to influence future velocities (and directions). (i.e.: velocity is not randomly selected.)

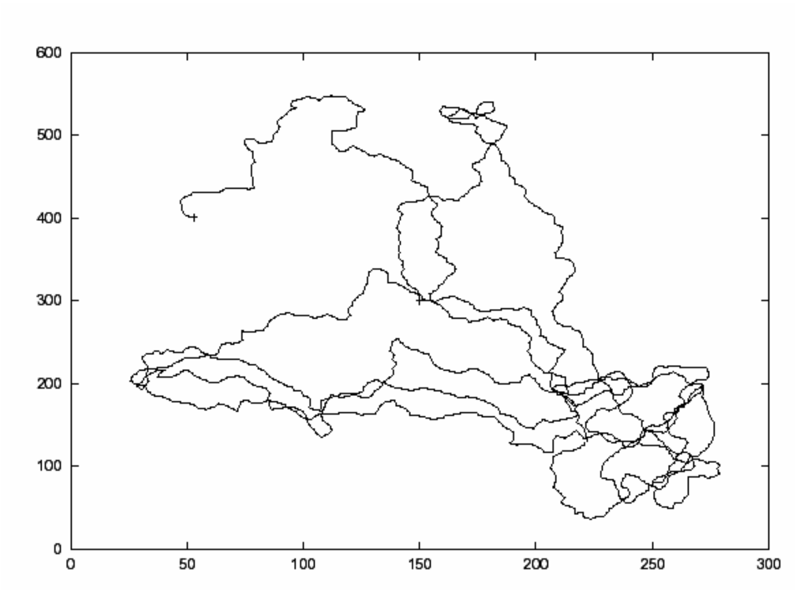


Figure 1-3 traveling pattern of an MN using the Gauss Markov mobility model [4]

By the nature of Gauss-Markov mobility model (i.e.: more realistic to mimic a mobile's movements) and the duplications of the mobile movements of the most popular mobility models by tuning the memory level α, we choose it to predict the oncoming location and velocity of the mobile node.

1.3.3 Adapting the refresh interval via mobility prediction

In order to facilitate communication within the networks, many routing protocol are proposed to discover routes between nodes [25]. On-Demand Multicast Routing Protocol (ODMRP) [14] applies on-demand [18] [23] routing techniques to avoid channel overhead and improve scalability. Moreover, ODMRP is well suited for ad hoc networks with mobile hosts where bandwidth is limited, topology changes frequently, and power is constrained. We then design our routing assignment based on ODMRP.

With the issue of mobility in MANET, we must find the optimal refresh time interval which adapts to mobility patterns in each round while we apply ODMRP [15]. We can find out that the route expiration time *t* is the minimal effective duration time of the links on this path in each round. Therefore, we predict the expiration time (D_t) of all links on the path and choose the smallest one, which is the duration of time slot division in this round.

We predict the link effective duration time by the concept of under this moving scenario of MANET, how long they can sustain connected. That is, we use both relay node's power radius and the mobility pattern of the two end points between this link to do the prediction. Figure 1-4 illustrates the approach:

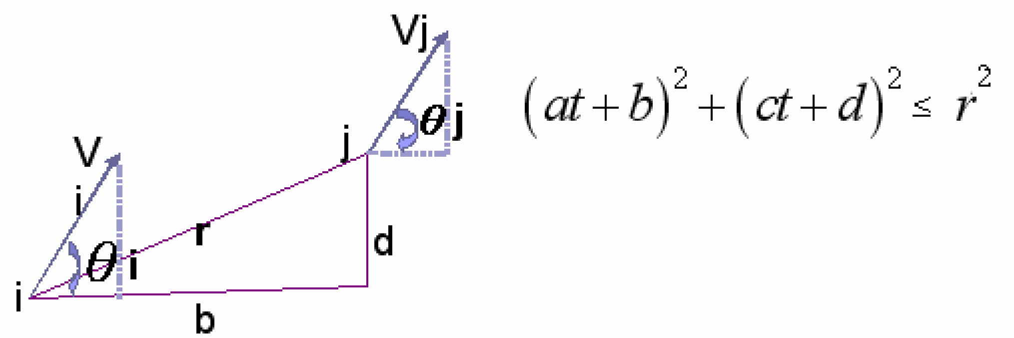


Figure 1-4 the link effective duration time calculating with mobility pattern.

The amount of time that the link $\overline{ij}$ will stay connected, D_t , is predicted by

$$D_t = \frac{-(ab+cd)+\sqrt{(a^2+c^2)r_{un}^{\ 2}-(ad-bc)^2}}{a^2+c^2}$$ [15] ;

Where

a= The difference of horizontal velocity of node *i,j* $= v_i \cos\theta_i - v_j \cos\theta_j$

b= The difference of horizontal position of node *i,j* $= x_i - x_j$

c= The difference of vertical velocity of node *i,j* $= v_i \sin\theta_i - v_j \sin\theta_j$

d= The difference of vertical position of node *i,j* $= y_i - y_j$

1.3.4 Lagrangian relaxation

In the 1970 [8], the Lagrangian relaxation method was first used in solving large scale linear programming problem. In brief [8] [1], it is a flexible solution strategy that permits us to exploit the fundamental structure into all possibilities of optimization problems by relaxing complicating constraints into objective function with multiplying corresponding Lagrangian multipliers. Accordingly, the primal optimization problem can be transformed to the Lagrangian relaxation problem. Furthermore, we could decompose complex mathematical models into stand-alone subproblems. Finally, we could optimally solve each subproblems using some proper algorithm. By the nature of decomposition, it can effectively lesson the complexities and difficulties comparing to the origin problem. In fact, it has become one of the best tools for solving optimization problems such as integer programming, linear programming combinatorial optimization, and non-linear programming.

The fundamental principle of this method is to “pull apart” models by removing constraints and place them in objective function with associated Lagrangian multipliers. By applying Lagrangian relaxation method, it helps us to find out the boundary of our objective functions. Thus, we can use it to implement heuristic algorithms to obtain feasible solutions.

However, for minimization problems, the optimal value of the relaxed problem is always a lower bound to the origin problem. In order to obtain the tightest lower bound, we need to choose a minimization multiplier so that the optimal value of the Lagrangian subproblem is as large as possible. Although we can solve the Lageangian multiplier problem in a variety of ways, the subgradient optimization technique is one of the fit techniques for solving the problem.

Figure 1-5 explains Lagrangian relaxation in a straightforward way, and Figure 1-6 gives a detailed procedure for Lagrangian relaxation.

