A DESIGN OF MINIMUM COST MULTICAST ROUTING ALGORITHM

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A DESIGN OF MINIMUM COST MULTICAST ROUTING ALGORITHM.

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ABSTRACT

This research aims to design a delay-constrained minimum cost multicast routing algorithm used to support the real-time multimedia multicast application.

My process of developing the model for my Delay Constrained Multicast Routing (DCMR) is separated into two parts. The first part is designed for finding a multicast tree with minimum cost, whereas the second part is mainly to discover the process of iterative path switching. It aims to find new paths within the delay bound by iteratively replacing the old ones with new ones. The computation complexity of this approach is moderate, in the order of $O(n^3\log(n))$.

After designing the DCMR algorithm, we initially test the work with some fixed graphs. We further perform the experiment with the Random Graph based on Waxman's algorithm with 9 graph sizes at 10, 15, 20, 25, 30, 60, 90, 120 and 150 nodes. Each size consists of 100 different forms of network graphs, with one randomly selected source node and four destination nodes.

The results obtained from DCMR are then compared with another approach — Bounded Shortest Multicast Algorithm. First, as to the cost issue, the cost of the trees obtained from DCMR algorithm is approximately 20% higher. Secondly, as to the issue of delay, DCMR is much less efficient, however, in some cases, the results are just the opposite, depending on the delayed bound, the graph structures, and the positions of both source and destination nodes. Finally, as to the computation time, the DCMR algorithm is about 2-4 times faster simply because it requires fewer iterations.

In conclusion, my Delay-Constrained Multicast Routing algorithm is suitable for real-time multimedia multicast applications because it generates multicast trees that requires less computation time than any other algorithms and most likely cost less for an equal level of performance.

KEYWORDS : MULTICAST ROUTING / DELAY-CONSTRAINED

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การออกแบบวิธีการหาเส้นทางการส่งข้อมูลแบบมัลติคาสก์ที่มีค่าใช้จ่ายน้อย (A DESIGN OF MINIMUM COST MULTICAST ROUTING ALGORITHM)

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บทคัดย่อ

งานวิจัยครั้งนี้เป็นการออกแบบวิธีการหาเส้นทางสำหรับการส่งข้อมูลแบบมัลติคาสก์ โดยมีเป้าหมายให้มีค่าใช้จ่ายน้อย และมีค่าของดีเลย์อยู่ภายใต้ค่าดีเลย์ที่กำหนดไว้ ซึ่งเป็นวิธีหนึ่งในการจำแนกประเภทของวิธีการหาเส้นทางการส่งข้อมูล เพื่อต้องการให้สนับสนุนกับงานที่ต้องการความรวดเร็วในการส่งข้อมูล โดยสามารถนำไปประยุกต์ใช้กับงานมัลติคาสก์ที่ต้องการส่งอย่างทันทีทันใด (real-time multicast application)

ในการออกแบบอัลกอริทึ่มสำหรับหาเส้นทางการส่งข้อมูลที่ชื่อว่า Delay Constrained Multicast Routing ซึ่งเรียกสั้นๆว่า DCMR นี้ ในส่วนแรกจะทำการหาเส้นทางการส่งข้อมูลให้ค่าใช้จ่ายน้อยก่อน หลังจากนั้นจึงทำการวนซ้ำเพื่อหาเส้นทางใหม่มาแทนเส้นทางเก่าเพื่อให้ค่าของดีเลย์ไม่เกินค่าที่กำหนดไว้ โดยที่ความซับซ้อนของการคำนวณของ DCMR อยู่ที่ $O(n^3\log(n))$

เมื่อออกแบบ DCMR แล้ว ได้ทำการทดลองกับรูปกราฟบางรูปก่อนซึ่งได้ผลที่ดี จากนั้นจึงได้ทดลองโดยใช้ Random Graph เพื่อเป็นเครื่องมือในการสร้างรูปกราฟที่มีขนาดแตกต่างกัน 9 ขนาดคือ 10 15 20 25 30 60 90 120 และ 150 จุด แต่ละขนาดมีรูปกราฟที่แตกต่างกัน 100 รูปแบบ และได้สุ่มเลือกจุดต้นทาง 1 จุด และจุดปลายทาง 4 จุด

ผลการทดลองในเชิงเปรียบเทียบระหว่าง DCMR กับงานวิจัยที่ชื่อ Bounded Shortest Multicast Algorithm (BSMA) ในประเด็นแรกในเรื่องของค่าใช้จ่ายโดยรวมพบว่า DCMR จะสร้างเส้นทางการส่งข้อมูลที่มีค่าใช้จ่ายสูงกว่า BSMA แต่จะไม่เกินร้อยละ 20 ในประเด็นที่สองในเรื่องของดีเลย์พบว่า เส้นทางการส่งข้อมูลที่ได้จาก DCMR จะมีประสิทธิภาพด้อยกว่า BSMA แต่บางกรณี DCMR ก็สามารถสร้างเส้นทางการส่งมูลได้มีประสิทธิภาพดีกว่า BSMA ทั้งนี้ ขึ้นอยู่กับการกำหนดค่าดีเลย์ (Δ) ในประเด็นสุดท้ายในเรื่องของเวลาการคำนวณหาเส้นทางการส่งข้อมูล จะพบว่า DCMR จะใช้เวลาการคำนวณน้อยกว่า BSMA เสมอ โดยใช้เวลาน้อยกว่า 2 – 4 เท่า จึงสรุปได้ว่า DCMR จะเหมาะกับการใช้งานมัลติคาสก์ที่เป็นมัลติมีเดียที่ต้องการส่งข้อมูลอย่างทันทีทันใด

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CONTENTS

Page

ACKNOWLEDGEMENT iii

ABSTRACT iv

LIST OF TABLES ix

LIST OF FIGURES x

CHAPTER I. INTRODUCTION

1.1 Introduction 1

1.2 Chapter Organization 2

CHAPTER II. PROBLEM STATEMENTS

2.1 Motivations 4

2.2 Literature Survey 6

2.2.1 Multicasting 6

2.2.1.1 Overview 6

2.2.1.2 Characteristics of Multicast Applications 7

- Real-Time Multimedia Applications
- Real-Time Data Applications
- Non Real-Time Data Applications

2.2.2 Network Model 9

2.2.3 Tree Algorithms 11

2.2.3.1 Shortest Path Tree 11

2.2.3.2 Minimum Spanning Tree 11

2.2.3.3 Steiner Tree 12

2.2.4 Multicast Routing Algorithm 12

2.2.4.1 Multicast Routing Algorithm Classification 12

2.2.4.2 Review of the Previous Works 14

- Multicast Routing Heuristic; KMB algorithm
- Bounded Shortest Multicast Algorithm (BSMA)

2.2.5 Criteria for Evaluating Multicast Routing Trees 17

2.3 Problem Statements 18

2.4 Objectives 19

2.5 Problem Scope 20

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CONTENTS (Cont.)

		Page
CHAPTER III.	APPROACH	
3.1	Graph-Tree Approach	21
3.2	Delay Constrained Multicast Routing (DCMR) Model	22
	3.2.1 Participant Declaration	26
	3.2.2 Minimum Cost Multicast Routing Heuristic	26
	3.2.3 Constrained Checking	27
	3.2.4 Iteration Process	28
CHAPTER IV	IMPLEMENTATION	
4.1	Hardware and Software Environment	31
4.2	Random Graph Model	32
4.3	Implementation of the Participant Declaration	34
4.4	Implementation of the KMB Heuristic	35
4.5	Implementation of Constrained Checking Process	36
4.6	Implementation of Iteration Process	37
CHAPTER V	EXPERIMENTAL RESULTS	
5.1	Experimental Setup	41
5.2	Cost Issue	43
	5.2.1 Average total cost	43
	5.2.2 Average cost ratio	44
5.3	Delay Issue	48
	5.3.1 Average longest delay	48
	5.3.2 Average delay optimization ratio	50
5.4	Scalability Issue	54
	5.4.1 Average number of iteration	54
	5.4.2 Average shortest path calculation per round	55
	5.4.3 Average time per round	56

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CONTENTS (Cont.)

		Page
CHAPTER VI	DISCUSSION & CONCLUSION	
	6.1 Discussion	58
	6.1.1 Overall Analysis	58
	6.1.2 Cost Analysis	59
	6.1.3 Delay Analysis	59
	6.1.4 Scalability Analysis	60
	6.1.5 Complexity	61
	6.2 Conclusion	62
CHAPTER VII	SUGGESTIONS FOR FUTURE WORK	64
REFERENCES		65
APPENDIX A		67
APPENDIX B		69
BIOGRAPHY		72

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LIST OF TABLES

		Page
Table 2.1	Comparing of the transmission of IP network	6
Table 2.2	Order of complexity of multicast routing algorithm	12
Table 2.3	Properties of good multicast tree	17
Table 3.1	Conventional TTL Scope Control Values	22
Table 3.2	Comparison on Method between Two Algorithms	29
Table 5.1	The average number of iteration of BSMA and DCMR algorithm	53
Table 5.2	The average calculation of shortest path per round of BSMA and DCMR algorithms	54

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LIST OF FIGURES

		Page
Figure 2.1	An example of Unicast, Multicast, and Broadcast Transmissions	5
Figure 2.2	Examples of Multicast Applications	8
Figure 2.3	Network model	9
Figure 2.4	The example of network (Undirected Graph)	10
Figure 2.5	The example of a Steiner tree constructed by KMB algorithm	15
Figure 2.6	Flowchart of basic approach used in BSMA	16
Figure 3.1	Flowchart of DCMR Heuristic	23
Figure 3.2	Example of iterative optimization in DCMR model	24
Figure 3.3	DCMR Model	25
Figure 3.4	Participant Declaration Process	26
Figure 3.5	KMB Heuristic Process	26
Figure 3.6	Constrained Checking Process	27
Figure 3.7	Iteration Process	28
Figure 3.8	Delay-Constrained multicast tree	30
Figure 4.1	Example of network from Random Graph	33
Figure 4.2	Flowchart of Participant Declaration Process	34
Figure 4.3	Flowchart of KMB Heuristic Process	35
Figure 4.4	Flowchart of constrained checking process	36
Figure 4.5	Flowchart of Iteration process	38
Figure 5.1	Experimental Framework	40
Figure 5.2	The samples of network graph in different sizes that are generated from the Random Graph	41
Figure 5.3	The average cost relates to the difference of group size (small group)	43
Figure 5.4	The average cost relates to the difference of group size (medium to large group)	44
Figure 5.5	The average cost ratio of SPT and BSM algorithms comparing with KMB algorithm for the small group size	45

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LIST OF FIGURES (Cont.)

Page

Figure 5.6 The average cost ratio of SPT and BSM algorithms comparing with KMB algorithm for the medium to large group size 45

Figure 5.7 The average cost ratio of SPT and DCMR algorithms comparing with KMB algorithm for the small group size 46

Figure 5.8 The average cost ratio of SPT and BSM algorithms comparing with KMB algorithm for the medium to large group size 46

Figure 5.9 The average cost ratio of DCMR algorithm comparing with BSM algorithm for the small group size 47

Figure 5.10 The average cost ratio of DCMR algorithm comparing with BSM algorithm for the medium to large group size 47

Figure 5.11 The average longest delay of the small group of network graphs 48

Figure 5.12 The average longest delay of medium to large group of network graphs 48

Figure 5.13 The average longest delay of DCMR algorithm comparing with BSM algorithm on the small group size of network graphs 49

Figure 5.14 The average longest delay of DCMR algorithm comparing with BSM algorithm on the medium to large group size of network graphs 49

Figure 5.15 The average delay optimization ratio of KMB and BSM algorithms comparing with SPT algorithm on the small group size of network graphs 51

Figure 5.16 The average delay optimization ratio of KMB and BSM algorithms comparing with SPT algorithm on the medium to large group size of network graphs 51

Figure 5.17 The average delay optimization ratio of KMB and DCMR algorithm comparing with SPT algorithm on the small group size of network graphs 52

Figure 5.18 The average delay optimization ratio of KMB and DCMR algorithms comparing with SPT algorithm on the medium to large group size of network graphs 52

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LIST OF FIGURES (Cont.)

Page

Figure 5.19 The average delay optimization ratio of DCMR algorithm comparing with BSM algorithm on the small group size of network graphs 53

Figure 5.20 The average delay optimization ratio of DCMR algorithm comparing with BSM algorithm on the medium to large group size of network graphs 53

Figure 5.21 The average time per round ratio of DCMR algorithm comparing with BSM algorithm for small group 56

Figure 5.22 The average time per round ratio of DCMR algorithm comparing with BSM algorithm for medium to large group 56

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CHAPTER I
INTRODUCTION

1.1 Introduction

Multicasting is an ability of a communication network to accept a single message from an application and to deliver copies of the message to multiple recipients at different locations. Multicast is the technology in the midway between unicast and broadcast transmissions.

Multicast transmission makes better bandwidth utilization and reduces the computation at hosts or routers. Moreover, it is not necessary to know the real receiver's address because it uses group addresses to represent the destination of route.

The basic mechanisms to support IP multicast transmission are as follows:

- IP address class D allocation;
- Group membership management (Internet Group Management Protocol; IGMP);
- Routing of multicast data.

The main objective of the multicast routing is to find a good multicast tree that is optimal. After obtaining the optimal multicast tree, the multicast router will forward multicast packets from a source to any multicast groups.

The essences of multicast routing are as follows [1]:

1) Routing and forwarding techniques; which are used for making the route of multicast flow and forwarding multicast packets. The forwarding technique for several multicast routing protocols today is Reverse-Path Multicasting (RPM). RPM has been developed from Reverse-Path Forwarding (RPF) as found in forwarding technique for unicast transmission.

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2) Routing protocols; the main multicast routing protocols for intranet multicast routing today are Distance-Vector Multicast Routing Protocol (DVMRP), Multicast Extensions to OSPF (MOSPF), Protocol Independent Multicast (PIM), and Core-Based Tree (CBT).

3) Routing algorithms; are the procedures for determining a multicast tree, which is used to forward multicast packets. In general, most of the routing algorithms today have been developed just for academic applications.

The multicast routing algorithm can be classified into many types, depending on the user's criteria or specification of the multicast tree. For example, the types of multicast tree can be divided into two types: unconstrained and constrained trees.

The most widely used technique is delay constrained, which is necessary for multimedia multicast application as it requires the minimum end-to-end delay between source-destination pairs.

This research proposes a multicast routing algorithm, which can be classified as the delay-constrained multicast routing (DCMR). A DCMR algorithm will focus on the network cost and delay optimization by using suitable resources such as the computation time.

The experiment uses weighted graphs to represent the network model, in which Random Graph is a tool for generating network graphs in the experiment.

1.2 Chapter Organization

This thesis is organized in seven chapters as the following:

Chapter I: introduction.

Chapter II: a review of current researches related to our works such as classification of multicast routing algorithms, constrained and unconstrained multicast routing algorithms.

Chapter III: a design of delay-constrained minimum cost multicast routing algorithm.

Chapter IV: the algorithm implementation and simulation model.

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Chapter V: the results of the experiment and network parameters that used in the simulations.

Chapter VI: the discussion, and conclusion.

Chapter VII: the suggestion for future works.

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CHAPTER II
PROBLEM STATEMENTS

This chapter will present the background of multicasting, identify the research problems and survey literatures on multicast routing. The performance comparison of multicast routing algorithm, and the objectives and scopes of this thesis will also be included.

2.1 Motivations

Computers and communication networks have been continually developed in the fields of equipments, applications or technologies, especially the internet technology. These are the factors making computer network highly developed and widely used.

Presently, the computer network equipment is highly efficient. It provides faster communication with low cost. Then multimedia applications, which used to run only on high performance personal computers (PCs), can use via computer network also. At first, there was only one sender and one receiver, which called “client-server system”. The packets were sent by a computer network called “unicast”. This was the type of one-to-one communication. Later, more receivers needed to receive the same applications, the type of communication was changed to one-to-many. So, the computer network was changed to “multiple unicast” or “replicated unicast”.

Multiple unicast or replicated unicast had the weak point that when the same data was sent from the same source many times, it caused many messages in the computer network, also the traffic congestion problem. When the communication network was developed to be “multicast”, it solved the traffic problem because multicast transmission had one copy of data from one source as shown in Figure 2.1.