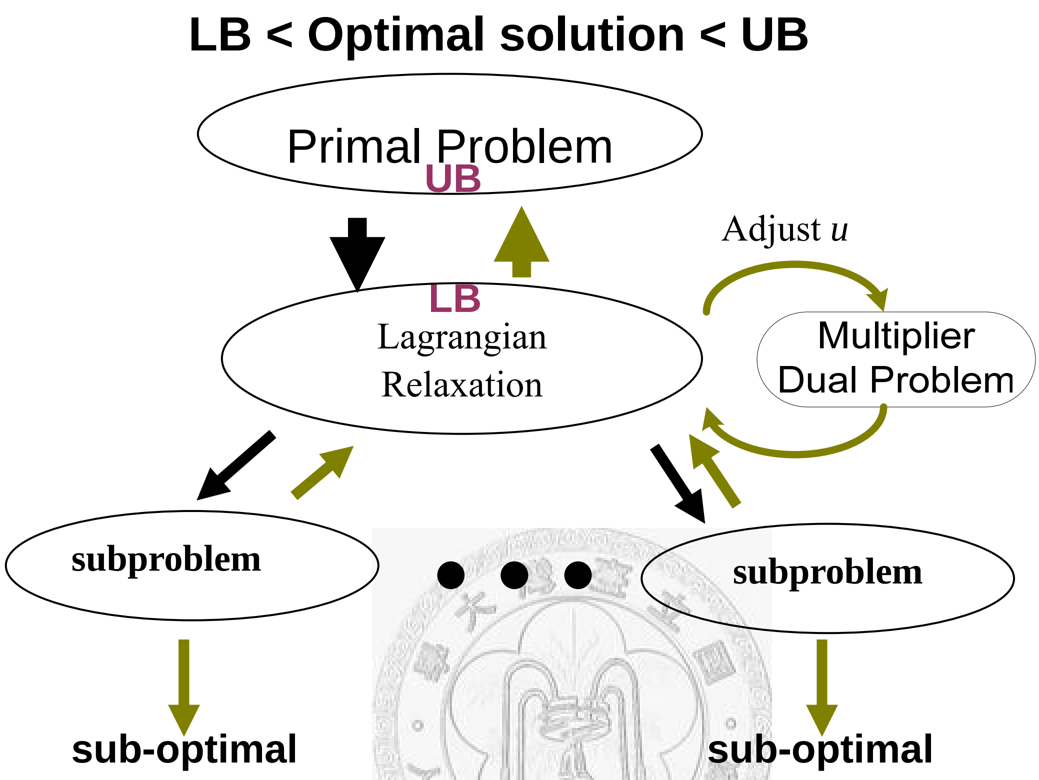


Figure 1-5 Lagrangian relaxation illustration

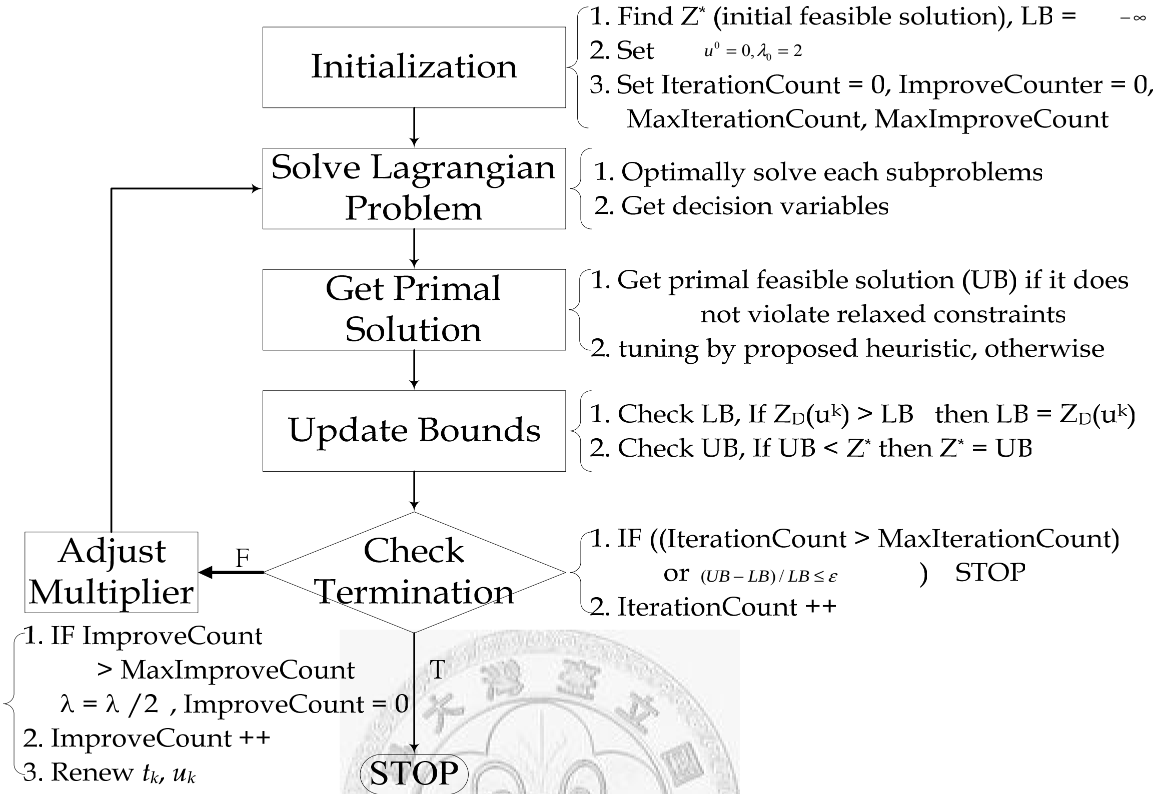


Figure 1-6 Lagrangian relaxation procedures

1.4 Proposed Approach

We model the problem as linear integer mathematical programming problems. Besides, we develop heuristics and apply the Lagrangian relaxation method to solve the problems. While we solve the Lagrangian relaxation, subgradient method is used to find the extreme points.

Chapter 2 Problem Formulation

2.1 Problem description

The problem we address is reliable and energy efficient single source multicast routing in wireless Mobile Ad hoc Networks (MANET).

It's a challenging environment since all nodes operate on limited battery resource, and multi-hop routing paths are used over constantly changing network environments due to node mobility.

Our approach to energy-efficient communication departs from the traditional layered structure in that we jointly address the issues of transmitted power levels (a network connectivity function, related to the Physical layer) and multicast tree formulation (a routing function, associated with the Network layer). We argue that with jointly considering on connectivity and routing can result in significant improvement in energy efficiency, as compared to a rigid layered structure that makes these decisions independently.

We have chosen the problem of multicasting as the focus of our energy-efficient networking studies. In addition to node mobility (and hence, variable connectivity in the network), there are additional trade-off between the reach of wireless transmission (namely, the simultaneous reception by many nodes of a transmitted message) and the resulting interference by that transmission.

Our goal is to think about the property of mobility, to predict the future position, and then make a reliable routing decision with minimal power consumption.

The method we could get the location and mobility information is provided by GPS. By Gauss-Markov mobility model, we could probabilistically predict the oncoming positions and velocities of nodes in the network. In this way, we can capture the essence of the correlation of a mobile's velocity in time. Besides, in order to simplify our problem, we assume that the prediction is correct.

By means of the prediction, we could obtain the network topology at time ($t_1 + t_2 + t_3$) as input information at time t_1 to run our routing assignment.

We can see clearly from Figure 2-1, which is the pictorialization of several composed processes in each round:

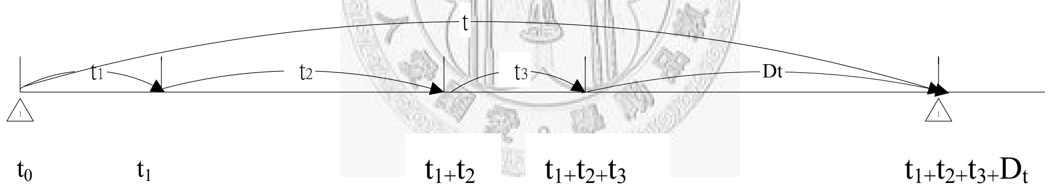


Figure 2-1 composed processes of each round.

t_1 : The time needed to collect global information. (The velocity, direction, and position of the node)

t_2 : The time needed to run the routing assignment.

t_3 : The time needed to relay the routing decision to all nodes.

D_t : The route expiration time is the time slot division in this round.

Also, we predict the expiration time D_t of all active links on the multicast tree, and choose the smallest one which is the route expiration time of this division in this round. For all destinations, until the flow of traffic corresponding to the required transmission time is satisfied in serveral rounds, then we finish making a reliable routing decision with minimal power consumption.

Table 2-1 Problem Description

Assumptions: 1. We can get the location and mobility information provided by GPS (Global Positioning System). 2. All nodes in the network have their clock synchronized. 3. By Gauss-Markov mobility model, we can probabilistically predict the oncoming positions of nodes in the network. In order to simplify our problem, we assume the prediction is correct. 4. All nodes have omni-directional antennas. 5. No power expenditure is involved in signal reception/processing activities. **Given:** 1. The ad hoc network topology. 2. The set of possible transmission radius. 3. The set of possible link connection time. 4. Total lead time sum of global collection, computation time of routing decision, and relay time. 5. Current velocity, direction, and position of nodes in each time slot. 6. The effective link duration time calculating function. 7. The energy consumption calculating function for node to transmit one unit of data packet. 8. The transmission time corresponding to the traffic demand is given. **Objective:**

To minimize total power consumption.

Subject to:

1. Node n can receive Node k's transmission only when the power radius turning on by k is higher than the distance between $\overline{nk}$
2. For each destination, there must have one path to transmit data packet.
3. The link which is on the selected path must be connected.
4. For each multicast member, there must have one incoming link to it, so that we can assure that data delivery to destination is ok.
5. There must have at least one outgoing link from the source node, so that we can assure that data delivery from it is ok.
6. We introduce a hop count constraint to limit the degree of delay.
7. The time of each round should be larger than the lead time.
8. The flow of traffic corresponding to the required transmission time should be satisfied in u rounds.
9. In each round, the route expiration time is the minimal effective duration time of the active links on the multicast tree, which is a function of the power radius of the relay node.

To determine:

1. Which node is the relay node and how far is its required power radius.
2. Routing assignment of each destination.

2.2 Notation

Table 2-2 Notations of given parameters

Given Parameters	
Notation	**Definition**
N	Set of all nodes in the network
$P_{u(sd)}$	Set of candidate paths for each destination $\overline{sd}$ in u round
$d_{u(nk)}$	Distance between node(n,k), in u round
$\delta_{p(nk)}$	1 if path p uses link $\overline{nk}$, 0 otherwise
R_{un}	Set of possible transmission radius of node n in u round
S_u	Set of possible link connection time in u round
δ	Total lead time sum of global collection, computation time of routing decision, and relay time
T	The required time to complete this transmission
U	On the worst case, we predict that how many times we need to finish this transmission
v_n	The velocity of node n
θ_n	The direction of node n
(x_n, y_n)	The position of node n
a	The difference of horizontal velocity of node $n,k = v_n \cos\theta_n - v_k \cos\theta_k$
b	The difference of horizontal position of node $n,k = x_n - x_k$
c	The difference of vertical velocity of node $n,k = v_n \sin\theta_n - v_k \sin\theta_k$
d	The difference of vertical position of node $n,k = y_n - y_k$

$\Phi_k(r_{un})$	The effective connecting time between node *n,k*, which is a link duration time function of r_{un}
$\Psi_{un}(r_{un})$	Energy consumption for node *n* in *u* round to transmit one unit of information to up to distance r_{un} (define $\Psi_{un}(0)=0$), which is a power consumption function of r_{un}
D_s	The set of destination nodes which is the multicast member of source node *s*
s	The source node
H_d	Hop constraint for each destination *d* $(\forall \text{ d} \in \text{D}_s)$
M	The big number *M* where we use it to close in the connection time of this multicast tree

2.3 Problem Formulation

Table 2-3 Notations of decision variables

Decision Variables	
Notation	**Description**
$y_{u(nk)}$	1 if link $\overline{nk}$ is used to transmit signal in *u* round, 0 otherwise
x_{up}	1 if path *p* is selected in *u* round, 0 otherwise
r_{un}	Transmission radius of node *n* in *u* round
s_u	The connection time of this multicast tree in *u* round

Optimization Problem：

$$\min \sum_{u \in U} \sum_{n \in N} \psi_{un}(r_{un}) \qquad \text{(IP1)}$$

Subject to:

$$y_{u(nk)} \times d_{u(nk)} \le r_{un} \qquad \forall n,k \in N, u \in U \qquad (2.1)$$

$$y_{u(nk)} = 0/1 \qquad \forall n,k \in N, u \in U \qquad (2.2)$$

$$\sum_{p \in P_{sd}} x_{up} = 1 \qquad \forall u \in U, d \in D_s \qquad (2.3)$$

$$x_{up} = 0/1 \qquad \forall p \in P_{sd}, d \in D_s, u \in U \qquad (2.4)$$

$$\sum_{p \in P_{u(sd)}} x_{up}\delta_{p(nk)} \le y_{u(nk)} \qquad \forall n,k \in N, d \in D_s, u \in U \qquad (2.5)$$

$$\sum_{n \in N} \sum_{k \in K} \sum_{p \in P_{u(sd)}} x_{up}\delta_{p(nk)} \le H_d \qquad \forall d \in D_s, u \in U \qquad (2.6)$$

$$\sum_{k \in N} y_{u(nk)} \ge 1 \qquad \forall n \in s, u \in U \qquad (2.7)$$

$$\sum_{n \in N} y_{u(nk)} \ge 1 \qquad \forall k \in D_s, u \in U \qquad (2.8)$$

$$1 \geq \sum_{n \in N} y_{u(nk)} \qquad \forall k \in N, u \in U \qquad (2.9)$$

$$r_{un} \in R_{un} \qquad \forall n \in N, u \in U \qquad (2.10)$$

$$s_u \in S_u \qquad \forall u \in U \qquad (2.11)$$

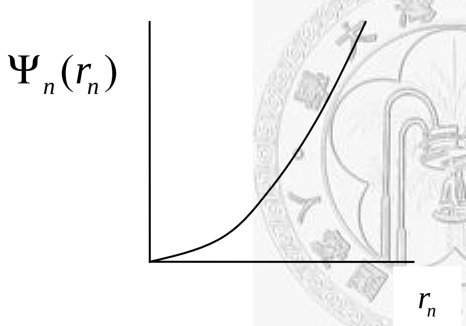
$$\Phi_k\left(r_{un}\right) = \frac{-\left(ab+cd\right)+\sqrt{\left(a^2+c^2\right)r_{un}{}^2-\left(ad-bc\right)^2}}{a^2+c^2}$$

$$\forall n,k \in N, u \in U \qquad (2.12)$$

$$s_u \text{ - M } (1\text{-}y_{u(nk)}) \leq \Phi_k\left(r_{un}\right) \qquad \forall n,k \in N, u \in U \qquad (2.13)$$

$$s_u + \text{M } (1\text{-}y_{u(nk)}) \geq \delta \qquad \forall n,k \in N, u \in U \qquad (2.14)$$

$$\sum_u s_u \geq T \qquad (2.15)$$



$\Psi_{un}(r_{un})$ is a power consumption function of r_{un}.

Explanation of Constraints：

The object function (IP1) of this problem is to minimize the total power consumption of relay nodes *n* ($\Psi_{un}(r_{un})$) that subject to:

1) Routing assignment Constraints:

Constraints (2.1) (2.10).The power radius of the relay node must be larger than the distance between the two nodes, and choose from the discrete radius set.

Constraints (2.3) (2.4).In each round, per destination must find exactly one path to transmit packet.

Constraints (2.2) (2.5).The link which is chosen by the O-D pair to compose its path must be the relay link. Once the path p is selected and the link $\overline{nk}$ is on the path, then the decision variable $y_{uw(nk)}$ must be enforced to 1 (i.e.: link $\overline{nk}$ must be connected) in this round.

Constraints (2.2) (2.4).It enforces the integer property of the decision variables.

Constraint (2.6).It limits the hop count less than given value H_d for each destinations.

Constraint (2.7).Using this, we can enforce that there must exist at least one outgoing link from the source node. So that we can assure the source node can correctly delivery the data packet.

Constraint (2.8).Using this, we can enforce that there must exist at least one incoming link to each destinations. So that we can assure each multicast member can correctly receipt the data packet.

Constraint (2.9).It limits the in-degree branch less or equal to 1 as multicast tree constraint.

2) Time slot division Constraints:

Constraint (2.12).By relay node's power radius and the mobility pattern of the two end points between this link*(n,k)* to predict the link effective duration time.

Constraints (2.11) (2.13).In each round, the route expiration time *(t)* is the minimal effective duration time of the active link on this multicast tree, and chooses the near value from the discrete candidate time set.