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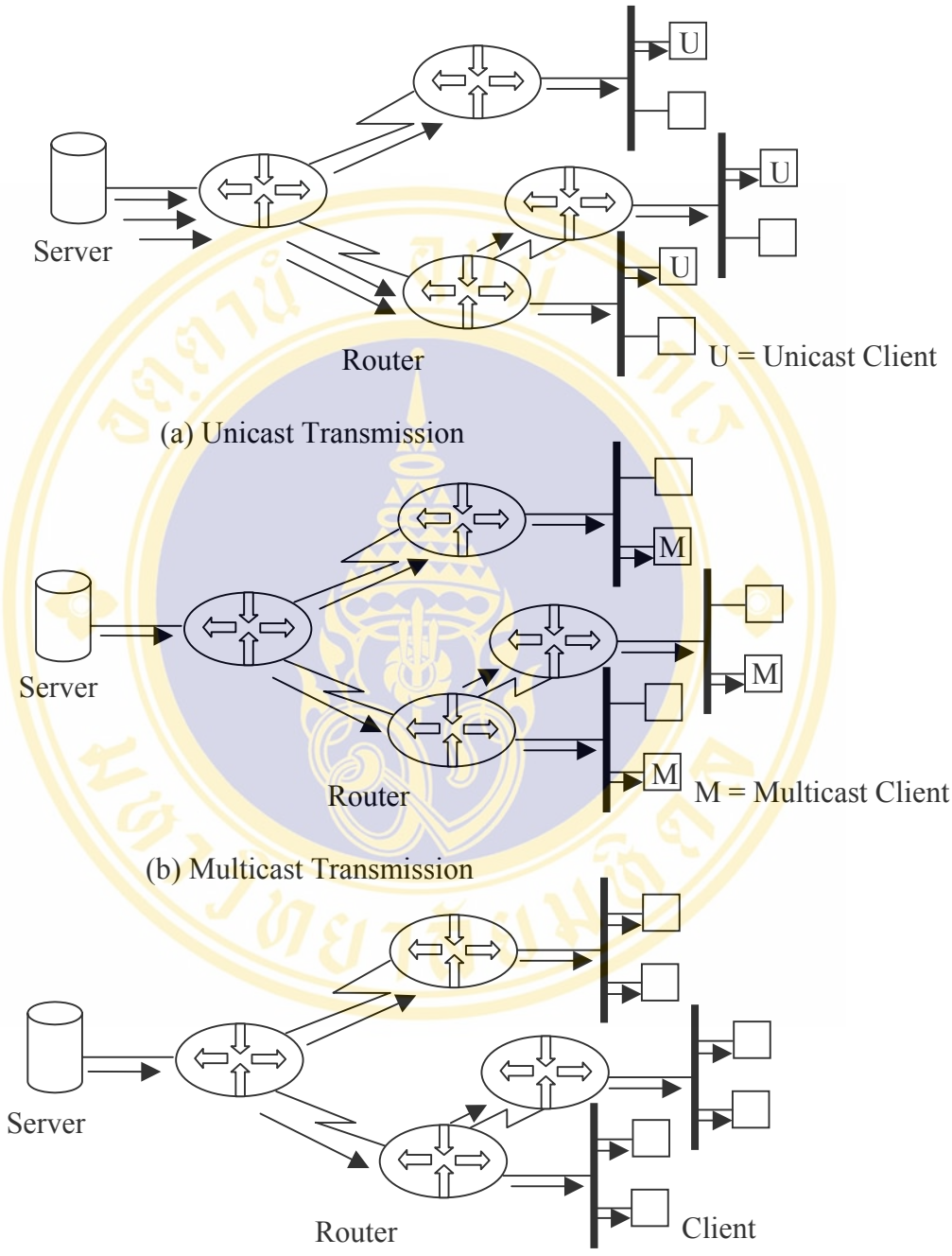

Figure 2.1: An example of Unicast, Multicast, and Broadcast Transmissions: (a) Unicast Transmission with three unicast clients, (b) Multicast Transmission with three multicast clients, (c) Broadcast Transmission.

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Figure 2.1(a) has illustrated the unicast transmission. According to the number of destinations, if a server employs many separated point-to-point connections, there are many copies of data needed to be sent over a single link. For multicast transmission (Figure 2.1(b)), one copy of data has been sent from the source along the link to the multicast router. For broadcast transmission in Figure 2.1(c), every client in the network receives a packet, which has been broadcast. Even though they do not want to receive it.

According to the benefits of multicasting in saving computer network resources, especially the bandwidth utilization, when developed the multicast transmission, it could reduce the cost of operation among organizations. For the efficiency of multicasting, the mechanisms of finding multicast routing are important. If we are able to find a good multicast routing algorithm that possibly builds a good multicast routing tree, it would be efficient for multicast transmission. This study then focuses on finding the efficient multicast routing algorithm for supporting the multicast transmission.

2.2 Literature Survey

2.2.1 Multicasting

2.2.1.1 Overview

Multicasting is an ability of a communication network to accept a single message from an application and to deliver copies of the message to multiple recipients at different location [2] as depicted in Figure 2.1. Multicast is the technology in the midway between unicast and broadcast transmissions as shown in Table 2.1.

Table 2.1: Comparing of the transmission of IP network

Mode	Source	Destination
Unicast	One	n = 1
Multicast	One/Many	1 < n < N
Broadcast	One	n = N

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In order to support IP multicast transmission efficiently, the following mechanisms are required [3]:

- Class D address allocation (Range 224.0.0.0 – 239.255.255.255);
- Group membership management (Internet Group Management Protocol; IGMP);
- Routing of multicast data.

2.2.1.2 Characteristics of Multicast Applications

Most multicast applications are multipoint applications, in which they can be classified into three categories as follows [4]:

(1) Real-Time Multimedia Applications

Real-Time multimedia applications do not need absolute reliability but demand tight limits of timing jitter. They are sub-divided into two types:

(1.1) Many-to-Many conferencing applications: An example of applications is video conferencing. In this type, each member is a source as well as a destination. Scaling is not an issue as the size of the group is typically less than 100.

(1.2) One-to-Many "event" applications: An example of applications is live broadcasting. In this type there are one source and many receivers (thousands) in the network.

(2) Real-Time Data Applications

These applications are commonly known as "Data Streaming" applications. They are put in the "gray area" in terms of reliability and latency requirements depending on the type of applications. They are further sub-divided into two types:

(2.1) Many-to-Many data streaming applications: An example of applications is "whiteboard" sharing. This type is similar to a video

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conferencing that it requires the reliability on data delivery. However, the timing requirements are not as critical as in video conferencing.

(2.2) One-to-Many data streaming applications: An example of applications is the financial data delivery. It needs high requirements in scalability (millions) but latency requirements are not as stringent. However, the reliability requirements depend on the users such as casual traders and brokers who have different reliability requirements.

(3) Non Real-Time Data Applications

Reliability requirements are very important for these types of applications. The sequencing of transferred data is also significant, for example: file transfer, software distribution, data and file replication, video-on-demand, etc.

Examples of multicast applications in different categories are shown in Figure 2.2.

	REAL-TIME	**NON REAL-TIME**
MULTIMEDIA	Video Server Video Conferencing Internet Audio Multimedia Events	Video and Web Servers Multimedia Kiosks
DATA-ONLY	Stock Quotes News Feeds White Board Applications Interactive Gaming	Server-Server Data Delivery Server-Desktop Data Delivery Database Replication Software Distribution

Figure 2.2: Examples of Multicast Applications

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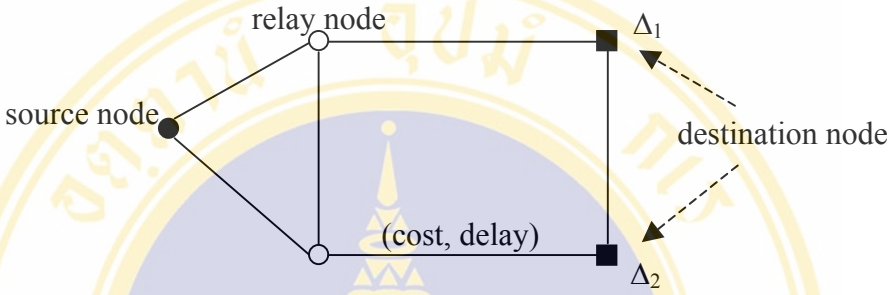
2.2.2 Network Model

Communication links in a network may have different characteristics, for example, fiber optic links usually provide more bandwidth than copper wired ones. A characteristic of a communication link is represented by a *weight* of the corresponding link in a graph as shown in Figure 2.3 [5].



link cost = bandwidth utilization of channels
link delay = queuing delay + transmission delay + propagation delay
Δ_i = delay bound from the source to destination i

Figure 2.3: Network model

A network is modeled as a weighted graph G = (V, E), as shown in Figure 2.3, with node set V and edge set E.

The nodes in set V can be one of the following three types:

- Source node(s): It is the node connecting to the source when it sends out the data stream.

- Destination node(D): It is the node connecting to the destination when it receives the data stream. The set of destination nodes in a multicast tree is denoted by $D \subseteq V - s$.

- Relay node: It is the node of an intermediate hop in the path from the source to a destination.

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The links in the set of E are positive real-value functions. They are defined:

- Link-Cost Function (c: E $\rightarrow \Re^{+}$): The cost of a link is its utilization, for example, the bandwidth. A higher utilization is represented by a higher link cost.

- Link-Delay Function (d: E $\rightarrow \Re^{+}$): The delay of a link is the sum of the queuing delay, transmission delay, and propagation delay over that link.

These links can be classified as symmetric and asymmetric. The symmetric links have the same weight in both directions, whereas asymmetric links have different weight in each direction. So, the type of graphs can be classified in undirected and directed graph. The example of network that represented by undirected graph is shown in Figure 2.4.

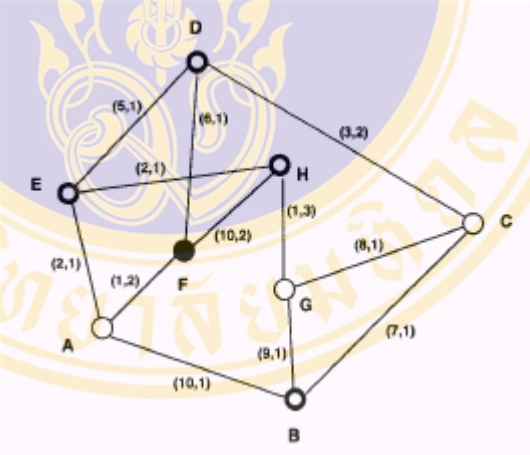

Figure 2.4: The example of networks (Undirected Graph)

This figure was shown in the work of Kompella et. al. in 1993 [6] and Zhu et. al. in 1995 [5].

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2.2.3 Tree Algorithms

The main issue of routing for multicast is to find an efficient multicast routing tree from a given network. There are quite a number of algorithms for finding the tree from the graph such as [7]

- Shortest path tree
- Minimum spanning tree
- Steiner tree

2.2.3.1 Shortest Path Tree

Shortest path tree (SPT) is the tree that comes from the several shortest links of the end-to-end node. Dijkstra's algorithm and Bellman-Ford's algorithm are the two that most widely used for finding the shortest path of the end-to-end node. These algorithms have been applied in unicast transmission.

For multicast routing, the SPT algorithm is more suitable for finding the constraint-tree, especially the delay-constrained one, because that tree needs low delay time between source-destination pairs.

2.2.3.2 Minimum Spanning Tree

Minimum spanning tree (MST) is the tree that comes from the links that the sums of weight of those links are totally minimal. According to the graph G = (V, E), the MST has the vertexes that contain all of the members of group. The famous MST algorithms are Kruskal's and Prim's algorithms.

For multicast routing, the MST algorithm is suitable for finding unconstrained tree because it yields the minimum cost of the tree.

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2.2.3.3 Steiner Tree

The Steiner problems in a graph are those of finding the minimal tree in case of the members of the group are more than two but not equal to all members. The "Steiner Node" is not a participant node but can be an intermediate hop of tree. The comparison among each algorithm is shown in Table 2.2.

Table 2.2: Order of complexity of multicast routing algorithm

No. of M	Routing algorithm	Complexity
M = 2	Shortest path routing	O(|E| log |V|)
2 < M < V	Minimum Steiner Tree	O(|M| $\|V\|^2$)
M = V	Minimum Spanning Tree	O(|E| log |V|)

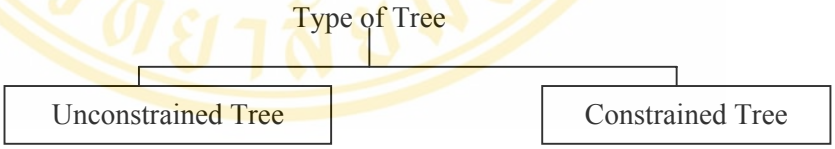
M = multicast participant node
V = all of vertexes in graph
E = all of edges in graph

2.2.4 Multicast Routing Algorithm

2.2.4.1 Multicast Routing Algorithm Classification

There are quite a number of categories in classifying the multicast routing. For this study, it will be categorized into five types as follows:

1) Type of trees: It can be divided into 2 sub-types, unconstrained tree and constrained tree.



Unconstrained algorithm: - It is mostly developed from the Reverse Path Forwarding (RPF) algorithm that used for several multicast routing protocols in present.

Constrained algorithm: - The mostly constrained is end-to-end delay constrained that used for multimedia applications. The others are delay jitter bound, minimum bandwidth, packet loss probability.

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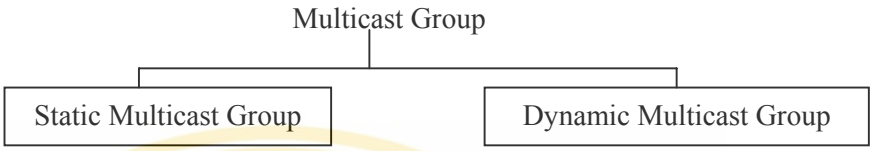
2) Multicast Group: It can be classified into static multicast group and dynamic multicast group.



Static multicast group: - In this type, the number of group member will be static throughout the session on finding multicast routing tree.

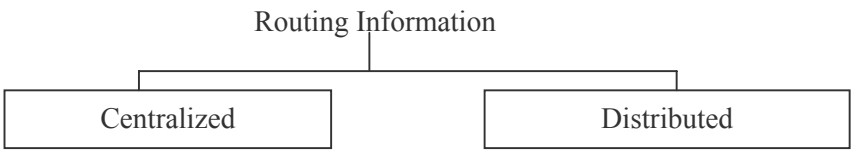
Dynamic multicast group: - In this type, the number of group members is dynamic. It can join or leave the session of finding multicast routing tree all the time.

3) Hop-to-Hop link: It can be classified to symmetric link and asymmetric link.

Symmetric link: - In this type, the weight of link from node u to node v will be equal to the weight of link from node v to node u.

Asymmetric link: - In this type, the weight of link (u, v) depends on the direction of data transmission.

4) Routing Information: The routing information such as network topology or link state information is necessary for determining the multicast tree. In this algorithm, it can be further divided into two sub-types.



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Centralized algorithm: - It consists of the central node that is responsible for computing the tree. It mostly used the source node, therefore, it will be called "source-based algorithm". The studies of multicast routing algorithms that can be classified to centralized algorithms are KPP(1993)[6], Widyono Algorithm(1994)[8], Sun-Langendoerfer Algorithm(1995)[9] and BSMA(1995, and 1998)[5, 10].

Distributed algorithm: - In this type, it consists of more than one node that can compute the routing tree. Actually, it is distributed computing. The studies of multicast routing algorithms that can be classified to distributed algorithm are Bauer & Varma Algorithm(1996)[11], and Jia's Algorithm (1998)[12].

5) Approaches of algorithm: It can be classified to graph-tree approach and neural network approach.

Graph-tree approach: - The most of routing algorithms can be classified to this type. It builds the multicast tree from the graph that is represented for the whole network. Random Graph model by Waxman(1988) [13] and Hierarchical Graph model by Doar & Leslie(1993)[14] are the examples of this type.

Neural network approach: - It is similar to graph-tree approach, in which it uses network graph to represent the network topology, but neural heuristic for computing the multicast tree. The example of this type is the work of Gelente et. al. (1997)[15].

2.2.4.2 Review of the Previous Works

This study will review the previous work that is related to those important multicast routing algorithms. There are two important multicast routing algorithms as follows:

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- **Multicast Routing Heuristic; KMB algorithm**

In 1981, the paper of L. Kou, G. Markowsky, and L. Berman was published in Acta Infomatica Journal entitled "A Fast Algorithm for Steiner Trees". They explained the design and development of unconstrained multicast routing algorithm. Later, this algorithm is called "KMB algorithm" in the short name. KMB algorithm has the following steps [2].

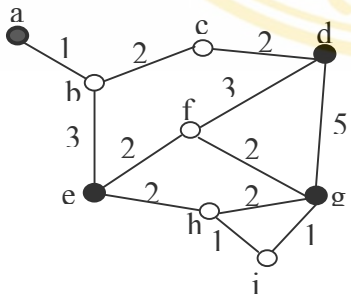
1) According to graph G = (V, E), it uses the participant nodes in the multicast group in the graph G. Then, it constructs an undirected closure graph G_1. Thus, every participant node is the node in G_1. Weights of edge (u, v) in G_1 will be equal to the one of shortest path between the node u and the node v.

2) Then finds the minimum spanning tree (MST) of closure graph G_1.

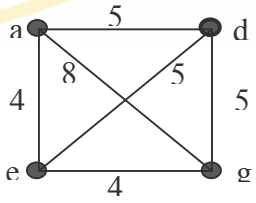
3) Constructing the graph G_2 by replacing each link in spanning tree of G_1 by the corresponding shortest path in G.

4) It found the minimum spanning tree T_2, of the graph G_2.

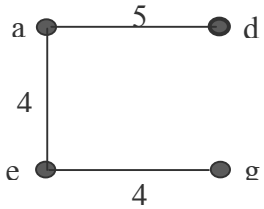
5) Constructing the multicast tree T_m by deleting links in T_2, if necessary. Figure 2.5 shows the operation of KMB algorithm.



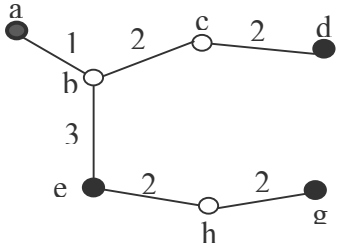
(a) Weighted graph(G) D = {a, d, e, g}



(b) Closure graph of D (G[D])



(c) Minimum spanning tree for G[D]



(d) MST solution, cost = 12

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Figure 2.5: The example of a Steiner tree constructed by KMB algorithm.

- **Bounded Shortest Multicast Algorithm (BSMA)**

BSMA is a delay-bounded multicast routing algorithm. It was first published in 1995 [5] by three researchers from University of California, Santa Cruz: Qing Zhu, Mehrdad Parsa, and J.J. Garcia-Luna-Aceves. It worked with undirected network graph. In 1998, BSMA was published again [10], but it worked with directed network graph.

BSMA has two operations, at first, it builds shortest delay multicast tree and next, it adjusts the tree iteratively. Flowchart of BSMA algorithm is shown in Figure 2.6 and pseudo-code of BSMA is shown in Appendix A .