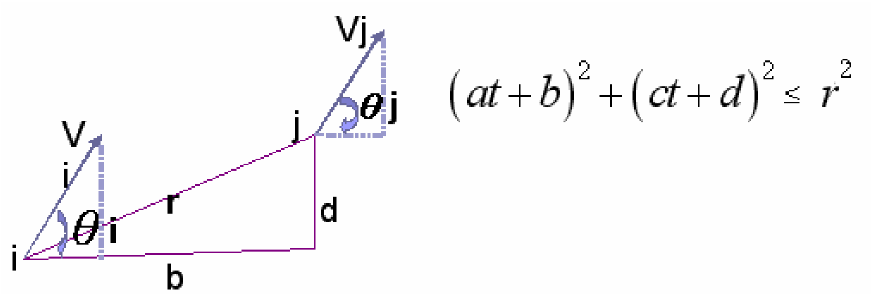


Figure 2-2 the link effective duration time calculating with mobility pattern.

Constraint (2.14).The time of each round should be larger than the lead time. Before next round starts, t_4 must sufficient enough ($t_4 > t_1+t_2+t_3$) to complete routing assignment of next round at time $t_1+t_2+t_3+t_4$.

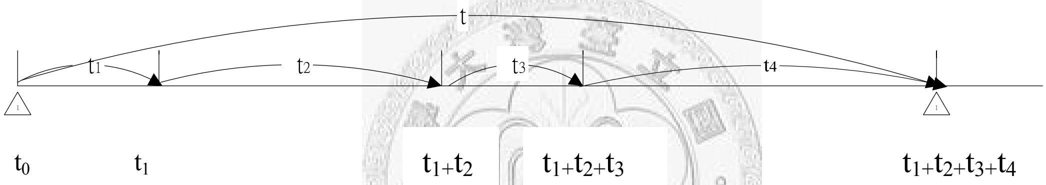


Figure 2-3 pictorial composed processes of each round.

t_1 : The time needed to collect global information. (the velocity, direction, and position of the node.)

t_2 : The time needed to run the routing assignment.

t_3 : The time needed to relay the routing decision to all nodes.

t_4 : The route expiration time, which is the time slot division in this round.

Constraint (2.15).The flow of traffic corresponding to the required transmission time should be satisfied in *u* rounds, which is the terminate condition.

By the way, we can jointly consider load balancing during the design stage. In order to avoid the appearance of hot spot, we add one constraint in our problem formulation with limiting the power consumption of each node should be smaller than the threshold value.

Besides, we can transform this problem into a MinMax problem, which is to minimize the maximum power cost of the hot spot.

Chapter 3 Solution Approach

3.1 Lagrangian Relaxation

We can transform the above primal problem (IP1) into the following Lagrangian relaxation problem (LR) where constraints (2.1), (2.5), (2.13), and (2.14) are relaxed. For a vector of non-negative Lagrangian multipliers, a Lagrangian relaxation problem of IP1 is given by an optimization problem (LR) as below:

Optimization Problem (LR):

$$Z_{LR}(\mu^1_{unk},\mu^2_{unk},\mu^3_{unk},\mu^4_{unk}) =$$

$$Min \sum_{u\in U}\sum_{n\in N}\psi_{un}(r_{un}) + \sum_{u}\sum_{n}\sum_{k}\mu^1_{unk}\ (y_{u(nk)}d_{u(nk)} - r_{un})$$

$$+\sum_{u}\sum_{n}\sum_{k}\sum_{d}\mu^2_{unkd}\ (\sum_{p\in P_{u(sd)}} x_{up}\delta_{p(nk)} - y_{u(nk)})$$

$$+\sum_{u}\sum_{n}\sum_{k}\mu^3_{unk}\ (s_u - M(1-y_{u(nk)}) - \Phi_k(r_{un}))$$

$$+\sum_{u}\sum_{n}\sum_{k}\mu^4_{unk}\ (\delta - s_u - M(1-y_{u(nk)}))$$

(LR)

Subject to:

$y_{u(nk)} = 0/1$	$\forall n,k\in N, u\in U$	(3.1)
$\sum_{p\in P_{sd}} x_{up} = 1$	$\forall u\in U, d\in D_s$	(3.2)
$x_{up} = 0/1$	$\forall p\in P_{sd}, d\in D_s, u\in U$	(3.3)

$$\sum_{n\in N}\sum_{k\in K}\sum_{p\in P_{u(sd)}} x_{up}\delta_{p(nk)} \le H_d \qquad \forall d\in D_s, u\in U \tag{3.4}$$

$$\sum_{k\in N} y_{u(nk)} \ge 1 \qquad \forall n\in s, u\in U \tag{3.5}$$

$$\sum_{n\in N} y_{u(nk)} \ge 1 \qquad \forall k\in D_s, u\in U \tag{3.6}$$

$$1 \ge \sum_{n\in N} y_{u(nk)} \qquad \forall k\in N, u\in U \tag{3.7}$$

$$r_{un} \in R_{un} \qquad \forall n\in N, u\in U \tag{3.8}$$

$$s_u \in S_u \qquad \forall u\in U \tag{3.9}$$

$$\sum_{u} s_u \ge T \tag{3.10}$$

where μ_1, μ_2, μ_3, and μ_4 are the vectors of non-negative Lagrangian multipliers $\{\mu^1_{unk}\}$, $\{\mu^2_{unkd}\}$, $\{\mu^3_{unk}\}$, and $\{\mu^4_{unk}\}$. To solve LR, we decompose the problem into the following four independent and solvable optimization subproblems.

3.1.1 Subproblem1 (related to decision variable r_{un})

Objective function:

$$Z_{sub3.1}(\mu_1,\ \mu_3)$$

$$= \min \sum_{u}\sum_{n}[\ \Psi_{un}(r_{un}) - \sum_{k}\mu^{1}_{unk} r_{un}\ -\ \sum_{k}\mu^{3}_{unk}\Phi_{k}(r_{un})\ ] \qquad \text{(SUB3.1)}$$

Subject to:

$r_{un} \in R_{un}$ $\qquad \forall n \in N, u \in U$ $\qquad$ (3.8)

This subproblem is related to power radius r_{un}, and can be further decomposed to $|U||N|$ subproblems.

Optimization problem:

$$Z_{sub3.1.1}(\mu_1,\ \mu_3)$$

$$= \min\ \Psi_{un}(r_{un}) - \sum_{k}\mu^{1}_{unk} r_{un} - \sum_{k}\mu^{3}_{unk}\Phi_{k}(r_{un}) \qquad \text{(SUB3.1.1)}$$

Subject to:

$r_{un} \in R_{un}$ $\qquad$ (3.8)

For each subproblem of (SUB3.1.1), we choose r_{un} from set of possible transmission radius of node *n*. The most important is that we try to minimize the objective function which all terms are associated with power radius r_{un}.

3.1.2 Subproblem2 (related to decision variable x_{up})

Objective function:

$$Z_{sub3.2}(\mu_2)$$

$$= \min \sum_{u} \left(\sum_{p} \left(\sum_{n} \sum_{k} \sum_{d} \mu_{unkd}^2 \delta_{p(nk)} \right) x_{up} \right)$$

(SUB3.2)

Subject to:

$$\sum_{p \in P_{sd}} x_{up} = 1 \qquad \forall u \in U, d \in D_s \qquad (3.2)$$

$$x_{up} = 0/1 \qquad \forall p \in P_{sd}, d \in D_s, u \in U \qquad (3.3)$$

$$\sum_{n \in N} \sum_{k \in K} \sum_{p \in P_{u(sd)}} x_{up} \delta_{p(nk)} \le H_d \qquad \forall d \in D_s, u \in U \qquad (3.4)$$

We can clearly see the character of this problem after rearranging the objective function of SUB3.2

$$Z_{sub3.2}(\mu_2) = \min \sum_{u} \sum_{n} \sum_{k} \sum_{d} \mu_{unkd}^2 \sum_{p} x_{up} \delta_{p(nk)} = \sum_{u} \left(\sum_{p} \left(\sum_{n} \sum_{k} \sum_{d} \mu_{unkd}^2 \delta_{p(nk)} \right) x_{up} \right)$$

This subproblem is related to to-be-admitted O-D pairs x_{up} and can be further decomposed to $|U||D_s|$ subproblems.