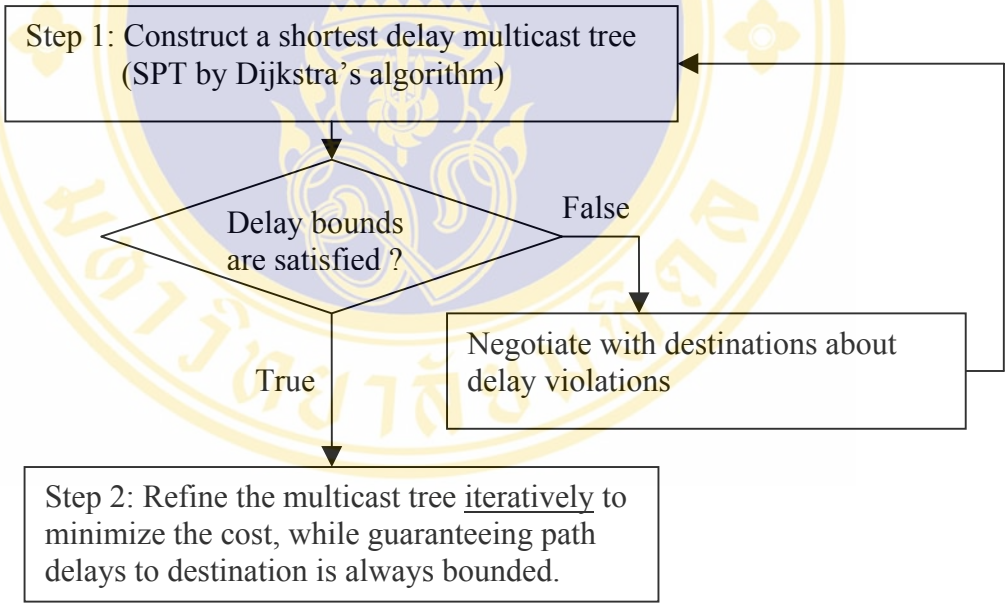

Figure 2.6: Flowchart of Basic Approach used in BSMA.

In 1997, the paper by Salama et. al. [16] concluded the evaluation of delay-constrained multicast routing algorithms, in which the BSMA algorithm was the best algorithm that determined the optimal cost multicast tree.

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2.2.5 Criteria for Evaluating Multicast Routing Trees

Types of multicast applications were dominated in designing a multicast routing algorithm for constructing the multicast tree. In the year 2000, the paper by Sahasrabuddhe and Mukherjee [2] explained properties of multicast tree and categorized it into three priority levels: high, medium, and low, that are shown in Table 2.3.

Table 2.3: Properties of good multicast tree

Priority levels	Property	Description
High Priority	Low Cost	The cost (or weight) of a multicast tree is the sum of costs (or weight) of all links which are in the multicast tree. A good multicast tree tries to minimize this cost.
	Low Delay	The end-to-end delay from the source node to the destination node is the sum of the individual link delays along the route. A good multicast tree tries to minimize the end-to-end delay for every source-destination pairs in the multicast group.
	Scalability	A good multicast tree is scalable in two respects. First, constructing a multicast tree for a large multicast group should require reasonable amounts of time and resources. Second, the switches in the communication network should be able to simultaneously support a large number of multicast trees.
Medium Priority	Support for dynamic multicast group	Multicast groups can be classified as static and dynamic. The members of a static multicast group do not change over time; in a dynamic multicast group, new members may join or existing members may leave. A good multicast tree should allow multicast members to join or leave the multicast tree in a seamless fashion. Moreover, the properties of a good multicast tree should not degrade due to the dynamic nature of the multicast group.
	Survivability	A good multicast tree should be able to survive multiple nodes and link failures.

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Priority levels	Property	Description
Low Priority	Fairness	A good multicast tree is fair in two respects. First, it tries to provide a minimum quality of service (e.g., bounded delay) to each member in the multicast group. (It is not fair to unnecessarily punish one member in order to improve the quality of service to other members.) Second, it tries to evenly divide the multicasting effort (e.g., packet duplication effort) among the participating node.

From Table 2.3, the goal of designing of multicast routing algorithms should nearly meet the "High Priority" properties.

2.3 Problem Statements

From the network model point of view that shown in section 2.2.2, we have found that the problem of designing multicast routing algorithm would be how to find the minimum cost multicast tree that is not over constrained, especially delay constrained, as used in the case of Real-Time multicast applications.

The problem of designing minimum cost multicast routing algorithm can be observed as follows:

1. Cost Optimization: The cost (or weight) of a multicast tree is the sum of the costs (or weights) of all links in the multicast tree. A good multicast tree simply tries to minimize this cost. Approximation algorithms for optimizing the cost of a multicast tree employ different kinds of heuristics. If the multicast group consists of all the nodes in the graph, the problem will be reduced to the well-known minimum spanning tree problem. Some approximation algorithms are based on the so-called minimum spanning tree heuristic, but the node in the tree is not equal to the total nodes in the graph. So, the problem is changed to the Steiner tree problem, because there are some relay nodes or Steiner nodes in that tree.

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2. Objective Constraints: The constraints imposed can be classified into two categories

- Link constraints are restrictions on the use of links for route selection. For example, one may request that the bandwidth or buffer available on a link is greater than or equal to a pre-determined value.
- Tree constraints are either:
  - Bounds on the combined value of a performance metric along each individual path from the source to a receiver in a multicast tree (e.g., the end-to-end delay bound on the paths from the source to all the receivers). A good multicast tree tries to minimize the end-to-end delay for every source-destination pairs in the multicast group.
  - Bounds on the difference of the combined value of a performance metric along the paths from the same source to any two different receivers. For instance, the interreceiver delay jitter bound is defined as the difference between the end-to-end delays along the paths from the same source to any two different receivers. In the case of heterogeneous Quality of Service(QoS), a different constraint may be imposed on each receiver.

2.4 Objectives

The study of Multicast Routing Algorithms is with the following objectives.

1. To study an Internet Protocol multicast packet.
2. To study and analyze how the network parameters effect the multicast network.
3. To design and develop a multicast routing algorithm.
4. To improve the delay-constrained minimum cost multicast routing algorithm.

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2.5 Problem Scope

This research work will be confined to the study, analysis and design of delay-constrained minimum cost multicast routing algorithm. It aims to find a better solution and to improve the algorithms that can solve both cost and delay optimization problem in source-specific multicast network by using suitable resources such as computation time.

The environments of this research are

1. Designing of multicast routing algorithm based on source-specific tree and centralized algorithm.
2. The network model that used for this study is symmetric network.
3. Group membership is static.

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CHAPTER III
APPROACH

This chapter will propose an approach to solve the aforementioned problem and describe how to develop the multicast routing algorithm with delay-constrained. The main concern of developing the multicast routing algorithm is to find the optimal multicast tree. Moreover, the model of Delay-Constrained Multicast Routing (DCMR) that has been influenced from Bounded Shortest Multicast Algorithm (BSMA) will be proposed also.

3.1 Graph-Tree Approach

There are two approaches to find the route for forwarding the multicast data; graph-tree approach and neural heuristic approach. Graph-tree approach is the one that is used to solve the Steiner tree problem in graph, whereas the neural heuristic approach uses neural network to improve the work for solving Steiner tree problem in graph. In the present work, graph-tree approach will be used to find the multicast tree.

A network in this study is modeled in weighted graph G = (V, E), where V is denoted as vertexes of nodes in graph, and E as edges or links that connected the two nodes. In each graph, the nodes can be 4 to 5 nodes to 200 nodes or more, based on the value of time to live (TTL) scope of multicast IP of IPv4 that is shown in Table 3.1.

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Table 3.1: Conventional TTL Scope Control Values

TTL	Scope threshold
0	Restricted to the same host
1	Restricted to the same subnetwork
15	Restricted to the same site
63	Restricted to the same region
127	Worldwide
191	Worldwide; limited bandwidth
255	Unrestricted in scope

From Table 3.1, there are 7 values of TTL scope and the values of TTL that are used to set up the size of network being 4 values, 15, 63, 127, and 191 respectively.

3.2 Delay Constrained Multicast Routing (DCMR) Model

DCMR algorithm assumes that the source node has the complete information of all links in network to construct a multicast tree. So, it is a source-based multicast routing algorithm. This requirement can be supported by using one of many broadcast topology algorithms, such as flooding algorithm.

The concepts of designing the DCMR algorithm are originated from the concept of BSMA, that is an iteration scheme for gradually adjusting the multicast tree and finally ending up with an optimal solution tree. But the difference from BSMA is that, in first step, DCMR considers the unconstrained multicast routing by using KMB algorithm. If the multicast tree from this step is not over the delay bound, it can find the multicast tree for forwarding multicast packet. On the other hand, if that tree has end-to-end delay of source-destination pairs over the delay bound, we have to adjust the tree by replacing the path that is over delay bound to the new ones iteratively.

The flowchart of DCMR heuristic is shown in Figure 3.1.

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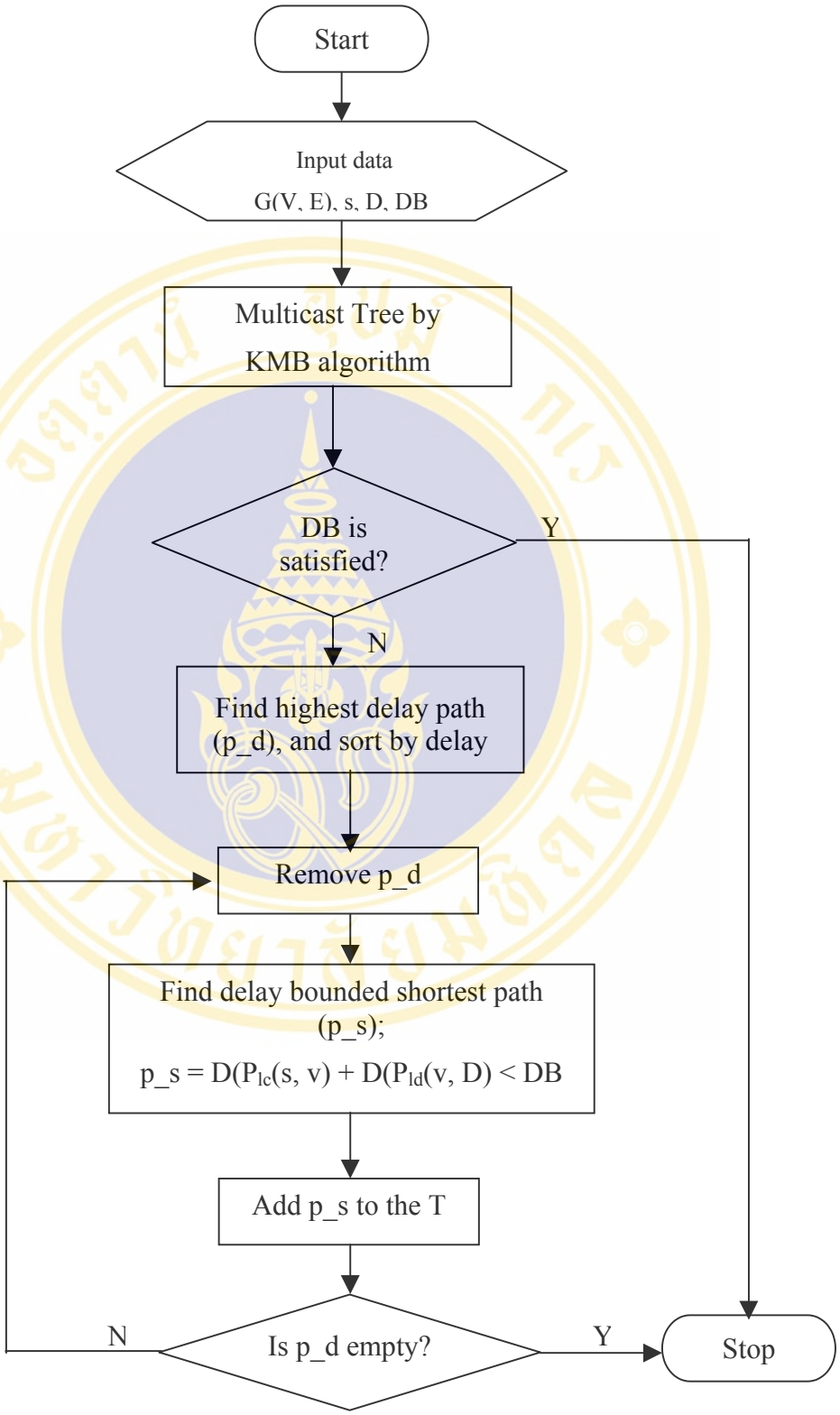

Figure 3.1: Flowchart of DCMR Heuristic

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Examples of DCMR model on the network graph are shown in Figure 3.2.

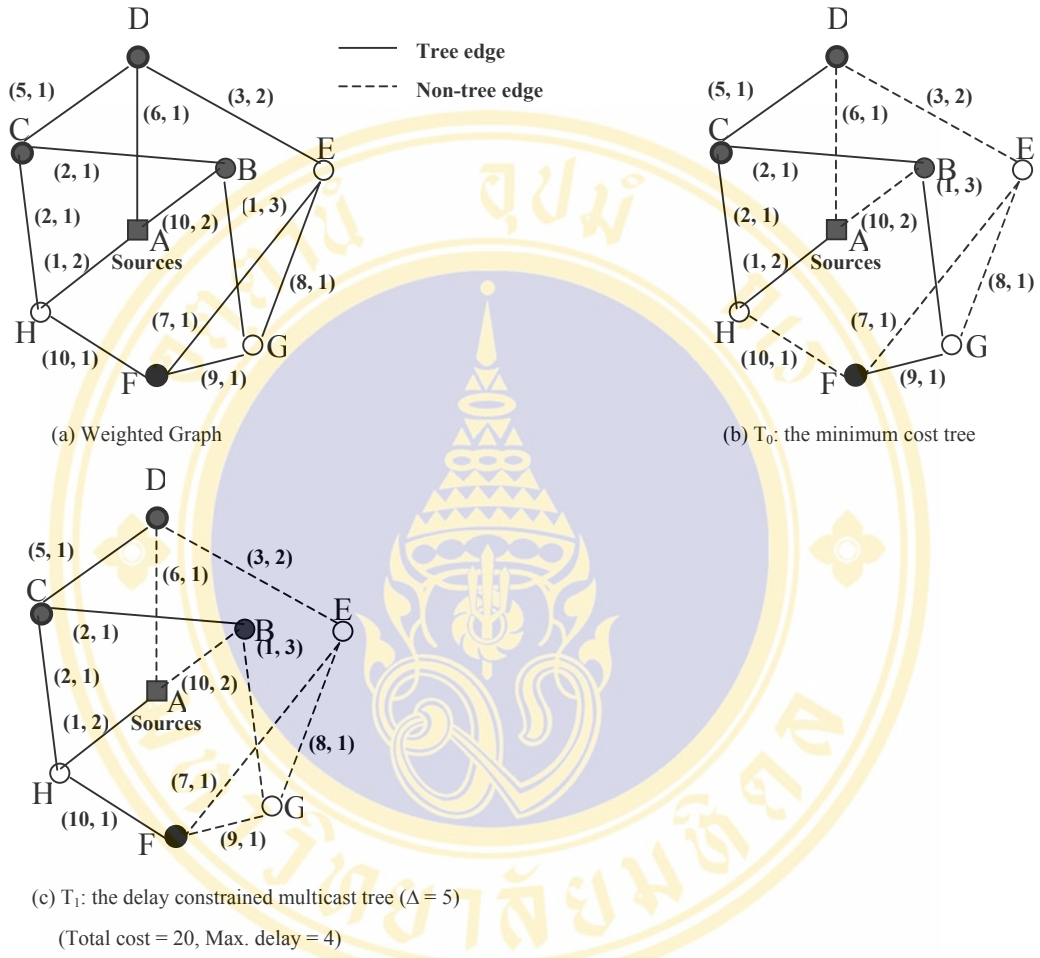

Figure 3.2: Example of iterative optimization in DCMR model

The example of DCMR model shown in Figure 3.2 describes the mechanisms of DCMR algorithm with a weighted graph. Figure 3.2(a) is the weighted graph that represents the topology and information of a network. The tree from finding of minimum-cost multicast tree by KMB heuristic is shown in Figure 3.2(b). From Figure 3.2(b), the path that over the delay-bound ($\Delta = 5$) is the path between source node A and receiver node F. So, when we switch the path BF that is the part of AF to path HF, we have found the delay constrained multicast tree. The tree has total cost = 20 and maximum source-to-destination delay = 4 which is shown in Figure 3.2(c).

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Main process of DCMR is shown in Figure 3.3.

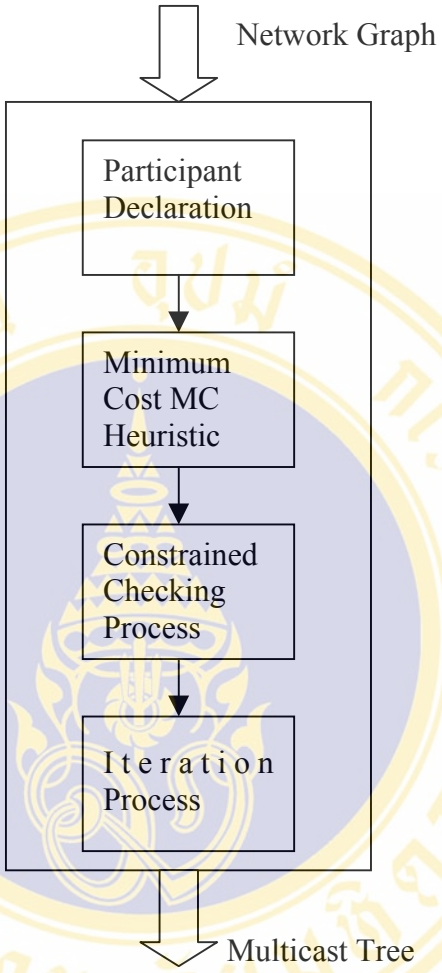

Figure 3.3: DCMR Model

From Figure 3.3, it shows that the input data of DCMR model is the information of network graph and the output is information of multicast tree. DCMR process is divided into 4 sub-processes as follows:

1) Participant declaration

2) Minimum cost multicast heuristic

3) Constrained checking

4) Iteration

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3.2.1 Participant Declaration

The participant declaration process is the process that receives the input data, the information of weighted graph, and declares the participant nodes, source and receiver nodes, for computing the multicast tree later.

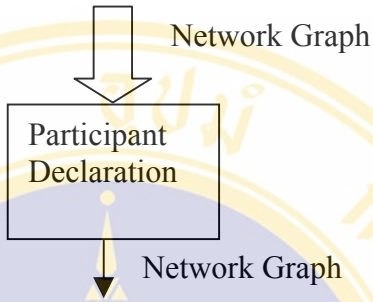

Figure 3.4: Participant Declaration Process

The participant declaration process shown in Figure 3.4 describes input from network graph and then declares the source node and receiver nodes according to the number of members of group (receiver node varies from 2 to n-1 node where n is total nodes).

3.2.2 Minimum Cost Multicast Routing Heuristic; KMB algorithm

This process uses KMB heuristic (that mentioned in Chapter II) to find the minimum-cost multicast tree. It receives the information of network graph from participant declaration process and finds the multicast tree by using KMB algorithm.

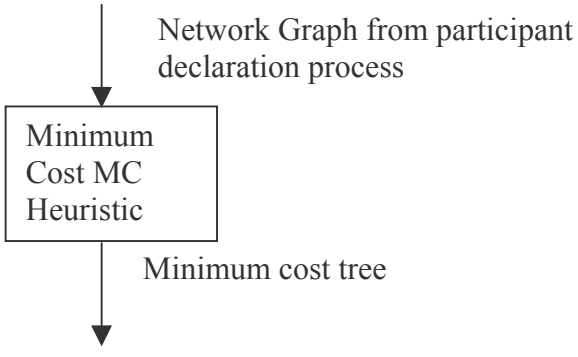

Figure 3.5: KMB Heuristic Process

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From Figure 3.5, when minimum-cost multicast heuristic process receives the information of network graph from participant declaration process, it computes the tree by using KMB algorithm to find minimum-cost multicast tree and sends this information to the next process.

3.2.3 Constrained Checking

Constrained checking process is the process that checks the conditions for constructing the multicast tree. In this study, it is source-to-destination delay constrained. There is delay bound (Δ) that is set for the condition of the multicast tree, especially for multimedia multicast applications. The multicast tree must have end-to-end delay that is not over the delay bound.

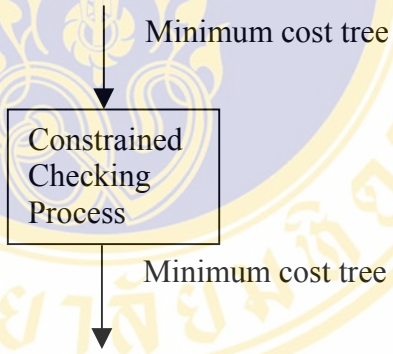

Figure 3.6: Constrained Checking Process

From Figure 3.6, when minimum cost tree is entered to constrained checking process, it checks the delay bound. If the total end-to-end delay from source to any destinations is not over the bound, the DCMR model will simply stop because it has found the delay-constrained multicast tree. But, if there are end-to-end delay of source-destination pairs, which are over the delay bound, it will be put to the next process.

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3.2.4 Iteration Process

The iteration process is the process for finding the new paths, and replacing the old paths that make the end-to-end delay of sources-receiver pairs over the delay bound. The iteration will go on until there are no more paths that are over the delay bound.

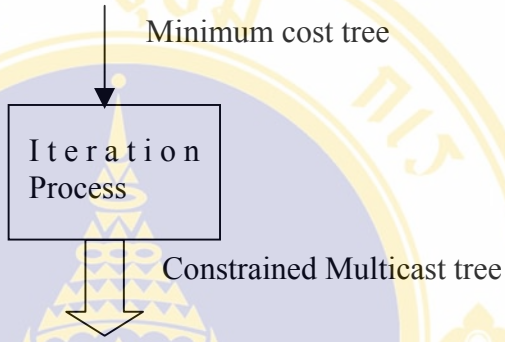

Figure 3.7: Iteration Process

From Figure 3.7, when minimum cost tree that is over the delay bound is entered to the iteration process, it will find the new paths to replace the old ones until it finds the delay-constrained multicast tree.

The method of finding the new paths to replace those old ones which are over the delay bound or "path switching", is from Zhang et. al.'s work published in 2000 [17, Appendix B]. It was named "Delay-Constrained Multicast routing Algorithm (DCMA)". This algorithm has the method in finding the multicast tree efficiently. That is, it uses only the shortest cost path (P_{lc}) and the shortest delay path (P_{ld}) values on path switching method.

The difference between BSMA algorithms and DCMR algorithm will be shown in Table 3.2.

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Table 3.2: Comparison on Method between Two Algorithms

Issue	**Zhu at al. (UCSC)' BSMA**	**DCMR Heuristic**
1. start tree (T_i) T_i = superedge + T_i^1 + T_i^2	Minimum delay tree (Dijkstra's algorithm)	Minimum cost Steiner tree (KMB algorithm)
2. Superedge: - the longest path which all internal nodes are the relay nodes and each relay node connects exactly two tree edges.	The longest path ordered by cost (It visits all paths in start tree.)	The longest path ordered by delay between source and each destination (It visits only the path that is over the delay bound; Δ)
3. the new path for path switching	k-shortest path (It searches every multicast group pair that can connect T_i^1 and T_i^2.)	1) search backward from destination to S along least delay; LD, from S to destination 2) until it found the relay node that delay of least cost; LC, for S to relay plus delay of LD from relay to destination are under the delay bound (search only source & destination pair)

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The difference between BSMA and DCMR algorithms on working process will be shown in Figure 3.8.

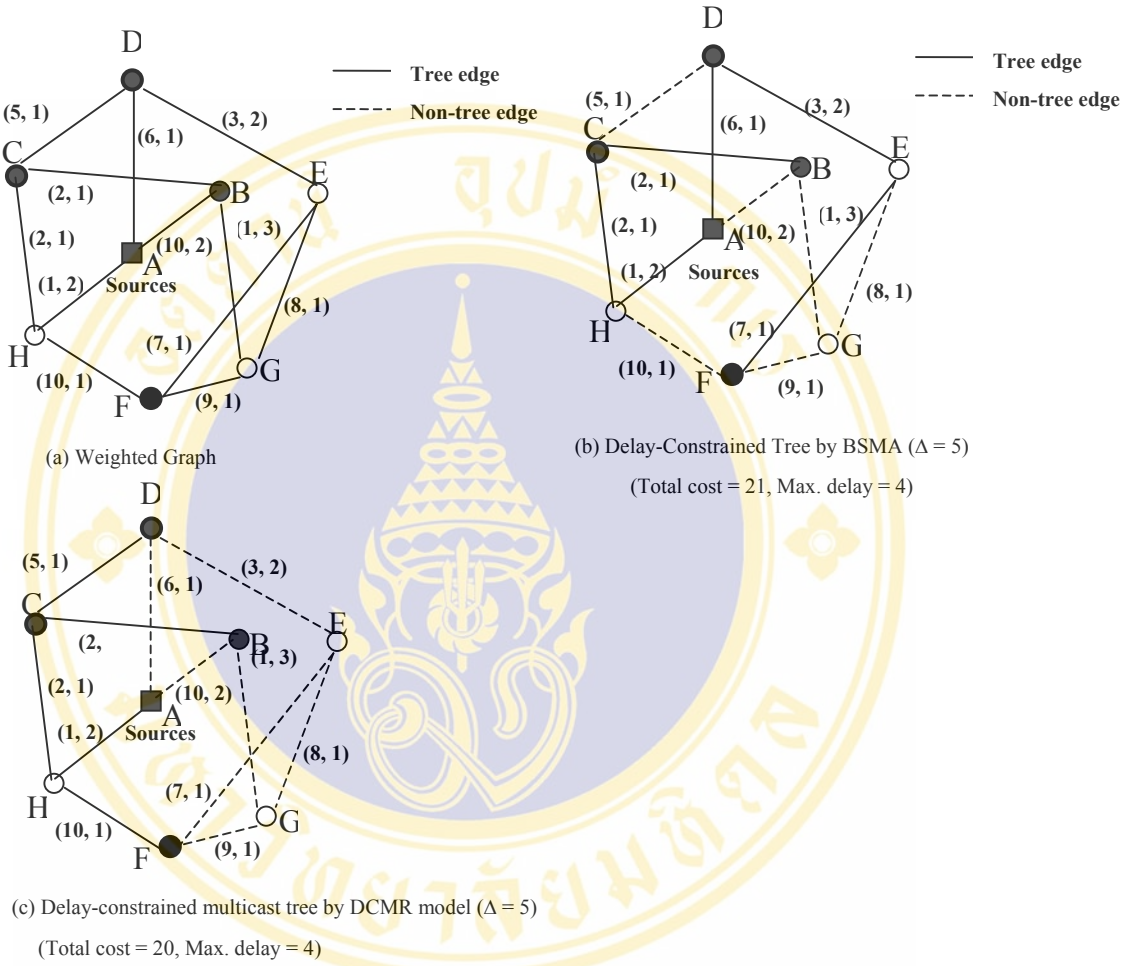

Figure 3.8: Delay-Constrained multicast tree (b) BSMA (c) DCMR

Figure 3.8 is the example of finding delay-constrained multicast tree by two algorithms; BSMA algorithm and DCMR algorithm. It finds the value from the weighted graph (Figure 3.8(a)) that was set the delay bound (Δ) to 5.

The result from the algorithm shows that BSMA constructs the delay-constrained multicast tree giving the total cost value equal to 21 and the maximum delay value of 4. Whereas, DCMR constructs the delay-constrained multicast tree giving the total cost value equal to 20 and the maximum delay value of 4. Both algorithms are not over the delay bound constraint.

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CHAPTER IV
IMPLEMENTATION

In this Chapter, we will present the implementation of the Random Graph software used to generate networks and the DCMR model as stated in the previous Chapter, including the environment that used for this experiment.

4.1 Hardware and Software Environment

In this experiment, we have developed a set of programs and tested program on a PC with the following specifications: Intel Pentium III 500 MHz of CPU speed, 256 MB of memory size, and 4 GB of hard disk capacity.

The program was implemented in C/C++ programming language in which the Random Graph was developed by referencing from the source code of "rtg: Random Topology Generator" of Liming Wei [18]. In addition, we obtain the source code from the book entitled: "Data Structures: An Advanced Approach Using C" of Jeffrey Esakov and Tom Weiss [19] for the development of various algorithms.

The experiment was started from running the developed program on the C compiler[1]. The input data are separated into two types as the following: 1) parameters of Random Graph, which will be mentioned in Section 4.2, such as maximum value of X axis and Y axis, degree of graphs that varied the β values, and the α values, 2) parameters of network, such as number of nodes and number of destinations. The output data were saved in text file, later, the results were analyzed in Microsoft Excel program.

[1] This experiment used the Microsoft Visual C++ version 6.0

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4.2 Random Graph Model

There are many ways to generate a network graph for testing the Multicast Routing Algorithm, but the most popular ones are using those network simulators, such as NS-2 of LBNL [20] or generating by using network generators, such as Random Graph.

The following is a model using the Random Graph method, which is based-on

$$P(u, v) = \beta \exp\left(\frac{-d(u, v)}{\alpha L}\right) \quad \text{----------(1)}$$

the Waxman's algorithm, published in 1988 [13]. Equation of probability formula is

where; d(u, v) is the distance between node u and node v.

L is the longest distance that enables for node u and node v.

α is the positive real value between 0 and 1. The higher value makes the longer distance of network graph, which means low density of node.

β is the positive real value between 0 and 2, which defines the degree of the graph. The higher value means higher degree of graph.

The probability value will be used to represent the weight of link of node u and node v for the cost function (as it was mentioned in section 2.2.2).

The weight of link of node u and node v for the delay function is set to 1 or a random number in [0, 1] time of its cost. This delay value is used to eliminate the unrealistic possibility of zero delay.

An example of the network graph that is generated from Random Graph is shown in Figure 4.1. This figure shows the network graph for 120 nodes in the area 100 x 100 unit of X x Y, α is 0.5, and β is 0.079.

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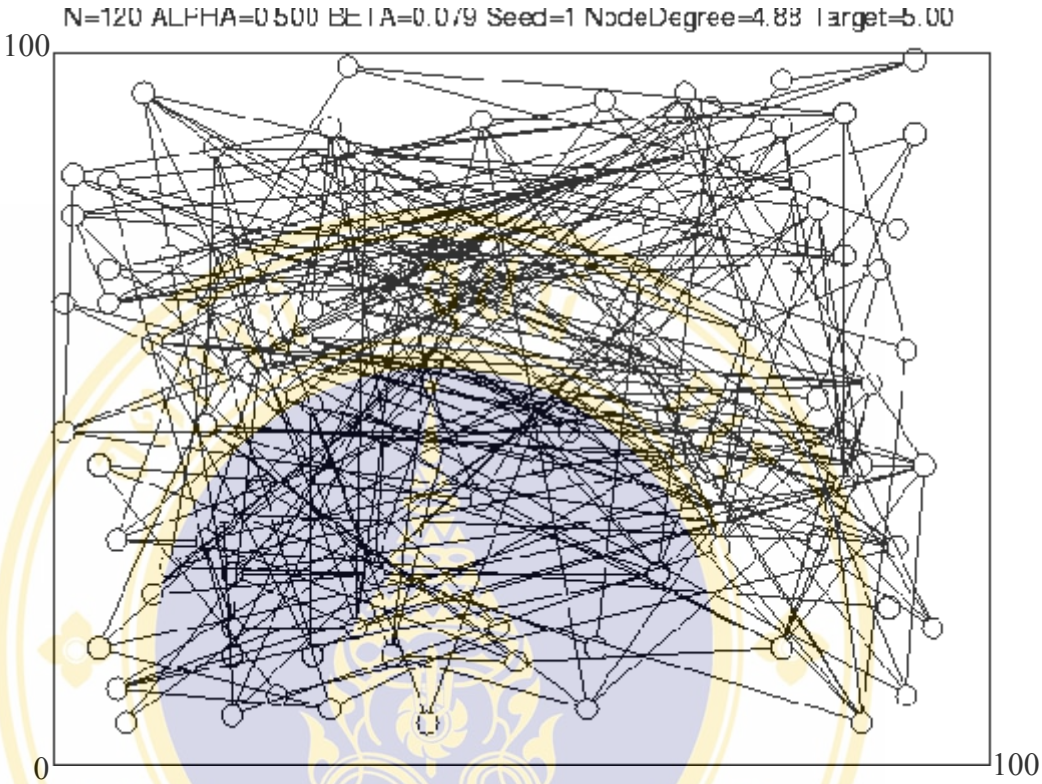

Figure 4.1: Example of network from Random Graph

After the network graph has been generated from the Random Graph program as Figure 4.1, the graph data will be saved in matrix data structure formatted for later used in calculation for multicast tree.

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4.3 Implementation of the Participant Declaration

To declare the participant nodes as source and receiver nodes in this experiment, we will randomize these nodes according to its ID for both source and destination nodes. The development of declaration for participant node ID will be stated as shown in Figure 4.2.

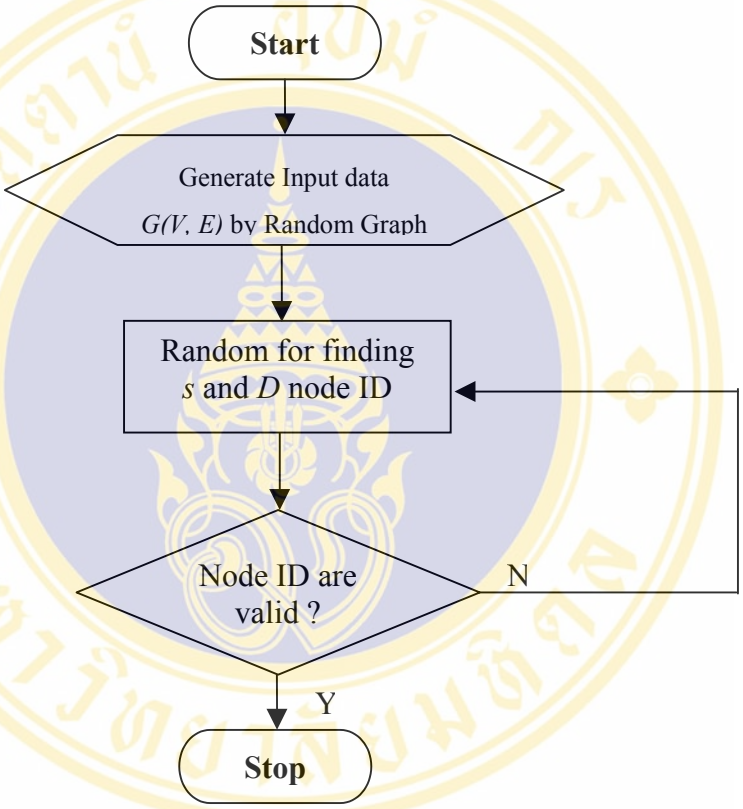

Figure 4.2: Flowchart of Participant Declaration Process

From Figure 4.2, after finishing the participant declaration process, we will obtain the information of G(V, E) and the source(s) and set of destinations(D) IDs for inputting to the next process.

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4.4 Implementation of the KMB Heuristic

After declaring the participant node, the next process in development of KMB algorithm is to develop the Shortest Path by Dijkstra's algorithm and the minimum spanning tree by Kruskal's algorithm. This KMB Heuristic process is shown in the flowchart below.