Optimization problem:

$$Z_{sub3.2.1}(\mu_2)$$

$$= \min \sum_{n} \sum_{k} \sum_{d} \mu^2_{unkd} \sum_{p} x_{up} \delta_{p(nk)} \quad \text{(SUB3.2.1)}$$

Subject to:

$$\sum_{p \in P_{sd}} x_{up} = 1 \quad (3.2)$$

$$x_{up} = 0/1 \qquad \forall p \in P_{sd} \quad (3.3)$$

$$\sum_{n \in N} \sum_{k \in K} \sum_{p \in P_{u(sd)}} x_{up} \delta_{p(nk)} \le H_d \quad (3.4)$$

Each subproblem of (SUB3.2.1) is a shortest path problem with hop count constraint. μ^2_{unkd} is the link cost, and H_d is the hop constraint. It can be solved by Bellman-ford algorithm [2].

3.1.3 Subproblem3 (related to decision variable $y_{u(ij)}$)

Objective function:

$$Z_{sub3.3}(\mu_1,\ \mu_2,\ \mu_3,\ \mu_4)$$

$$= \min \{ \sum_{u}\sum_{n}\sum_{k}[\ \mu_{unk}^{1} d_{u(nk)} - \sum_{d}\mu_{unkd}^{2} + (\mu_{unk}^{3} + \mu_{unk}^{4})M\ ]\ y_{u(nk)}$$

$$- (\mu_{unk}^{3} + \mu_{unk}^{4})M \ \} \qquad \text{(SUB3.3)}$$

Subject to:

$$y_{u(nk)} = 0/1 \qquad \forall n,k \in N, u \in U \qquad (3.1)$$

$$\sum_{k \in N} y_{u(nk)} \geq 1 \qquad \forall n \in s, u \in U \qquad (3.5)$$

$$\sum_{n \in N} y_{u(nk)} \geq 1 \qquad \forall k \in D_s, u \in U \qquad (3.6)$$

$$1 \geq \sum_{n \in N} y_{u(nk)} \qquad \forall k \in N, u \in U \qquad (3.7)$$

This subproblem is related to $y_{u(ij)}$, and can be further decomposed to $|U|$ subproblems.

Optimization problem:

$$Z_{sub3.3}(\mu_1, \mu_2, \mu_3, \mu_4)$$

$$= \min \{ \sum_{n}\sum_{k}[\, \mu^1_{unk} d_{u(nk)} - \sum_{d}\mu^2_{unkd} + (\mu^3_{unk} + \mu^4_{unk})M \,] y_{u(nk)} - (\mu^3_{unk} + \mu^4_{unk})M \;\} \quad \text{(SUB3.3.1)}$$

Subject to:

$$y_{u(nk)} = 0/1 \qquad \forall n, k \in N \qquad (3.1)$$

$$\sum_{k \in N} y_{u(nk)} \geq 1 \qquad \forall n \in s \qquad (3.5)$$

$$\sum_{n \in N} y_{u(nk)} \geq 1 \qquad \forall k \in D_s \qquad (3.6)$$

$$1 \geq \sum_{n \in N} y_{u(nk)} \qquad \forall k \in N \qquad (3.7)$$

Let $P_{nk} = \mu^1_{unk} d_{u(nk)} - \sum_{d}\mu^2_{unkd} + (\mu^3_{unk} + \mu^4_{unk})M$

There are two cases to consider:

Case1. If $P_{nk} < 0$, then assign $y_{uw(nk)} = 1$

Case2. If $P_{nk} \geq 0$, then assign $y_{uw(nk)} = 0$

With constraints $\sum_{k \in N} y_{u(nk)} \geq 1 \;\; \forall n \in s$ (3.5), $\sum_{n \in N} y_{u(nk)} \geq 1 \;\; \forall k \in D_s$ (3.6) and $1 \geq \sum_{n \in N} y_{u(nk)} \;\; \forall k \in N$ (3.7), at first, we should order P_{nk} in ascending sequence. Then, when we try to assign value of $y_{uw(nk)}$, whether in case1 or case2, we should take into account with constraints (3.5), (3.6)and (3.7) at the same time.

Go into details in the two cases:

Case1. For all $P_{nk} < 0$ in ascending sequence, we assign the first $y_{u(nk)} = 1$.

As to the remaining P_{nk}, we should first check for the node *k*, there may have at most one incoming link to it. If there already exists one relay link to it, then we assign $y_{u(nk)} = 0$; otherwise, we assign $y_{u(nk)} = 1$.

(i.e.: with respect to constraint $1 \geq \sum_{n \in N} y_{u(nk)}$ $\forall k \in N$ (3.7)).

Case2. For all $P_{nk} \geq 0$ in ascending sequence, we should both check for the source node *s*, there must exist one outgoing link to delivery data packet correctly; and for each destination *k*, there must exist one incoming link to delivery data packet correctly. If there are no relay links from the source node or to this destination, then we assign $y_{u(nk)} = 1$; otherwise, we assign $y_{u(nk)} = 0$.

(i.e.: with respect to constraint $\sum_{k \in N} y_{u(nk)} \geq 1$ $\forall n \in s$ (3.5), $\sum_{n \in N} y_{u(nk)} \geq 1$ $\forall k \in D_s$ (3.6)).

By the way, the choice of the big number *M* is also a good study. It is part of P_{nk}, (i.e.: $P_{nk} = \mu^1_{unk} d_{u(nk)} - \sum_{\mathrm{d}} \mu^2_{unkd} + (\mu^3_{unk} + \mu^4_{unk})M$), and we assign $y_{u(nk)}$ based on the value of P_{nk} and the associated constraints. It has great influence on the choice of the relay link. With jointly consider constraints (2.13) $s_u - \mathrm{M}\,(1\text{-}y_{u(nk)}) \leq \Phi_k(r_{un})$ and (2.14) $s_u + \mathrm{M}\,(1\text{-}y_{u(nk)}) \geq \delta$, we find that $M \geq -\Phi_k(r_{un}) + S_u$. So that the big number *M* should be chosen as $\max_u \{s_u\}$.

- Lemma 1:

Constraint (3.7) $1 \geq \sum_{n \in N} y_{u(nk)} \quad \forall k \in N$ is a redundant constraint.

Key point:

With this redundant constraint, it could lessen the region of feasible solution, but couldn't have any impact to the optimal solution. It means that although we reduce a non-tree structure to a multicast tree, it still can have the same transmission effect with the same cost. In other words, without this constraint, a non-tree structure transmission could find the optimal solution as well.

The goal is that we want to prove whether transmission graph is a tree structure or a non-tree structure, they should both find the same optimal solution to transmit their data packet. (i.e.: Both they have the same transmission effect with the same cost.)

Before proving, we first recall the property of the shortest path tree [1].

Property: If the path $s = i_1 - i_2 - ... - i_h = \mathrm{k}$ is a shortest path from node *s* to node *k*, then for every q = 2,3,...,h-1 , the subpath $s = i_1 - i_2 - ... - i_q$ is a shortest path from the source node to node i_q .

Following, by giving an example like Figure 3-1, we give the more detailed description and proof.

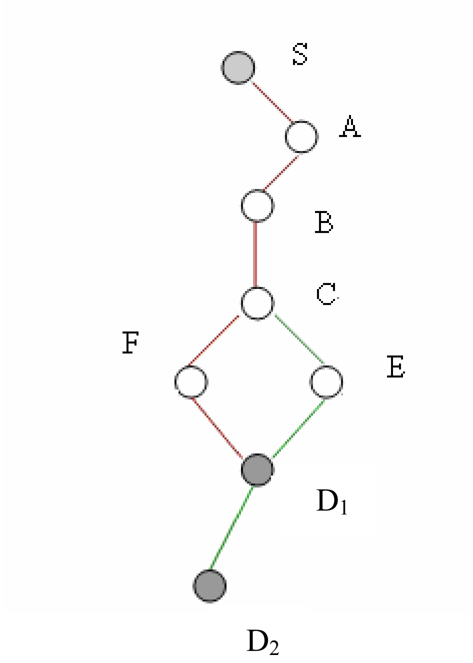


Figure 3-1 an arbitrary topology

S is the source node, while D_1 and D_2 are the destinations. (i.e.: There are 2 O-D pairs) Some nodes are selected as relay nodes which are assigned transmission radius, and the overall power assignment determines the transmission graph. During the selecting procedure, Node *i* can receive Node *j*'s transmission only when the power radius turning on by *j* is larger than the distance between $\overline{ij}$, so that we run shortest path algorithm to find the minimum total power consumption.