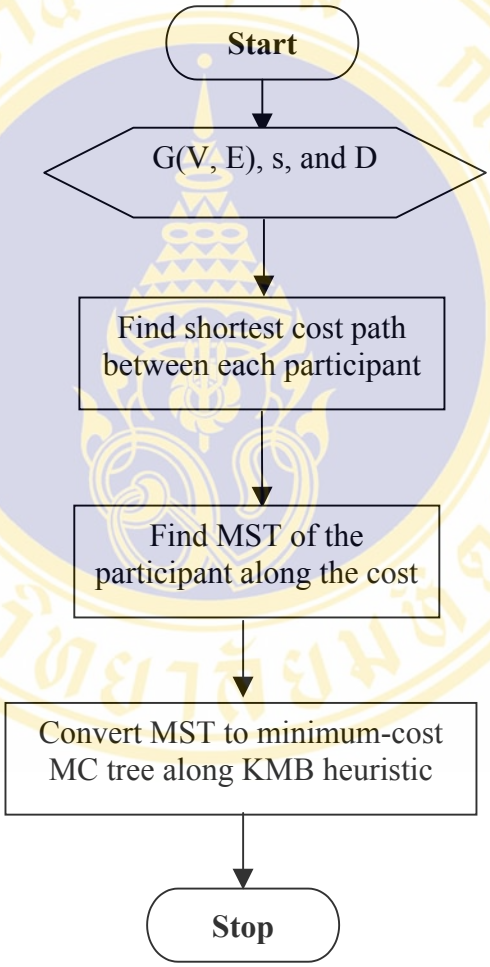

Figure 4.3: Flowchart of KMB Heuristic Process

From Figure 4.3, after finishing the KMB Heuristic process, we will obtain the minimum cost unconstrained multicast tree for inputting to the next process.

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4.5 Implementation of Constrained Checking Process

After obtaining the minimum cost unconstrained multicast tree from the KMB Heuristic process, we then go to the constrained checking process. For this case, it will be the end-to-end delay constrained. The flowchart of constrained checking process is shown in Figure 4.4.

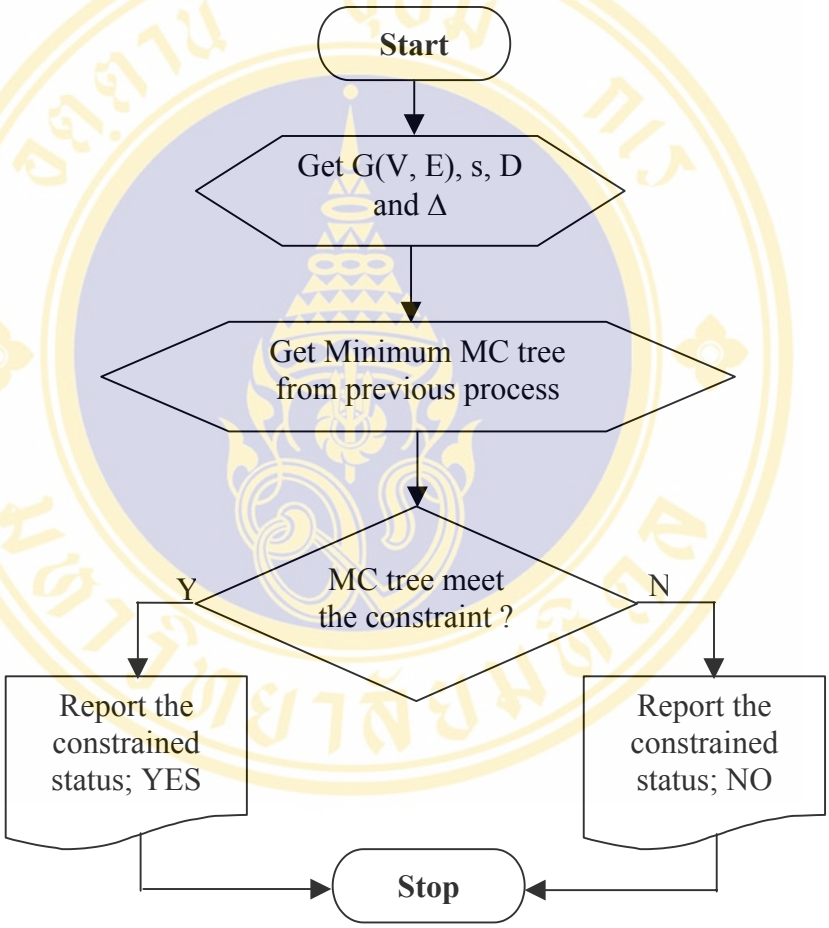

Figure 4.4: Flowchart of constrained checking process

After checking the end-to-end delay constrained, it will report the constrained status of this multicast tree before going to the next process.

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4.6 Implementation of Iteration Process

The constrained report will yield 2 output results as follows:

1) If the maximum end-to-end delay value of source-destination pairs of multicast tree is not over the delay constrained, this report of multicast tree will be kept to be an output data for analyzing the result in the next process, or
2) If the maximum end-to-end delay value of source-destination pairs of multicast tree is over the delay constrained, the program will find the new path to replace the old path, which was called “path switching.”

The main function to do the path switching process is to find out the shortest cost path from source to destination, and also to find out the shortest delay path from destination to source that is over the constrained by using Dijkstra’s algorithm. The iteration process is shown in the Figure 4.5.

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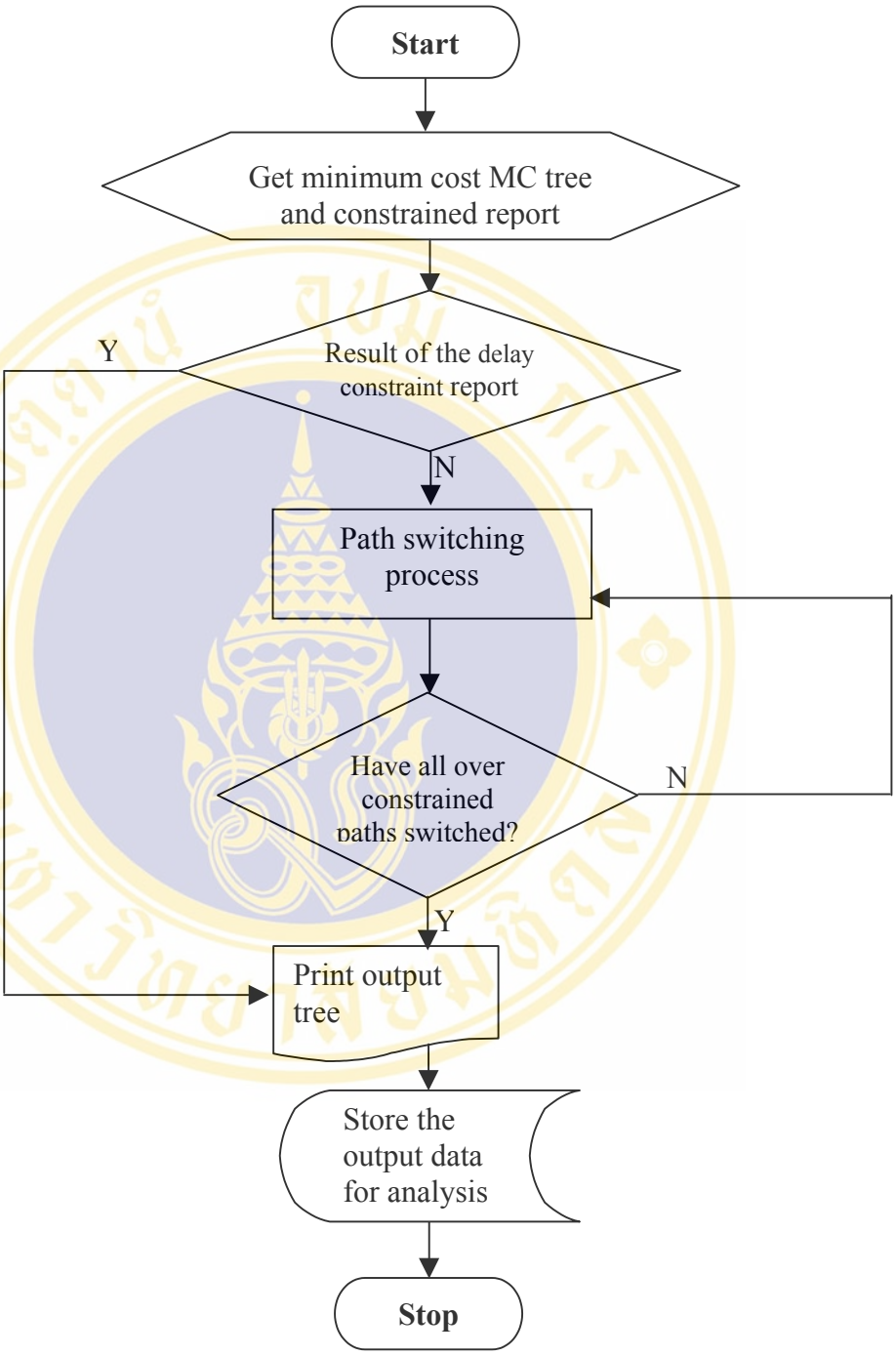

Figure 4.5: Flowchart of Iteration process

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CHAPTER V
EXPERIMENTAL RESULTS

In this chapter, we will present the experimental results that derive from the designing of Delay Constrained Multicast Routing Algorithm. The experimental framework is shown in Figure 5.1, which illustrates three types of variables as follows. "Independent variable" presents the number of nodes or multicast group sizes. There are totally 9 different sizes of network graph on trial in this study, which are separated into 2 groups as follows:

1) *A small sized group* with the node sizes of 10, 15, 20, 25 and 30, and
2) *A medium to large sized group* with the node sizes of 30, 60, 90, 120 and 150.

Each size consists of 100 different forms of the network graph. And each form of these graphs assigns a node to be the source node and 4 other nodes to be the destination nodes, which are classified to be "control variable." The Random Graph is used as a tool for generating the network graph in this experiment, as shown in Figure 5.2. In each experiment, the result will be measured in terms of the total cost, the longest delay from source to destination, the number of iterations, the calculation of shortest path per round by using Dijkstra's algorithm, and the average time per round, which are classified to be "dependent variable."

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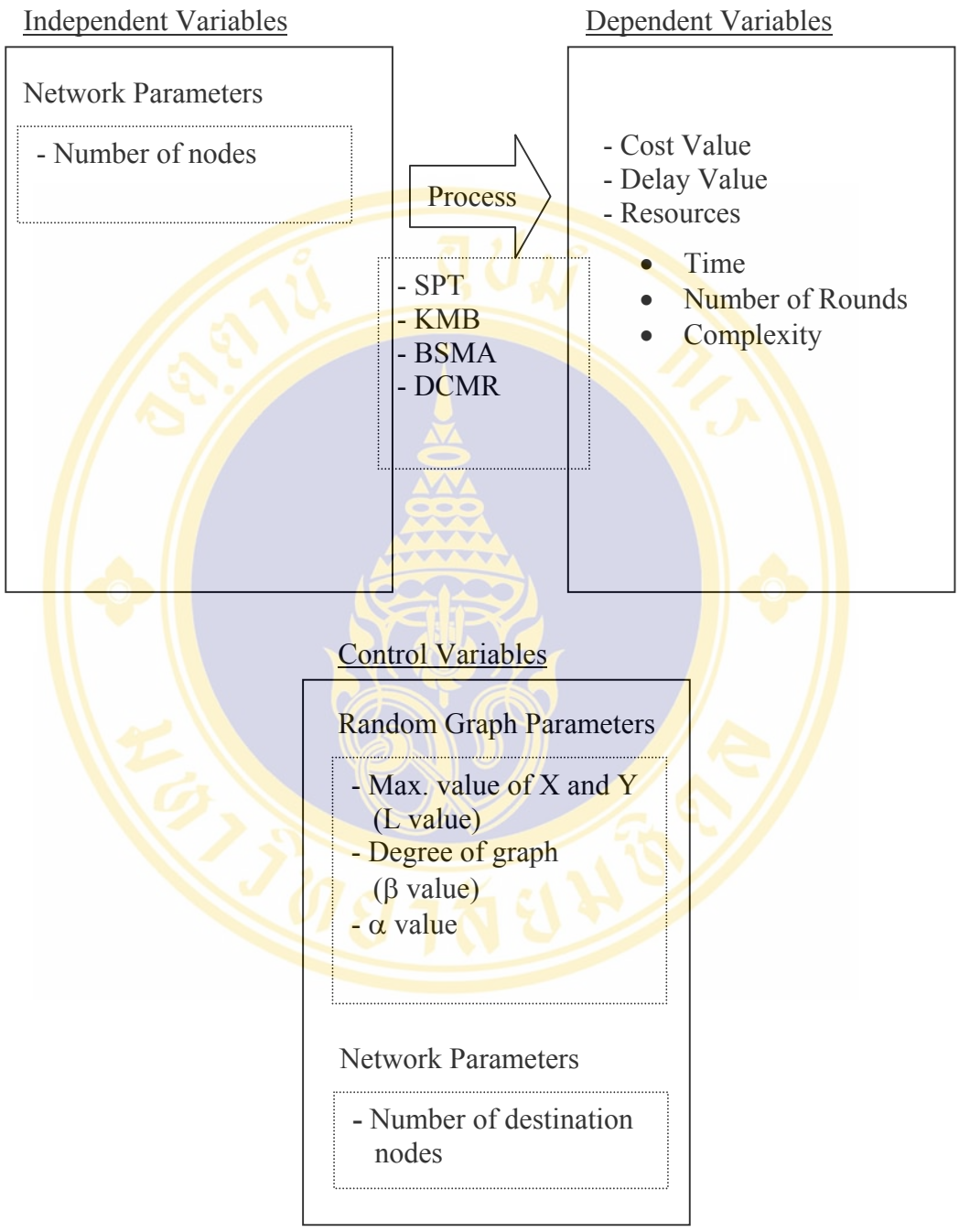

Figure 5.1: Experimental framework

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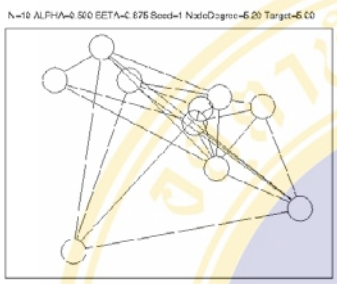
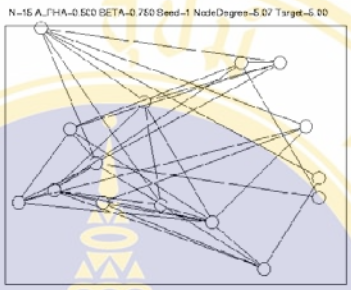
5.1 Experimental Setup

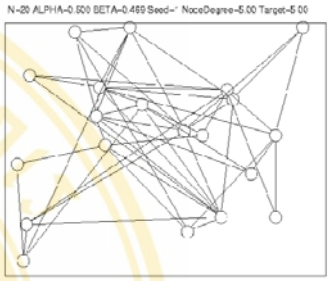
From the experiment, all 9 sizes of network graph that are generated from the Random Graph are shown in Figure 5.2. Each size consists of 100 different forms and each form of the graph assigns one node as source node and 4 others as destination nodes.



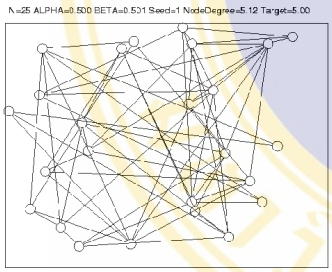
(a) A 10 node-network. Alpha=0.50, Beta=0.87



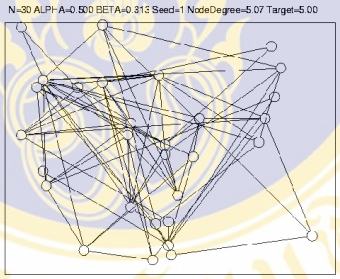
(b) A 15 node-network Alpha=0.50, Beta=0.75



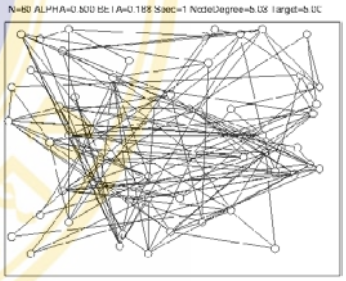
(c) A 20 node-network Alpha=0.50, Beta=0.47



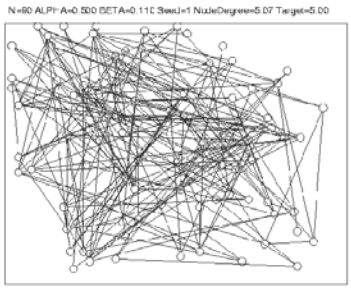
(d) A 25 node-network Alpha=0.50, Beta=0.50



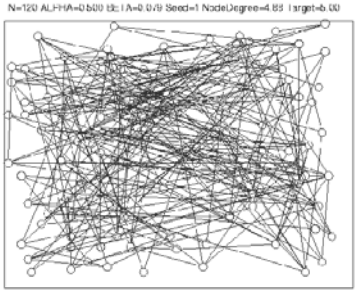
(e) A 30 node-network Alpha=0.50, Beta=0.31



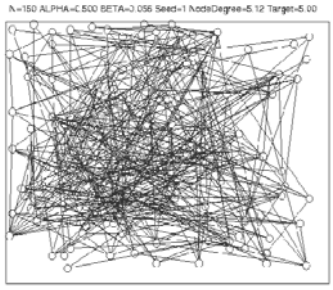
(f) A 60 node-network Alpha=0.50, Beta=0.19



(g) A 90 node-network Alpha=0.50, Beta=0.11



(h) A 120 node-network Alpha=0.50, Beta=0.08



(i) A 150 node-network Alpha=0.50, Beta=0.06

Figure 5.2: The samples of network graph with different sizes generated from the Random Graph

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Figure 5.2 shows the samples of network graphs that are generated from the Random Graph in 9 different sizes. Each graph is specified the average of the node degree at 5 with the deviation not more than 5% in the area 100 x 100 unit of X x Y as described below;

- Figure 5.2(a) is the network graph of 10 nodes size, alpha 0.5 and beta 0.87
- Figure 5.2(b) is the network graph of 15 nodes size, alpha 0.5 and beta 0.75
- Figure 5.2(c) is the network graph of 20 nodes size, alpha 0.5 and beta 0.47
- Figure 5.2(d) is the network graph of 25 nodes size, alpha 0.5 and beta 0.50
- Figure 5.2(e) is the network graph of 30 nodes size, alpha 0.5 and beta 0.31
- Figure 5.2(f) is the network graph of 60 nodes size, alpha 0.5 and beta 0.19
- Figure 5.2(g) is the network graph of 90 nodes size, alpha 0.5 and beta 0.11
- Figure 5.2(h) is the network graph of 120 nodes size, alpha 0.5 and beta 0.08
- Figure 5.2(i) is the network graph of 150 nodes size, alpha 0.5 and beta 0.06

It can be observed that when the network graph is increased in size and the alpha value and node degree is kept constant, the beta value will decrease. Furthermore, if the alpha value increases, the distance between nodes will be reduced. In addition, if the beta value increases, the degree of graph will be increased as well.

For the experiment of delay-constrained algorithm, it is specified the delay bound[1] (Δ) in three levels as follows;

1. Delay bound is equal to the longest delay, which derives from SPT algorithm, such as bsm-0 and dcm-0.
2. Delay bound is equal to the longest delay, which derives from KMB algorithm, such as bsm-1 and dcm-1.
3. Delay bound is a half value of the longest delay, which derives from SPT and KMB algorithm, such as bsm-1/2 and dcm-1/2.

[1] In real situations, delay bound from the source to each destination can be difference (as Figure 2.3 in Section 2.2.2). In this present work, we assume the delay bound in each of source-destination pairs is similar.

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5.2 Cost Issue

One of the main issues on finding the multicast routing tree is the cost. Specifically, this cost is the total cost of all trees. For a multicast routing tree, the optimal solution is to minimize its total cost.

5.2.1 Average Total Cost

The total cost is the summary of the cost of each link in the multicast tree. The average total cost is the average cost of each tree derived from the experiment of 100 graphs of each algorithm, including both unconstrained and delay-constrained algorithm.

The experimental results on the cost issue, which relates to two group sizes of the network graph, are shown in Figure 5.3 and 5.4.

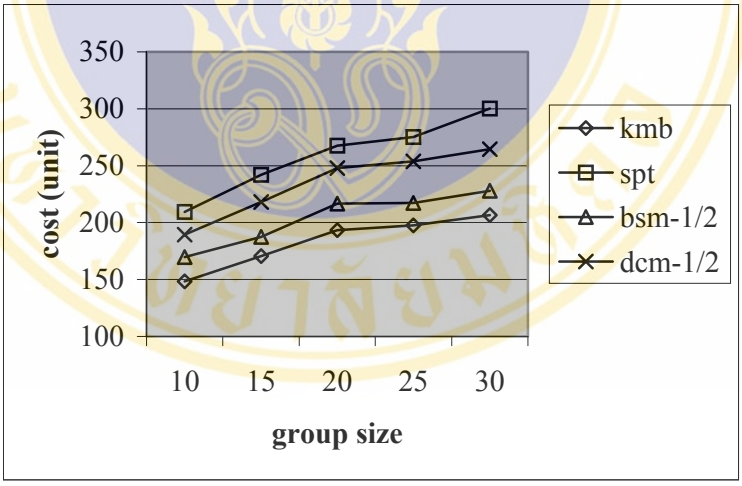

Figure 5.3: The average cost versus the different of group size (small sized group)

From Figure 5.3, it can be seen that the cost value increases as the group size increases. The KMB algorithm will obtain the least cost (148-206 units) for any sizes of the network graph, whereas the BSMA, DCMR and SPT algorithms will yield higher cost value from small to big respectively.

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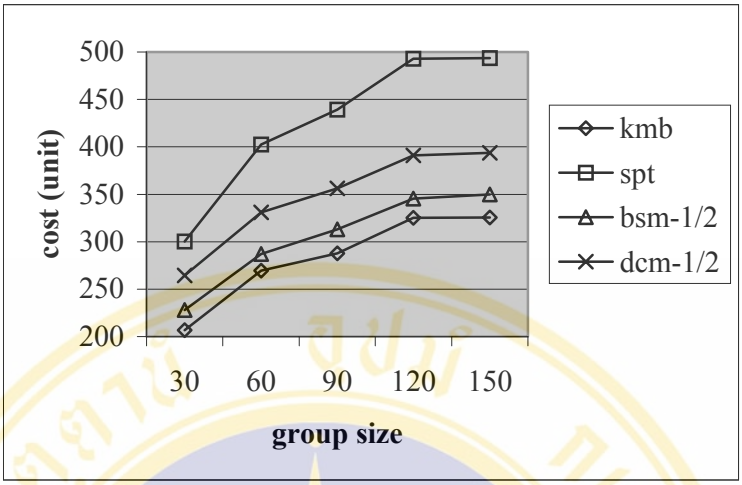

Figure 5.4: The average cost versus the different of group size (medium to large sized group)

From Figure 5.4, it can be seen that the cost value increases as the group size increase also. The KMB algorithm will obtain the least cost (206-326 units), whereas the BSMA, DCMR and SPT algorithms will yield high cost value from small to big respectively. It is further found from the experiment that the small sized group and medium to large sized group of network graphs yield similar average cost values.

5.2.2 Average Cost Ratio

The cost ratio is the cost of any algorithm divided by the cost obtained from the KMB algorithm. It is because the KMB algorithm is unconstrained algorithm that has the lowest cost in multicast tree.

The average cost ratio is the cost ratio of each tree derived from the experiment of 100 graphs of each algorithm.

The experiments on the average cost ratio will be compared among the delay-constrained algorithms. The results of the cost ratio of SPT and BSMA algorithms are shown in Figure 5.5 and 5.6, and the cost ratio of SPT and DCMR algorithms are shown in Figure 5.7 and 5.8.

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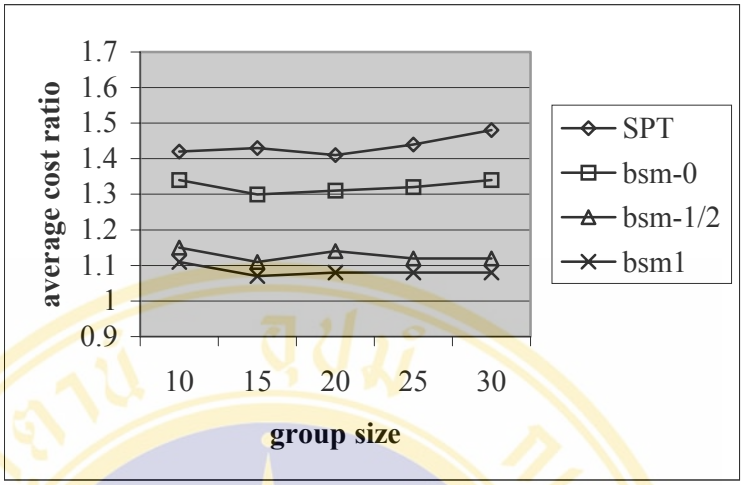

Figure 5.5: The average cost ratio of SPT and BSMA algorithms comparing with KMB algorithm for the small group size

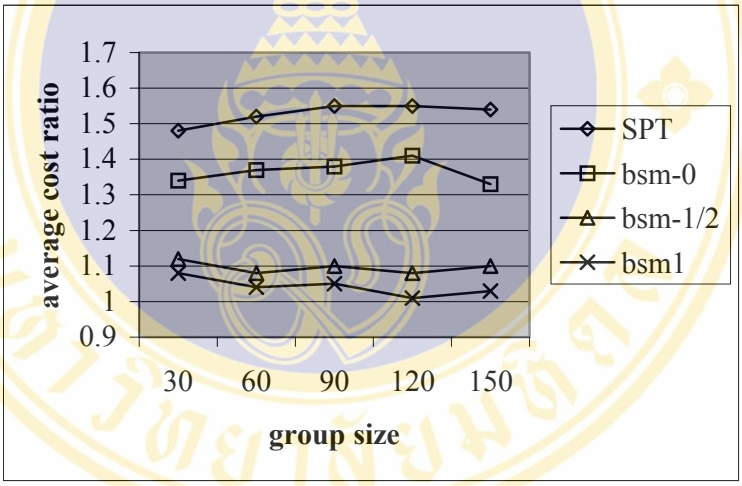

Figure 5.6: The average cost ratio of SPT and BSMA algorithms comparing with KMB algorithm for the medium to large group size

Figure 5.5 and Figure 5.6 show the comparison of the cost ratio of the different group size of network graph; the small group size and the medium to large group size. It can be seen that the bsm-1 obtain the lowest of cost ratio, following by the bsm-1/2, bsm-0 and SPT which have higher cost ratio respectively. The cost ratio values are in the range between 1:1 to 1.6:1.

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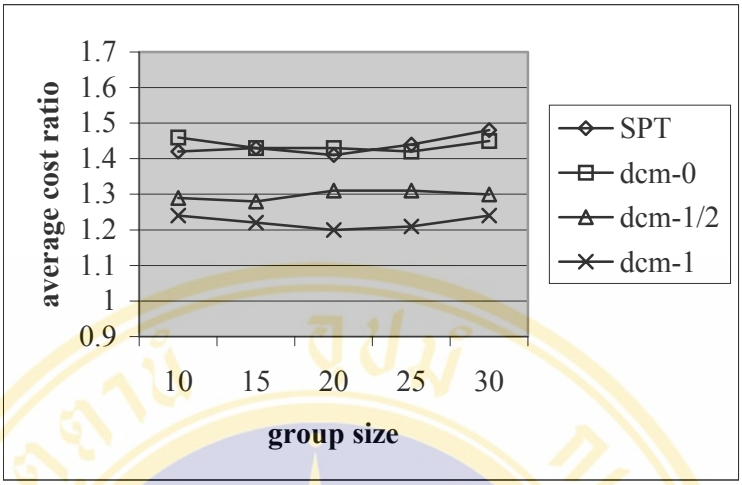

Figure 5.7: The average cost ratio of SPT and DCMR algorithms comparing with KMB algorithm for the small group size

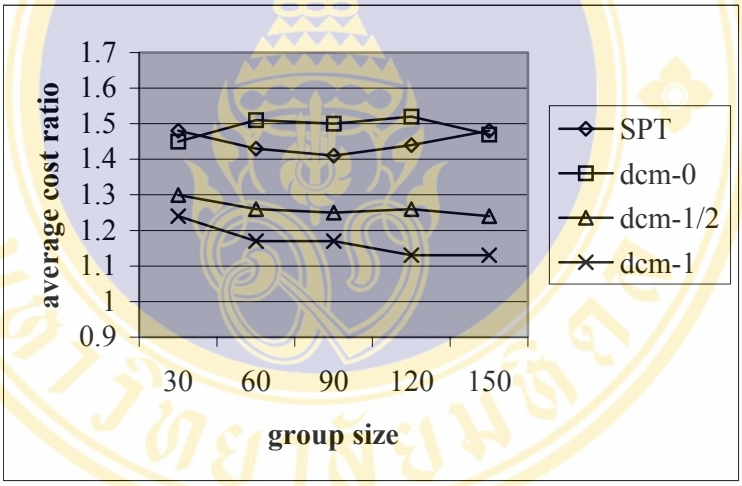

Figure 5.8: The average cost ratio of SPT and BSMA algorithms comparing with KMB algorithm for the medium to large group size

Figure 5.7 and 5.8 show the comparison of cost ratio of the different group size of network graph; the small group size and the medium to large group size. The results show that the dcm-1 obtains the lowest cost ratio, following by the dcm-1/2. The dcm-0 obtains the cost ratio lower than SPT's when the group size are 25 and 30 nodes, but the other sizes have cost ratio higher or equal to the cost of SPT algorithm. The cost ratio values are between 1.1:1 to 1.6:1.

However, the DCMR and BSMA algorithms, which are the type of delay-constrained are determined on the average cost ratio that is the cost of DCMR divided by cost of BSMA. The experimental results are shown in Figure 5.9 and 5.10.

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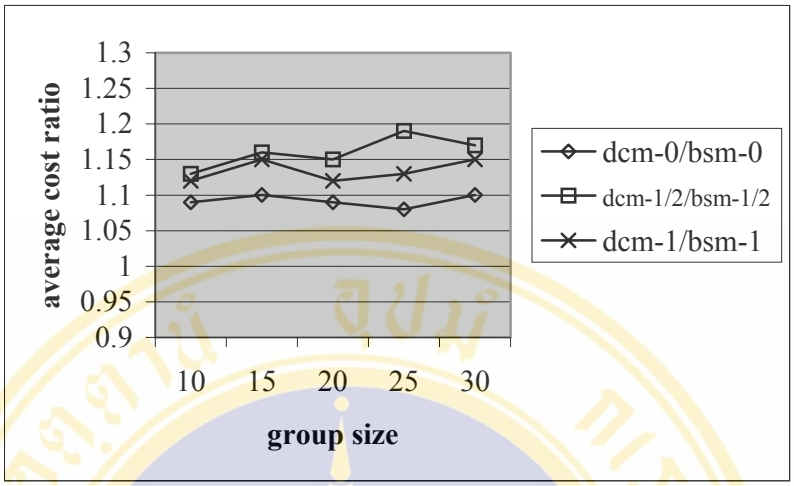

Figure 5.9: The average cost ratio of DCMR algorithm comparing with BSMA algorithm for the small group size

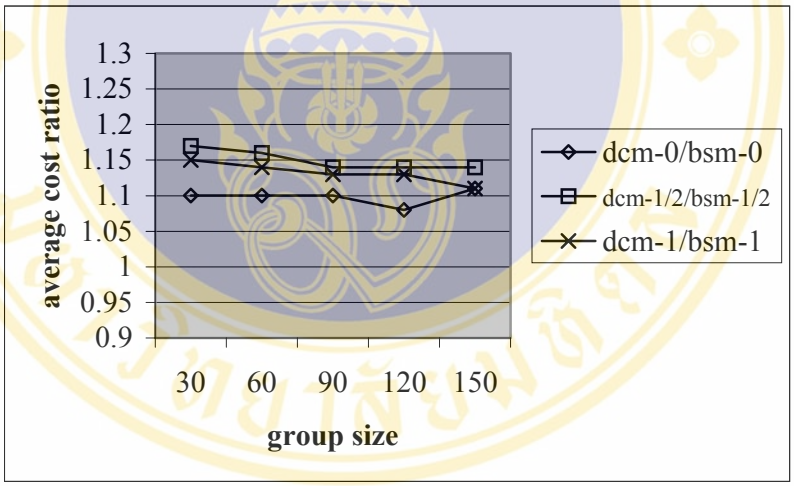

Figure 5.10: The average cost ratio of DCMR algorithm comparing with BSMA algorithm for the medium to large group size

Figure 5.9 and 5.10 show the comparison of the cost ratio between DCMR and BSMA algorithms for two aforementioned group sizes. The result shows that the cost ratio of DCMR per cost ratio of BSMA values is about 1.1:1 to 1.2:1.

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5.3 Delay Issue

The delay value or delay time is an important constraint for multimedia multicast transmission. A good multicast routing tree would yield minimum end-to-end delay between every pairs of a source to destination.

5.3.1 Average Longest Delay

The longest delay is the maximum delay value from a source to destination. The average longest delay is the average of the longest delay of each tree derived from the experiment of 100 graphs of each algorithm. The experimental results for the average longest delay are shown in the Figure 5.11 to Figure 5.14.

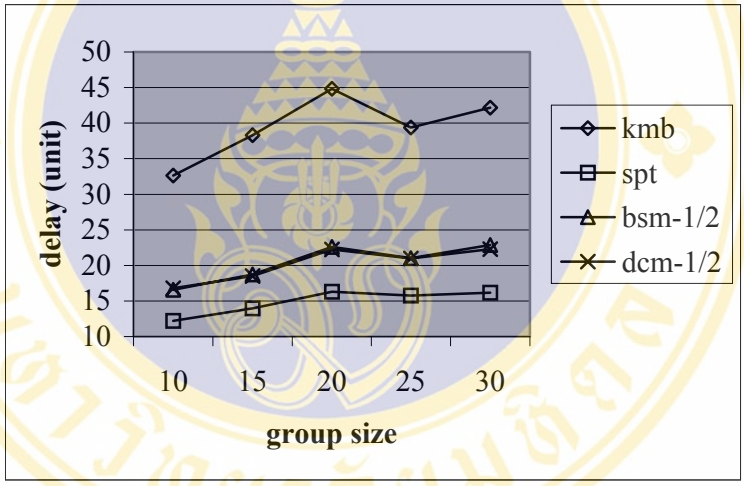

Figure 5.11: The average longest delay of the small group of network graphs

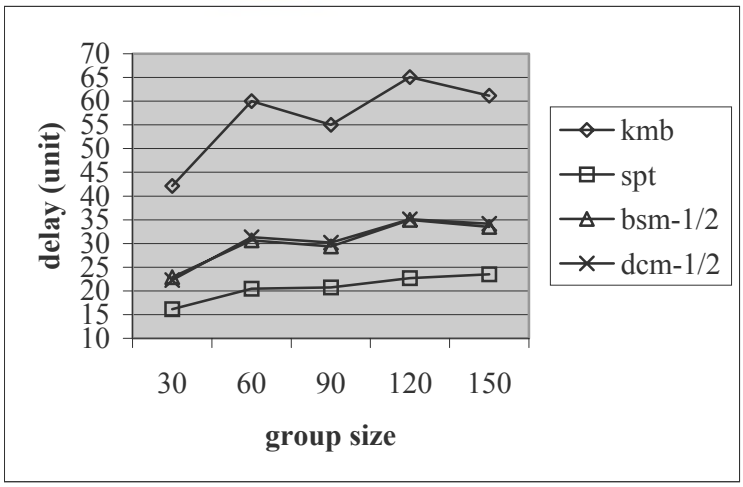

Figure 5.12: The average longest delay of medium to large group of network graphs

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As seen in Figure 5.11 and 5.12, it is found that the longest delay value tends to increase according to the group sizes. The SPT algorithm yields the least longest delay value whereas the KMB algorithm yields the most longest one. In addition, KMB has higher value than other algorithms so much. While the BSMA and DCMR algorithms have similar longest delay value at any group sizes.