We assume that after optimization, the routing assignment is as follows:

$S\text{-}A\text{-}B\text{-}C\text{-}F\text{-}D_1$

$S\text{-}A\text{-}B\text{-}C\text{-}E\text{-}D_1\text{-}D_2$

For D_2, ($S\text{-}A\text{-}B\text{-}C\text{-}E\text{-}D_1\text{-}D_2$) is a shortest path. According to the property of shortest path, the subpath ($S\text{-}A\text{-}B\text{-}C\text{-}E\text{-}D_1$) is also a shortest path.

For D_1, ($S\text{-}A\text{-}B\text{-}C\text{-}F\text{-}D_1$) is a shortest path. As we mentioned formerly, ($S\text{-}A\text{-}B\text{-}C\text{-}E\text{-}D_1$) is also a shortest path. That is, for D_1, there are two cost-equivalent relay paths

P_1 (S-A-B-C-E-D_1) and P_2 (S-A-B-C-F-D_1).

But with respect to the overall transmission cost, P_1 and P_2 should not coexist at the same time. Because in this way, both Node *E,* and *F* turn on their power, which cost more than only choose one path from them. It is contradiction that the optimal solution would not be this as we assume at beginning.

As above-mentioned, we proof that whether the structure is non-tree or multicast tree, we could find the optimal solution. It is undisputed that constraint (3.7) $1 \geq \sum_{n \in N} y_{u(nk)}$ $\forall k \in N$ is a redundant constraint.

Moreover, by adding the redundant constraint, we can get the tighter bound in subproblem3. Because this is a minimization problem, by limiting it we can assure that there is at most one incoming link to each node. With comparing to the method could have more incoming links to each node, the method we use has less choices when we try to solve this subproblem. Because this is a dual problem, we want to find the maximum lower bound. With respect to the primal problem, we can get the tighter bound, which is tighter than the origin one.

3.1.4 Subproblem4 (related to decision variable s_u)

Objective function:

$Z_{sub3.4}(\mu_3, \mu_4)$

$$= \min \sum_{u}\sum_{n}\sum_{k}[(\mu^3_{unk} - \mu^4_{unk})s_u + \mu^4_{unk}\delta] \quad \text{(SUB3.4)}$$

Subject to:

$$s_u \in S_u \qquad \forall u \in U \qquad (3.9)$$

$$\sum_u s_u \ge T \qquad (3.10)$$

This subproblem is related to s_u. At first, we calculate $p_{unk} = \mu^3_{unk} - \mu^4_{unk}$, and order p_{unk} in ascending sequence. For all $p_{unk} \le 0$ in ascending sequence, we assign s_u from the maximum value of possible link connection time in S_u. Then, we check whether $\sum_u s_u \ge T$ is satisfied or not.

IF it is satisfied, we calculate the value of objective function. Otherwise, for all $p_{unk} > 0$ in ascending sequence, we assign s_u one at a time from the minimum value of possible link connection time in S_u, and check whether $\sum_u s_u \ge T$ is satisfied or not. We finish our assignment until $\sum_u s_u \ge T$ is satisfied.

3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangian duality theorem [8], for any $\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk} \geq 0$, the objective value of $Z_D\left(\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk}\right)$ is a lower bound of Z_{IP1}. Based in problem (LR1), the following dual problem (D) is then constructed to calculate the tightest lower bound.

Dual Problem (D):

$$Z_D = \max Z_D\left(\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk}\right)$$

subject to:

$$\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk} \geq 0$$

There are several methods to solve the dual problem (D). One of the most popular methods is the subgradient method which employed here [11]. Let the vector g be a subgradient of $Z_D\left(\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk}\right)$. Then, in iteration k of the subgradient optimization procedure, the multiplier vector $\pi^k = \left(\mu^1_{unk}, \mu^2_{unkd}, \mu^3_{unk}, \mu^4_{unk}\right)$ is updated by $\pi^{k+1} = \pi^k + t^k g^k$. The step size t^k is determined by $t^k = \lambda \frac{(Z^h_{IP} - Z_{D1}(\pi_k))}{\left\|g^k\right\|^2}$. Z^h_{IP} 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

After optimally solving the Lagrangian dual problem, we get a set of decision variables. However, the solution wouldn't be a feasible one for primal problem since some of constraints are not satisfied. Thus, we need to develop some heuristics to tune these decision variables, so that they may constitute a primal feasible solution of problem (IP1).

Generally speaking, the better primal feasible solution is an upper bound (UB) of the problem (IP1), while Lagrangian dual problem solution guarantees the lower bound (LB) of the problem (IP1). Iteratively, both solving Lagrangian dual problem and getting primal feasible solution, we get the LB and UB, respectively. So the gap between UB and LB, computed by (UB-LB)/LB*100%, illustrates the optimality of problem solution. The smaller gap is computed, the better optimality is solved.
Here we propose a heuristic for getting primal feasible solution of this problem.

4.1 Heuristic for Routing Policy Adjustment

In this problem, we have three major decision variables, namely r_n, $y_{u(nk)}$, and x_{up}. $\{r_n\}$, represent that how far the power radius could meet the entire transmission requirement, have several possibilities of tree structures and could not easy be solved. $\{y_{u(nk)}\}$, describe which links are the relay links in this transmission. However, the value of $\{y_{u(nk)}\}$ would oscillate between 0 and 1. $\{x_{up}\}$, which could describe the routing situations of the entire network, is the most important factor in finding primal feasible solutions.

Once $\{x_{up}\}$ are determined, $\{y_{u(nk)}\}$ and $\{r_n\}$ are also determined. So we design a heuristic for routing policy adjustment based on $\{x_{up}\}$. But the solution set of $\{x_{up}\}$ might possibly not be a feasible solution to the primal problem, that is it might break some constraints. By designing a rerouting heuristic to do some adjustment, we try to make this infeasible solution become feasible. Here we propose a heuristic, denoted [Heuristic 4.1], shown in Table 4-1 for getting primal feasible solution in this problem, and explain our approach as follows:

In order to handle this problem, at first, we adjust arc weight $\overline{\mu^2_{unkd}} = \frac{\mu^1_{unk}}{\sum_u \sum_n \sum_k \mu^1_{unk}}$. Then we run Bellman-Ford algorithm to get the solution set of $\{x_{up}\}$.

The reason why we use μ^1_{unk} to adjust the arc weight is as follows:

μ^1_{unk} is related with $y_{u(nk)} \times d_{u(nk)} \le r_{un}$, and the larger penalty value μ^1_{unk}, the larger r_{un} is needed. Note that the problem is to minimize total power consumption, so that when we run shortest path algorithm with modified arc weight, we will find the smaller value arc weight μ^1_{unk}, and get the path with less transmission cost.

We can analyze and compare different performance metric [18] by the computer experiments of the chosen MANET simulator [5].