However, the DCMR and BSMA algorithms, which are the type of delay-constrained, are determined on the average longest delay that is the longest delay of DCMR divided by the longest delay of BSMA. The experimental results are shown in Figure 5.13 and 5.14.

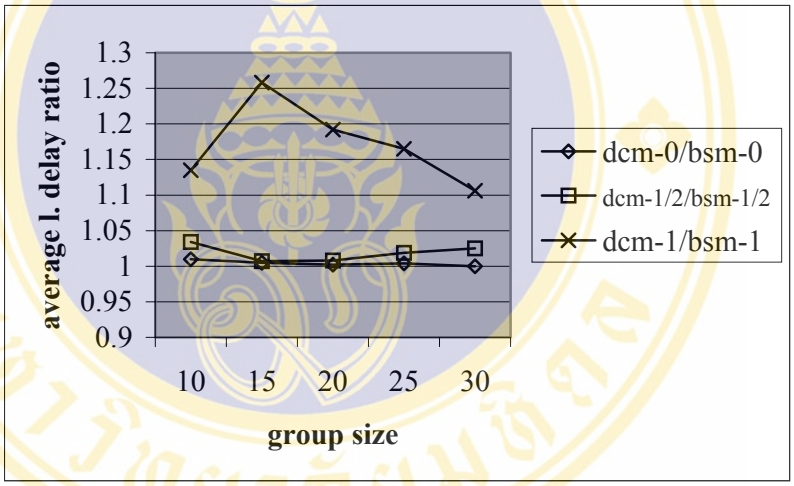

Figure 5.13: The average longest delay of DCMR algorithm comparing with BSMA algorithm on the small group size of network graphs

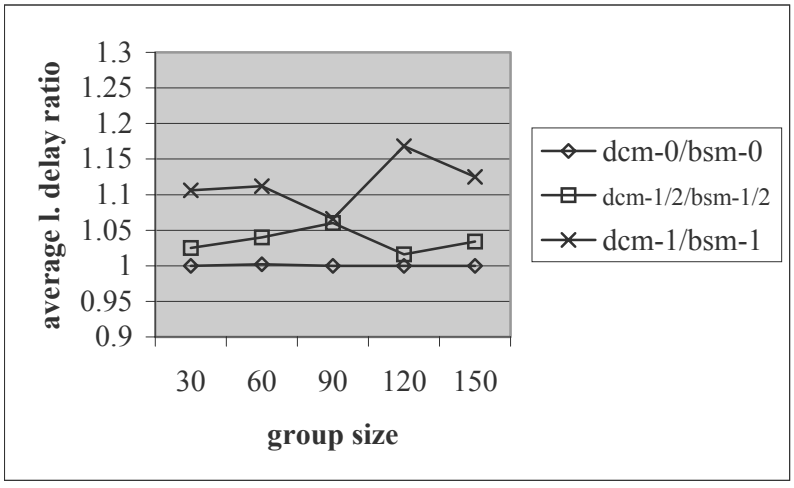

Figure 5.14: The average longest delay of DCMR algorithm comparing with BSMA algorithm on the medium to large group size of network graphs

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From the comparison on the ratio of the longest delay between DCMR algorithm and BSMA algorithm in the small group size (Figure 5.13) and the medium to large group size (Figure 5.14), it is found that the longest delay of DCMR values per BSMA values is 1:1 to 1.3:1.

5.3.2 Average Delay Optimization Ratio

The delay optimization (DO) of each tree is the delay value of source-destination pairs that calculated by the following equation:

$$DO = \frac{1}{|M|-1} \sum_{v \in M, v \neq s} P_d(s,v) \quad \text{----------(2)}$$

Where M is the multicast group

s is the source node, v are the set of destination nodes and

$P_d(s, v)$ is the delay value of the path from source node s to destination node v.

The delay optimization ratio is the delay optimization of any algorithms divided by delay optimization of SPT algorithm. It is because the SPT algorithm is the one that has the lowest delay tree. The average delay optimization ratio is delay optimization ratio of each tree derived from the experiment of 100 graphs of each algorithm. The results of the average delay optimization ratio are shown in Figure 5.15 to Figure 5.20.

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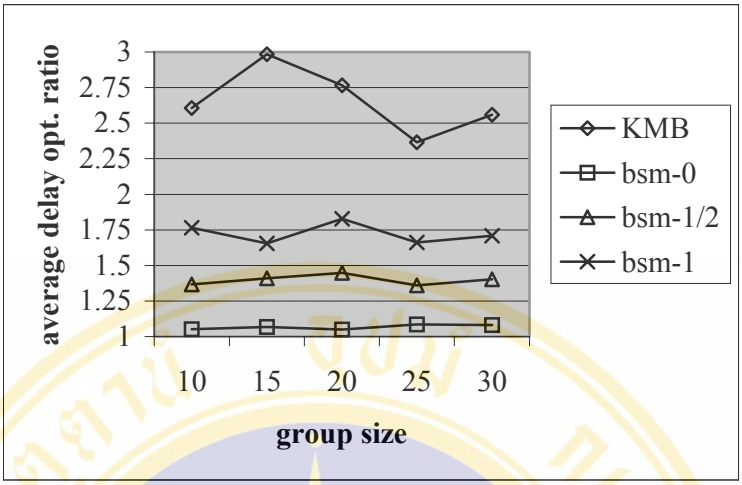

Figure 5.15: The average delay optimization ratio of KMB and BSMA algorithms comparing with SPT algorithm on the small group size of network graphs

From Figure 5.15, it is found from the comparison that the average delay optimization ratio at any group size of all algorithms increase in similar rate except the KMB algorithm. While the KMB algorithm yields the highest value of delay optimization ratio and its values are much higher than other algorithms. The bsm-0, bsm-1/2 and bsm-1 yield lower values respectively.

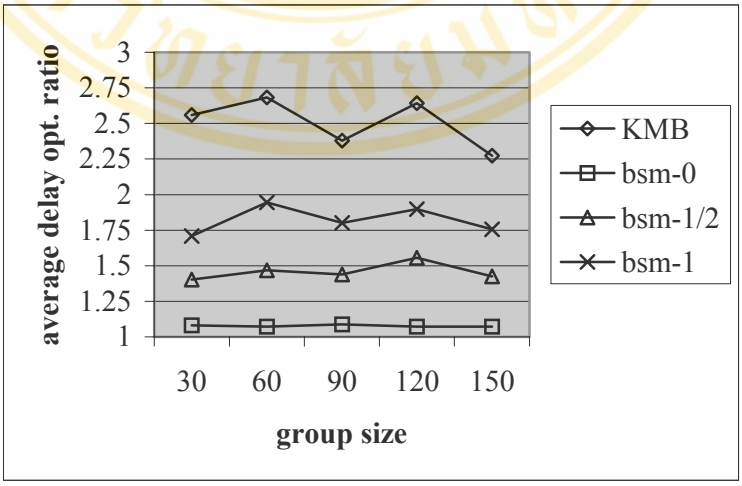

Figure 5.16: The average delay optimization ratio of KMB and BSMA algorithms comparing with SPT algorithm on the medium to large group size of network graphs

From Figure 5.16, it is found from the comparison that the average delay optimization ratio of all algorithms increase in similar ratio at any increasing group

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size except KMB algorithm. While the KMB algorithm yields the highest value of delay optimization ratio, and the bsm-0, bsm-1/2 and bsm-1 yield lower value respectively.

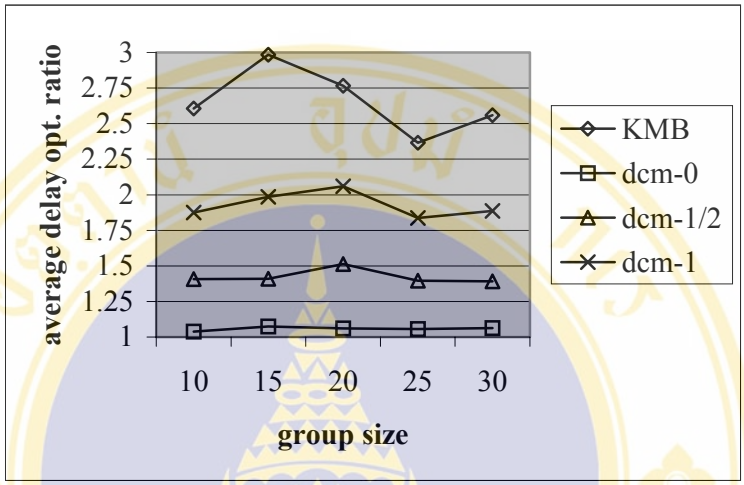

Figure 5.17: The average delay optimization ratio of KMB and DCMR algorithm comparing with SPT algorithm on the small group size of network graphs

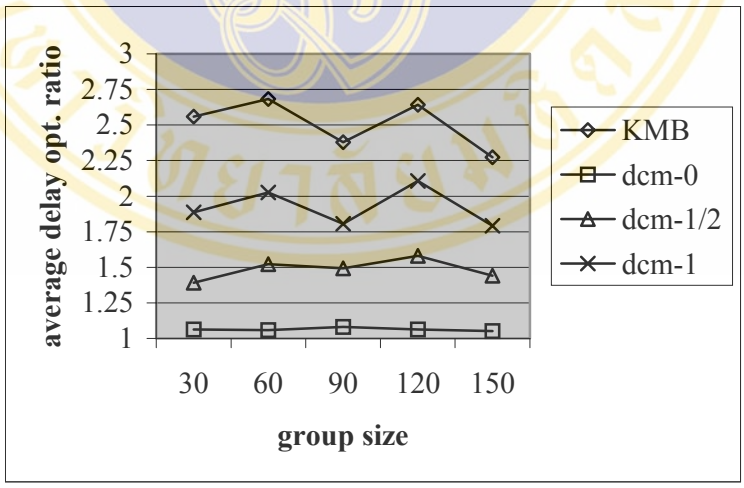

Figure 5.18: The average delay optimization ratio of KMB and DCMR algorithms comparing with SPT algorithm on the medium to large group size of network graphs

Figure 5.17 and 5.18 show the comparison results that the dcmr-0 yields nearly the same average delay optimization ratio at any increasing group sizes. Whereas the KMB algorithm yields the highest value. On the other hand, the dcmr-0, dcmr-1/2 and dcmr-1 yield lower value respectively.

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However, the DCMR and BSMA algorithms, which are the delay-constrained multicast routing algorithms, are tested on delay optimization ratio that is the delay optimization of DCMR divided by delay optimization of BSMA. The experimental results are shown in Figure 5.19 and 5.20.

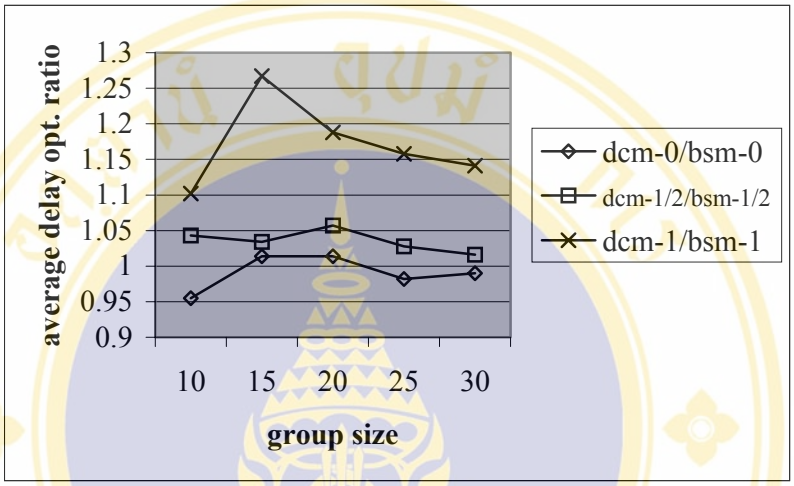

Figure 5.19: The average delay optimization ratio of DCMR algorithm comparing with BSMA algorithm on the small group size of network graphs

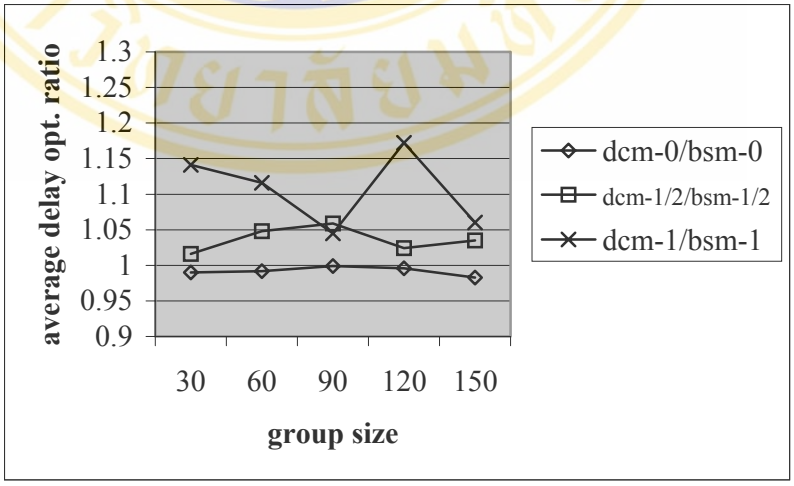

Figure 5.20: The average delay optimization ratio of DCMR algorithm comparing with BSMA algorithm on the medium to large group size of network graphs

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In comparison between DCMR and BSMA algorithm on two group sizes, it can be seen that the average delay optimization ratio of DCMR per BSMA values is 0.9:1 to 1.3:1. When the group size is small (Figure 5.19), the dcmr-1 per bsm-1 yields the highest ratio among any other algorithms. Its values are between 1.1:1 to 1.3:1, while the other DCMR per BSMA obtain value of delay optimization ratio between 0.9:1 to 1.1:1. And when the group size is big (Figure 5.20), the ratio of all types seem to yield similar value between 1:1 to 1.2:1.

5.4 Scalability Issue

The scalability issue concerns the measurement of the network resources, such as the average number of iterations and the time per round whether they are suitable for scalable network size.

5.4.1 Average Number of Iteration

The average number of iterations is the figure of each tree derived from the experiment of 100 graphs of both delay-constrained multicast routing algorithms; BSMA and DCMR algorithm, that use iterative technique for "path switching" process. The experimental results on average number of iteration are shown in Table 5.1 below.

Table 5.1: The average number of iteration of BSM and DCMR algorithm

Group Size	bsm-0 R	bsm-.5 R	bsm-1 R	dcm-0 R	dcm-.5 R	dcm-1 R
10	4.45	4.33	4.29	2.4	1.68	1.11
15	4.66	4.6	4.57	2.42	1.67	1.08
20	4.95	4.82	4.72	2.51	1.73	1.08
25	4.88	4.81	4.8	2.47	1.74	1.07
30	4.99	4.88	4.83	2.65	1.82	1.14
60	5.42	5.44	5.4	2.79	1.71	1.04
90	5.58	5.48	5.47	2.67	1.66	1.07
120	5.49	5.57	5.64	2.95	1.78	1.07
150	5.74	5.76	5.74	2.76	1.79	1.06

It can be observed from Table 5.1 that the number of iterations tends to increase continuously with a bigger group size of network graphs. The BSMA algorithm obtains the number of iterations between 4 to 6 rounds while the DCMR

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algorithm obtains between only 1 to 3 rounds. That means the BSMA obtains iterations more 2 to 4 times than the DCMR algorithm.

5.4.2 Average Shortest Path Calculation Per Round

The shortest path per round, which is calculated by using Dijkstra's algorithm, is the measurement of complexity of calculation whether it has more or less value. The average calculation of shortest path per round is the calculation of shortest path per round of each tree derived from the experiment of 100 graphs of both delay-constrained multicast routing algorithms.

Table 5.2: The average calculation of shortest path per round of BSMA and DCMR algorithms

Group Size	bsm-0 R	bsm-.5 R	bsm-1 R	dcm-0 R	dcm-.5 R	dcm-1 R
10	6.15	5.96	5.97	2	2	2
15	7.41	6.82	6.82	2	2	2
20	8.78	8.13	8.02	2	2	2
25	9.37	8.67	8.51	2	2	2
30	9.79	9.10	9.12	2	2	2
60	14.71	13.26	12.80	2	2	2
90	16.99	14.35	14.31	2	2	2
120	19.16	16.90	16.36	2	2	2
150	20.89	18.17	18.13	2	2	2

Table 5.2 shows the average calculation of the shortest path per round by using Dijkstra's algorithm for BSMA and DCMR algorithms. It has been found that although the group sizes increase, DCMR algorithm still calculates the shortest path only 2 rounds. The first time is to find the shortest cost path from source to destination, and the second is to find the shortest delay path from destination to source.

For BSMA algorithm, it has been found that when the group size increases, the average calculation of shortest path per round will increase also. The BSMA algorithm calculates the number of shortest path per round between 6 to 21 times.

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5.4.3 Average Time Per Round

The time per round is another important issue. For example, when we use the multimedia applications, it would like to spend less time in finding the multimedia routing tree. The average time per round is the time per round of each tree derived from the experiment of 100 graphs of both BSMA and DCMR algorithms.