As shown in Figure 1-6, according to the reactions of all the adjusted multipliers iteration by iteration, we could get better solution

Table 4-1 [Heuristic 4.1]: Heuristic for Routing Policy Adjustment

Step1. We adjust arc weight $\overline{\mu^2_{unkd}} = \frac{\mu^1_{unk}}{\sum_u \sum_n \sum_k \mu^1_{unk}}$, and then run Bellman -Ford algorithm to get the solution set of $\{x_{up}\}$.
Step2. Once $\{x_{up}\}$ are determined, $\{y_{u(nk)}\}$ and $\{r_{un}\}$ are also determined. We map each value of $\{r_{un}\}$ into the near value from $\{R_{un}\}$ and then calculate the effective connective time of each relay link $\{t(y_{u(nk)})\}$.
Step3. In each round, the route expiration time (s_u) is the minimal effective duration time of the active links on this multicast tree, with respect to constraint (2.13) s_u - M (1-$y_{u(nk)}$) $\le \Phi_k(r_{un})$. If the route expiration time < lead time, according to constraint (2.14) s_u + M (1-$y_{u(nk)}$) ≥ δ, we end heuristic algorithm and give up this iteration. Else, we proceed to step4.
Step4. We choose the near value from the discrete candidate time set. (i.e.: (2.11) $s_u \in S_u$)
Step5. The flow of traffic corresponding to the required transmission time should be satisfied in *u* rounds, which is the terminate condition. We check if constraint (2.15) $\sum_u s_u \ge T$ is satisfied for each destination until this round. If it is satisfied, we get all the solutions, and go to step7; otherwise, go to step6.
Step6. We predict the network topology after time δ as input parameters in the next round. We go back to step1, and rerun the reroute heuristic algorithm to tune this infeasible solution become feasible.
Step7. Finally, we could get the total power consumption required in this transmission. Generally speaking, we could tune tighter upper bound of the primal problem by this get primal feasible solution; otherwise, we minus 1

from improve counter.

Step8.End heuristic.

Chapter 5 Computational Experiment

5.1 Largrangian Relaxation Base Algorithm (LR)

This algorithm is based on the mathematical formulation described in Chapter2.

The relaxed problem is then optimally solved as described in Chapter3 to get a lower bound to the primal problem. We adopt a heuristic algorithm to readjust routing assignment, so that they may constitute a primal feasible solution of problem (IP1). Then, we use a subgradient method to update the Lagrangian multipliers. To sum up, the Lagrangian relaxation based algorithm (LR) is presented as follows:

Table 5-1 Algorithm 5-1: Lagrangian Relaxation Base Algorithm

Step1. Read configuration file to construct distribution of mobile nodes and all initial setting parameters. Step2. Initial multipliers. Step3. According to given multipliers, optimally solve these problems of SUB3.1, SUB3.2, SUB3.3, SUB3.4 to get the value of Z_{dual}. Step4. According to heuristics of Chapter4, we get the value of Z_{IP}. Step5. If Z_{IP} is small than Z^*_{IP}, we assign Z^*_{IP} to Z_{IP}. Otherwise, we minus 1 from improve counter. Step6. Calculate step size and adjust Lagrangian relaxation multipliers by using the subgradient method as described in section3.2. Step7. Iteration counter increases by 1. If iteration counter is over the threshold of the system, stop the program, and Z_{IP} is our best solution. Otherwise, go to step3, and repeat

until stopping criteria meets.

5.2 Experiment Environments

The computational experiments program has been written in C and implemented using a P4 2.8G, 512M system, working in FreeBSD environment.

5.2.1 Assumptions

The assumptions we make in this study are as follows:

1. We can get the location and mobility information provided by GPS (Global Positioning System).
2. All nodes in the network have their clock synchronized.
3. By Gauss-Markov mobility model, we can probabilistically predict the oncoming positions of nodes in the network. In order to simplify our problem, we assume the prediction is correct.
4. All nodes have omni-directional antennas.
5. No power expenditure is involved in signal reception/processing activities.

5.2.2 Parameters

For each scenario, the parameters are as follows:

1. Initial multiplier: 0
2. Maximum non-improvement counter: 30
3. Number of iterations: 2000
4. The area size: 1*1

5.3 Scenarios and Experiment Results

In our computational experiments, we generate several system scenarios with different 1) number of destination nodes, 2) mobility pattern, 3) maximum power radius. Then we apply LR algorithm to compute the minimum power consumption.

In addition, according to [17], we implement Multicast Link-based MST (MLiMST) Algorithm as Simple Algorithm 1 (SA1), and Multicast Least-Unicast-cost (MLU) Algorithm as Simple Algorithm 2 (SA2). We do some modifications in these algorithms to satisfy the constraints of our problem.

Also, we use SA1 and SA2 as benchmarks to evaluate our proposed LR algorithm.

We denote our dual solution as "Z_{dual}", and Lagrangian-based heuristic as "LR" . "Gap" is calculated to evaluate our solution quality. $Gap = \frac{LR - Z_{dual}}{Z_{dual}} * 100\%$. "Improvement" is our Lagrangian-based heuristic improvement on the simple algorithms. $Improvement = \frac{SA - LR}{SA} * 100\%$.

5.3.1 Scenario 1 (controlling factor: number of destination nodes)

To experiment 1) number of destination nodes, the parameters we set are listed below as Table 5-2, and the experiment results are given in Table 5-3 and *Figure 5-1*.

Table 5-2: Parameters of experiment 1) number of destination nodes

Number of Nodes	Power Radius	Mobility Pattern
100	0.16	0.2

Table 5-3 Experiment results for scenario1

# of destination nodes	Lower bound (Lb)	Upper bound (Ub)	(Ub-Lb)/Lb *100%	Simple algorithm1 (SA1)	(SA1-Ub)/Ub *100%	Simple algorithm2 (SA2)	(SA2-Ub)/Ub *100%
10	1.69	1.72	1.78%	2.78	61.63%	2.78	61.63%
20	2.07	2.08	0.48%	4.51	116.83%	4.24	103.85%
30	2.902	2.905	0.10%	4.80	65.23%	5.54	90.71%
40	2.97	2.98	0.34%	5.16	73.15%	5.33	78.86%
50	3.024	3.027	0.10%	4.86	60.56%	5.20	71.79%
60	3.344	3.347	0.09%	5.87	75.38%	6.98	108.54%
70	3.435	3.438	0.09%	5.72	66.38%	7.14	107.68%
80	3.154	3.156	0.06%	5.64	78.71%	5.89	86.63%
90	3.2633	3.2639	0.02%	5.32	63.00%	5.86	79.54%

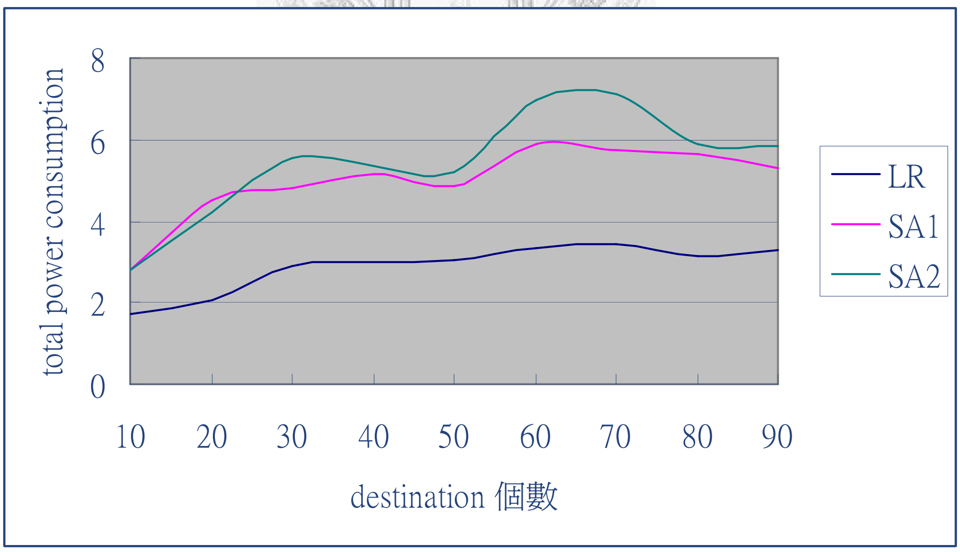


Figure 5-1 Experiment results for scenario1

5.3.2 Scenario 2 (controlling factor: mobility pattern)

To experiment 2) mobility pattern, the parameters we set are listed below as Table 5-4, and the experiment results are given in Table 5-5 and Figure 5-2.

Table 5-4: Parameters of experiment 2) mobility pattern

Number of Nodes	Number of Destinations	Power radius
200	40	0.13

Table 5-5 Experiment results for scenario2

Mobility pattern	Lower bound (Lb)	Upper bound (Ub)	Gap (Ub-Lb)/Lb *100%	Simple algorithm1 (SA1)	Improvement1 (SA1-Ub)/Ub *100%	Simple algorithm2 (SA2)	Improvement2 (SA2-Ub)/Ub *100%
0.06	2.78	2.80	0.72%	2.87	2.50%	2.87	2.50%
0.08	2.47	2.58	4.45%	2.70	4.65%	3.01	16.67%
0.10	2.67	2.75	3.00%	3.13	13.82%	3.13	13.82%
0.12	2.65	2.76	4.15%	2.86	3.62%	3.13	13.41%
0.14	2.63	2.68	1.90%	3.05	13.81%	3.15	17.54%
0.16	2.65	2.70	1.89%	4.28	58.52%	4.28	58.52%
0.18	2.68	2.81	4.85%	4.23	50.53%	4.43	57.65%
0.2	3.35	3.43	2.39%	5.88	71.43%	5.17	50.73%

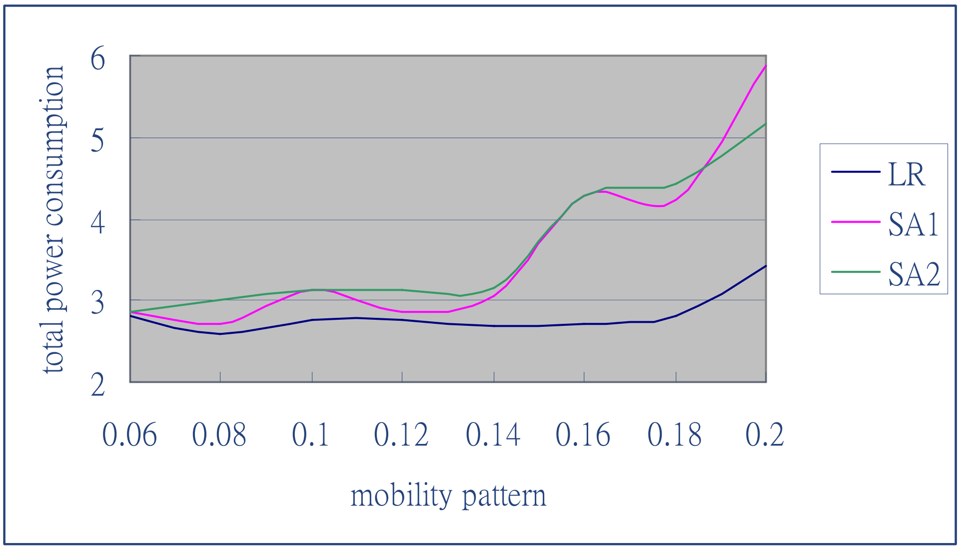


Figure 5-2 Experiment results for scenario2

5.3.3 Scenario 3 (controlling factor: maximum power radius)

To experiment 3) maximum power radius, the parameters we set are listed below as Table 5-6 , and the experiment results are given in Table 5-7 and Figure 5-3.

Table 5-6: Parameters of experiment 3) maximum power radius

Number of Nodes	Number of Destinations	Mobility pattern
150	40	0.16

Table 5-7 Experiment results for scenario3

Max power	Lower bound (Lb)	Upper bound (Ub)	Gap (Ub-Lb)/Lb *100%
0.13	2.781	2.785	0.15%
0.14	2.754	2.759	0.17%
0.15	2.751	2.756	0.18%
0.16	2.63	2.64	0.38%
0.17	2.664	2.668	0.16%
0.18	2.532	2.536	0.16%
0.19	2.47	2.48	0.40%
0.2	2.363	2.367	0.17%

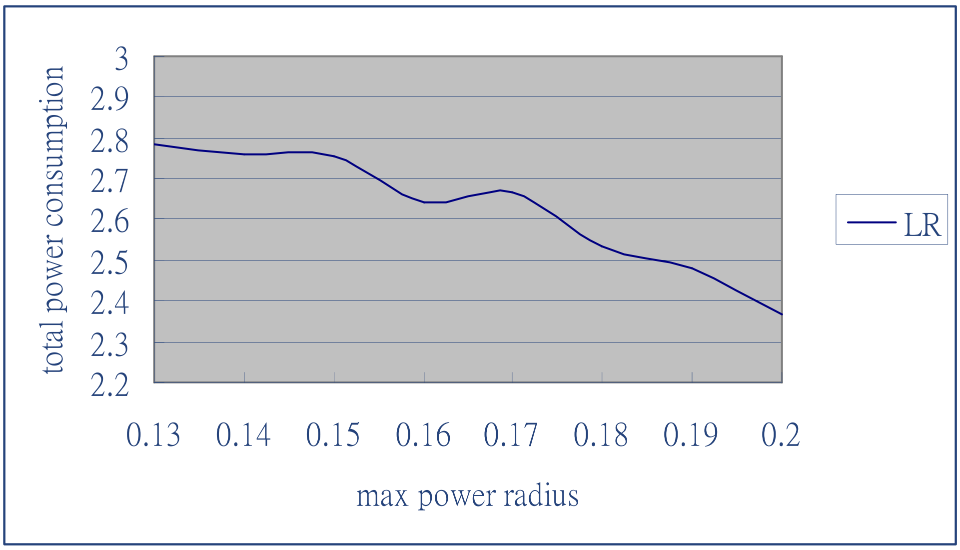


Figure 5-3 Experiment results for scenario3

Chapter 6 Conclusion

6.1 Summary

MANET is a challenging environment since all nodes operate on limited battery resource, and multi-hop routing paths are used over constantly changing network environments due to node mobility. Hence, efficient utilization of routing packets and immediate recovery of route breaks are critical in routing and multicasting protocols in this network topology.

In our research, we propose an approach to make reliable routing decisions with minimal power consumption in MANET, and formulate it as a mathematical problem. We model this problem as a linear integer mathematical programming problem. In addition, we take an optimal-based approach by applying the Lagrangian relaxation technique in the algorithm development.

We address the importance of routing algorithm on energy efficiency, and contribute to:

1) We propose a mathematical formulation and optimization-based algorithms with jointly considering energy-efficient and dynamic changes in network topology.
2) Our Lagrangian relaxation based solutions have more significant improvement than other intentional algorithm.

6.2 Future Work

In this thesis, we mimic the movements of mobile nodes by Gauss-Markov mobility model to probabilistically predict the future positions. We assume the prediction is correct in this model to simplify our problem. If we can apply some methodologies to approximate the situation when the prediction is not correct, it may be an interesting topic. In short, we describe this problem as follows:

The velocity of mobile node *m* is $\left(v_x^m t, v_y^m t\right)$, and the distance between node *m* and *n* is d_x^{mn}.

We could try game theory to find the worst bias when we made the prediction.

$Max \sum_{m,n \in N} \sqrt{\left[d_x^{mn} + \left(v_x^m - v_x^n\right)t\right]^2 + \left[d_y^{mn} + \left(v_y^m - v_y^n\right)t\right]^2}$, where

$\underline{v_x^m} \le v_x^m \le \overline{v_x^m}$, $\underline{v_y^m} \le v_y^m \le \overline{v_y^m}$, $\underline{v_x^n} \le v_x^n \le \overline{v_x^n}$, and $\underline{v_y^n} \le v_y^n \le \overline{v_y^n}$. Also, we can consider the probability of possibilities bias, and try to revise the network topology we predicted.

In addition, mobile devices are usually carried by humans, so the movement of such devices is necessarily based on human decisions and socialisation behaviour. If we can apply the new mobility model [21] that is founded on social network theory to run our routing algorithm, it may be more close to the real world and have more practical utility.

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簡歷

姓　　名：傅琳智

出生地：台灣省雲林縣

出生日：中華民國七十年四月二十四日

學　　歷：八十八年九月至九十二年六月

國立中央大學資訊管理學系

九十二年九月至九十四年七月

國立台灣大學資訊管理學研究所