The comparison of average time per round between BSMA and DCMR algorithm are shown in Figure 5.21 and Figure 5.22.

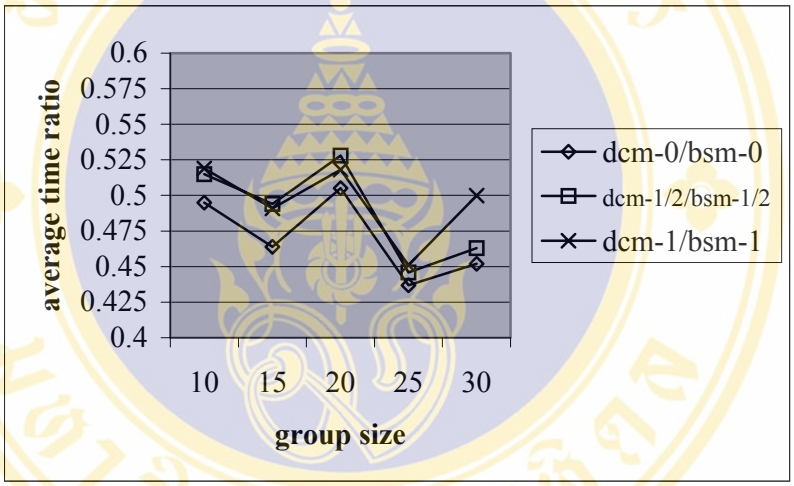

Figure 5.21: The average time per round ratio of DCMR algorithm comparing with BSMA algorithm for small sized group

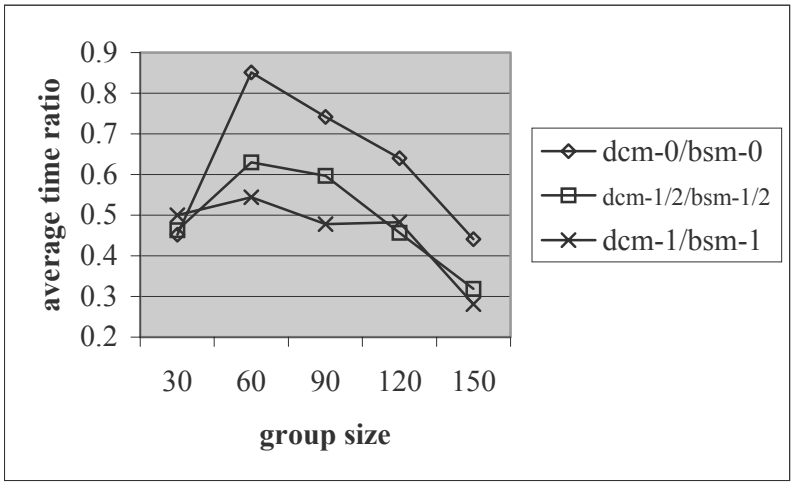

Figure 5.22: The average time per round ratio of DCMR algorithm comparing with BSMA algorithm for medium to large sized group

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From Figure 5.21 and 5.22, it can be seen that the average time per round of each group size of DCMR algorithm yields less value than BSMA algorithm's. Its time value is lesser about 2 to 4 times, especially when the group size is big.

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CHAPTER VI
DISCUSSION & CONCLUSION

This chapter will present the analysis and discussion of the results obtained from the experiment in the previous chapter. Particularly, the cost, delay, and scalability issues of multicast tree from the delay-constrained multicasting, will be discussed, and finally made the conclusion.

6.1 Discussion

The following will be the discussion on design of delay-constrained multicast routing algorithm on the issues of cost, delay, scalability, and complexity of algorithm respectively.

6.1.1 Overall Analysis

From the experimental results of Delay-Constrained Multicast Routing (DCMR), it is quite obvious that the DCMR algorithm could generate a multicast tree faster than the one from the BSMA algorithm. Therefore, the DCMR should be more suitable in real-time multicast applications, although both algorithms are given the same delay bound in the specification of delay time.

For the issue of cost with those graphs generated from the Random Graph program, we observed that some multicast trees obtained from the DCMA might yield higher cost in total. However, for some graphs such as Figure 3.8 in Chapter 3, the DCMR could yield the trees with lower cost in total than those obtained from the BSMA.

Therefore, when one applies the DCMR algorithm as a fast approach to obtain a multicast tree, there will be some chances, in which the cost is optimal. This would depend on the graph structures and the positions of both source and destination nodes.

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In case of both suitable nodes being selected, the DCMR would still produce a multicast tree with an optimal cost for sure.

6.1.2 Cost Analysis

The main purpose of generating a multicast tree is to obtain it with minimum cost. The present experiment measures the result on cost in two cases, one is its total cost obtained from the sum of the cost in each multicast tree, the other is its cost ratio obtained from the comparison of the total cost derived from each algorithm, such as from BSMA with KMB algorithm, or from DCMR with KMB algorithm.

For the cost issue as a whole, it is observed that for the case of delay-constrained multicast routing algorithm, the BSMA would be the one, which is able to yield the lowest cost. The cost obtained from the BSMA is less than the one from the DCMR by approximately not over 20% at any group sizes. The reason is that because the BSMA requires the procedure to find a new path in order to replace an old one by path switching, in which it would find a new path until finally it would no longer do so. The procedure is definitely quite different from the DCMR, in which the DCMR will still find a new path to replace the old one, as long as the old path is over the value of delay-bound (Δ). However, the total cost of delay-constrained multicast routing is still higher than the cost from the unconstrained multicast routing algorithm such as KMB algorithm.

6.1.3 Delay Analysis

For the issue of delay, the purpose of generating a delay-constrained multicast tree is to obtain it with delay value from the source to each destination that is not over the delay-bound (Δ). The present experiment measures the result on delay in two cases, one is its longest end-to-end delay from a source to destinations, another is the calculation of delay optimization (DO) from the equation (2) in Chapter IV, which is the total of delay value from each source-destination pairs divided by the number of destinations.

For the longest end-to-end delay value from a source to destinations, it is observed that the longest delay of trees that are generated from DCMR algorithm

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obtain lower efficiency than the one from BSMA algorithm, by approximately not over 30% for small group size and 20% for medium to large group size. The different efficiency of both algorithms may depend on the specified Δ value. However, it is observed that in some case the delay of tree that generated from BSMA obtains equal value to the one that generated from DCMR.

For the delay optimization (DO), the total delay is measured from all source-destination pairs divided by the number of destinations. It is observed in some cases that the tree obtained from BSMA is more efficient than the one from DCMR and vice versa.

Therefore, if we consider only the longest delay of source-destination pairs, the trees that are generated from BSMA will obtain lesser longest delay than the trees that are generated from DCMR. But if we consider all delay of source-destination pairs, the trees that are generated from DCMR may yield better delay, it depend on the delay bound (Δ) value as well. However, the total delays of both algorithms are still higher than the SPT, which is the end-to-end shortest delay tree.

6.1.4 Scalability Analysis

For the scalability issue, we would concern the number of iterations and the time per round of measurement, whether these are suitable for the group size of the network graph. The main point of iteration for delay-constrained is “path switching”, which repeats iteratively to find a new path to replace an old path that is not over the delay bound. While finding out the new path, it will calculate the shortest path per round of iteration by using Dijkstra’s algorithm.

In addition, it found from the experimental results that the average number of iteration and the shortest path calculation per round of the trees obtained from DCMR are lower than the one from BSMA. It is due to the path switching of DCMR, which will process only the path that over the delay bound (as stated in the Chapter 3). Furthermore, this experiment has specified four destination nodes, then the source-destination paths that over delay bound are between 1-2 paths only.

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In conclusion, the results from path switching of DCMR yield less number of iterations than of BSMA. Therefore, the time per round of DCMR will be less accordingly. It can be concluded that DCMR spends less time than BSMA in the magnitude about 2-4 times.

6.1.5 Complexity

When we consider the n nodes network that have m nodes participants of multicast group, the time complexity of DCMR algorithm will be considered as follows;

From flowchart of DCMR Heuristic as shown in Figure 3.1 in Chapter 3, we will see at the beginning part of DCMR that it uses the KMB algorithm, which has $O(m\ n^2)$ for the time complexity. The second part will be the same as the BSMA algorithm's on the iteration to find the "path switching".

However, Zhu et. al. (1995)[9] has proved the theory of the expected time complexity of BSMA. They found that it would be at $O(kn^3 \log(n))$; where "k" is the k-shortest path. They stated that the maximum expected number of path switching would be at $O(n\log(n))$. While the shortest path finding by using Dijkstra's shortest-path algorithm found the time complexity at $O(n^2)$. So, the second part will have the time complexity at $O(n^2 * n\log(n)) = O(n^3\log(n))$.

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6.2 Conclusion

This research emphasizes the multicast routing algorithm. There are many methods for classifying the algorithm's types, depending on the interested or specified criteria, such as types of tree and/or link, which were investigated in the experiment. For the type of tree, there are unconstrained and constrained trees. The experiment aims to investigate and develop the constrained multicast routing which is the end-to-end delay.

For the type of link, there are symmetric and asymmetric links, in which the symmetric link that the weight from node A to node B is equal to the weight from node B to node A has been investigated in the study.

The Delay Constrained Multicast Routing (DCMR) is designed by referencing the concept of KMB algorithm in the minimum cost tree (based on MST) combined with the concept of BSMA in case of the iterative path switching by using the Short Path Tree (SPT). The complexity of DCMR is in the order of $O(n^3 \log(n))$.

After designing the DCMR algorithm, we then initially test the work with some fixed graphs for experiment. It actually yields a multicast tree that has total cost lower than the one from BSMA algorithm as the consequence. Therefore, we further perform the experiment with the Random Graph based on Waxman's algorithm with 9 graph sizes such as 10, 15, 20, 25, 30, 60, 90 and 150 nodes. Each size was produced 100 different forms of network graphs, with randomly selecting 1 source node and 4 destination nodes.

The results show that the trees obtained from DCMR algorithm would yield higher total cost than those from BSMA algorithm, approximately less than 20 %. Furthermore, for the issue of delay, the longest end-to-end delay of the trees that obtained from DCMR would yield lower efficiency than those from BSMA, approximately less than 30 % for the small group size, and less than 20 % for the medium to large group size. However, for the delay optimization (DO) issue, the results could not be conclusive as in some cases, the trees obtained from DCMR algorithm yields better efficiency than those obtained from BSMA, whereas in some other cases, the results were in opposite, in which BSMA yields better efficiency

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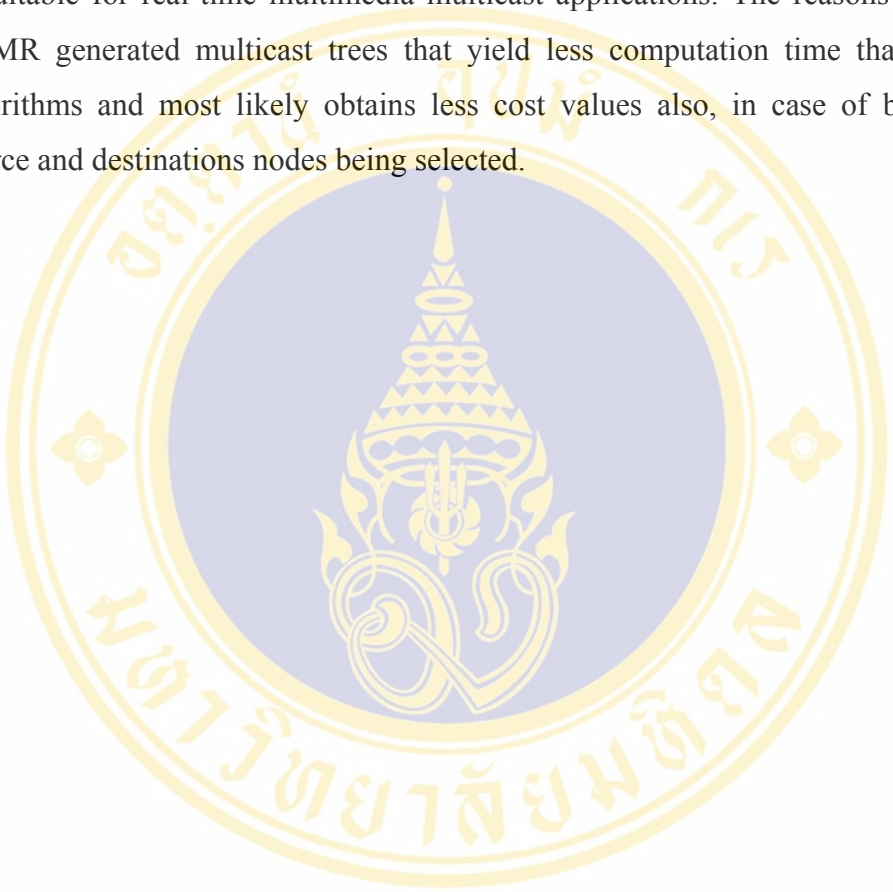
instead. Finally, for the average time per round issue, the DCMR algorithm always spends less time than BSMA algorithm in the magnitude about 2-4 times simply because the DCMR requires less number of iterations than BSMA algorithm.

In conclusion, DCMR is a delay-constrained multicast routing algorithm that is suitable for real-time multimedia multicast applications. The reasons are because DCMR generated multicast trees that yield less computation time than any other algorithms and most likely obtains less cost values also, in case of both suitable source and destinations nodes being selected.



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CHAPTER VII
SUGGESTIONS FOR FUTURE WORK

In this final chapter, we will propose some suggestions for further investigation that are related to the design of the multicast routing algorithm as follows;

1. Experiment with asymmetric link

This research is suitable for the symmetric link, in which most communication is a wired technology type. If there are other supports needed for wireless technology such as satellite communications, it should also be developed for asymmetric link.

2. Group membership

This research is suitable for unchanged of the group membership, or simply a static group. The future work should attempt on a dynamic group as well.

3. Routing information

The algorithm for this research is the source-based algorithm, or centralized characteristic. The future work should attempt on a distributed algorithm.

4. Large scale of network

In case of a very large network, it should be separated the network nodes by hierarchy or by group cluster to reduce the calculation task and save the time for calculation.

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APPENDIX A

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APPENDIX A
BSMA

INPUT

G(V, E) = graph, s = source node, D = set of destination node,
DB = set of delay bound for destination nodes,
id = cost function type for the tree, which can be
utilization driven, to minimize the total link cost, or
congestion driven, to minimize the maximal link cost.

OUTPUT

A delay bounded Steiner tree spanning $D \cup \{s\}$

PROCEDURE MulticastTree(G(V, E), s, D, DB, id) {

```
j ← 0;
T_j ← minimum-delay tree spanning D ∪ {s}
        found using Dijkstrs's algorithm
loop {
    if (id = utilization driven)
        p_h ← an unmarked superedge in T_j with the highest cost
            among all unmarked superedges (not compared with
            marked superedges);
    else if (id = congestion driven)
        p_h ← an unmarked superedge in T_j with the highest cost
            among all superedges (compared with marked superedges)
    if (p_h = NULL)
        Return;
    Mark superedge p_h;
    Remove p_h from tree T_j, getting two subtree T^1 and T^2;
    p_s ← DelayBoundedShortestPath (G, s, DB, T^1, T^2);
    j ← j + 1;
    T_j ← p_s ∪ T^1 ∪ T^2;
    if ( p_s ≠ p_h)
        Unmark all marked superedges;
}
}
```

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APPENDIX B

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APPENDIX B
DCMA

Notation used in DCMA	
s	Source node
D	Set of destination nodes
Δ	Delay constraint
active_node	Current active node during tree construction
Q	Vector of size |D|
m_1	The first member of D
ON	An integer vector of size |V|. ON[*i*] = 0 means node *i* is not on an exiting tree. If ON[*i*] > 0, the value of ON[*i*] represents the parent node of node *i* on the constructed tree.
ld_lhop	The predecessor of the current active_node on the path P_{ld}(s, active_node)
lc_lhop	The predecessor of the current active_node on the path P_{lc}(s, active_node)

/* The nodes of the network G(V, E) are numbered 1 through n. */

1. **Begin**
2. **for** each node v, v ∈ D, **do**
3. **if**(D(P_{ld}(s, v) > Δ), no feasible tree can be found and DMA terminates.
4. **end for**
5. **for** i ← 1 to n **do**
6. ON[i] ← 0
7. **end for**
8. **for** i ← 1 to |D| **do**
9. Q[i] ← NULL
10. **end for**

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11. ON[s] ← s; // s is the first node on the tree and its parent node on tree is simply recorded as itself
12. Sort the members of D in a descending order based on the delay of the LD path from node s to every group member
13. **while** D is not empty **do**
14. active_node ← m_1
15. d ← m_1
16. remove m_1 from D
17. **while** ON[active_node] = 0 **do**
18. $D(P_{ld}(active_node, d) = D(P_{ld}(s, d)) - D(P_{ld}(s, active_node))$[1]
19. **if** $D(P_{lc}(s, active_node)) + D(P_{ld}(active_node, d)) > \Delta$
20. ON[active_node] ← ld_lhop // record active_node's parent node on tree
21. active_node ← ld_lhop
22. **else**
23. Q[d] = active_node // Q[d] is the relay node for current group member d in constrained path obtained by SDCR
24. **break** // terminate the inner **while** loop
25. **end if-else**
26. **end while**
27. **end while**
28. **for** i ← 1 to |D| **do**
29. **if** Q[i] ≠ NULL
30. active_node ← Q[i]
31. **while** ON[active_node] = 0 **do**
32. ON[active_node] ← lc_lhop
33. active_node ← lc_lhop
34. **end while**
35. **end if**
36. **end for**
37. **End**

[1] The satisfaction of this equality is guaranteed because the LD path from active_node to d is exactly the last part of the LD path from s to d.

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